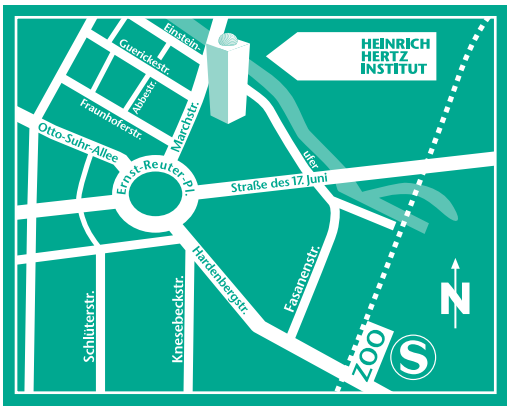




Fraunhofer
Institut
Nachrichtentechnik
Heinrich-Hertz-Institut

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Innovationen für die digitale Zukunft!

Die moderne Kommunikations- und Informationstechnik hat in nahezu allen Bereichen der Gesellschaft wie Industrie, Arbeit, Ausbildung, Verwaltung, Gesundheitsversorgung, Kultur und Unterhaltung zu grundlegenden Veränderungen geführt. Besonders sichtbar wird das durch die stetig steigende Nutzung des Internets und den raschen Ausbau der Breitband-Mobilkommunikation. Bandbreite für Jeden ist zukünftig ein Muß zur Aufrechterhaltung und Steigerung der Leistungsfähigkeit einer Nation im nationalen Maßstab wie auch im weltweiten Miteinander. Die gegenwärtige rasante Entwicklung der digitalen Medien, des Internets, der PCs sowie der digitalen Endgeräte wie DVD-Player, Camcorder und digitales Fernsehen ist der Motor für den Ausbau der Breitbandkommunikationsnetze.

Trotzdem stehen wir bisher erst am Anfang des Übergangs zur Wissensgesellschaft, deren Existenz von der Verfügbarkeit moderner Kommunikationsmittel abhängt. Viele Möglichkeiten moderner IT-Lösungen erschließen sich erst Schritt für Schritt und gewissermaßen in einem ständig fließenden Entwicklungszyklus. Wie schnelle Prozessoren die Grundlage für die Entwicklung noch schnellerer Prozessoren ist, so bekommt man erst durch die Anwendung von Breitbanddienstleistungen eine Vorstellung davon, wie die Arbeitswelt der Zukunft aussehen könnte. Integriertes Videoconferencing und das gemeinsame Bearbeiten von Dokumenten über unbegrenzte Entfernungen hinweg sind heute in modernen Unternehmen eine Selbstverständlichkeit, genauso wie das „Follow the Sun“-Prinzip, bei dem beispielsweise computerbasierte Konstruktionsunterlagen nahtlos von asiatischen Konstrukteuren an europäische und über amerikanische wieder zurück an asiatische übergeben werden. Die Effektivität von Entwicklungs- und Produktionsabläufen kann damit enorm gesteigert werden.

Innovationen für diese Zukunft – d. h. sowohl auf dem Gebiet der modernen Kommunikationssysteme als auch auf den Gebieten der digitalen Medien und der Dienstenutzung – stehen im Mittelpunkt der Forschungs- und Entwicklungsarbeiten des Heinrich-Hertz-Instituts auf seinen strategischen Geschäftsfeldern

- Kommunikationsnetze und -systeme
- Komponenten für Kommunikationsnetze
- Elektronische Bildtechnik für Multimedia und
- Dienste und Unterstützung in Messtechnik und Entwicklung.

Neue Techniken und Übertragungsverfahren zur besseren Nutzung der Glasfaserübertragungsstrecken sowie zur Steigerung der Leistungsfähigkeit photonischer Netze werden in dem Geschäftsfeld „Kommunikationsnetze

und -systeme“ entwickelt und untersucht. Hierbei werden Netze vom Core- über den Access- bis hin zum Customer-Bereich betrachtet. Schwerpunkte sind Entwicklungsarbeiten für Low-Cost-Systeme auf der Basis von Polymer-Fasern (POF) bis hin zu F&E-Arbeiten für Übertragungssysteme höchster Kapazität in Telekommunikations- und Datacom-Netzen, bei denen das gesamte zur Verfügung stehende Übertragungsband der Glasfaser genutzt werden soll. Steigerung der Übertragungsrate in Richtung auf 1 Terabit pro Sekunde mit Hilfe der optischen Zeitmultiplextechnik, Nutzung der Faserkapazität durch Einsatz der Wellenlängenmultiplextechnik, Dispersionskompensation, nichtlineare Effekte, höherwertige Modulationsverfahren und optische Signalregeneration sind wichtige Themen, die in diesem Zusammenhang bearbeitet werden. Neben der Betrachtung rein physikalisch-technischer Fragestellungen werden Untersuchungen und Entwicklungen zum Management photonischer Netze sowie zum Zusammenwirken der Protokollebenen mit der physikalischen Ebene durchgeführt. Es erfolgen Untersuchungen zu optischen Netzknoten für die Leitungs- und Burstvermittlung, zum Schaltverhalten des Netzes, zur Transparenz und zum Performance-Monitoring.

Für die mobilen Breitbandsysteme werden Algorithmen für Mehrantennensysteme, Mehrträgersysteme und CDMA-Systeme und Verfahren zum Ressourcenmanagement sowohl für zellulare Mobilfunksysteme als auch für WLAN, sowie zur QoS-Unterstützung der Teilnehmer in Abhängigkeit der jeweiligen Kanalqualität mittels neuer Cross-Layer-Optimierungsansätze entwickelt und untersucht. Dabei besteht die besondere Herausforderung in der Beherrschung der Komplexität dieser Aufgaben unter Berücksichtigung von Echtzeitanforderungen. Neben diesen Gebieten wurden neue Projekte im Bereich drahtloser Ad-hoc-Systeme, Car-to-Car-Kommunikation, Meshed Networks und drahtloser Sensorsysteme gestartet. Im Zentrum des Interesses stehen hier neben der Optimierung von Übertragungsverfahren auch Fragen des Routings, Scheduling und Load Balancings. Der gestiegenen Bedeutung der Gesamtsystemoptimierung konnte dahingehend Rechnung getragen werden, dass im Jahr 2005 mit Industriepartnern Projekte zum Access-Management unter Berücksichtigung des Mobilitätsverhaltens der Teilnehmer gestartet wurden. In diesen Projekten werden auch Architekturfragen für unterschiedliche Access-Systeme bearbeitet. Damit haben wir in diesem Geschäftsfeld den Fokus, der bisher ausschließlich auf der physikalischen Schicht lag, stark verbreitert.

Die für diese Netze erforderlichen optischen und optoelektronischen Komponenten und Module werden in dem Geschäftsfeld „Komponenten für Kommunikationsnetze“ entwickelt und hergestellt. Das Spektrum umfaßt sämtliche



Indiumphosphid-basierten Halbleiterkomponenten mit Schlüsselfunktionen für die optische Übertragung und Signalverarbeitung. Das sind u. a. breitbandig modulierbare Laser für ungekühlten Betrieb zur Verwendung in Metro- und Zugangsnetzen, Photodioden mit einer Bandbreite von bis zu 110 GHz für den Einsatz in hochkapazitiven Datennetzen sowie optische Halbleiterverstärker und laserbasierte Komponenten für die rein optische Signalregeneration. Für zukünftige, neuartige Funktionselemente werden F&E-Arbeiten zu photonischen Kristallen, d. h. im nanotechnologischen Bereich, durchgeführt. Neben den aktiven Komponenten werden passive planaroptische Bauelemente, insbesondere auf Polymerbasis, entwickelt und hergestellt. Diese umfassen u. a. Koppler, Wellenlängenmultiplexer und thermooptische Schaltmatrizen. Polymerkomponenten sind wegen der geringen Herstellungskosten besonders attraktiv für den Masseneinsatz in optischen Zugangsnetzen und Inhouse-Systemen. Ein weiterer Schwerpunkt ist die Realisierung komplexer opto-elektronischer ICs in hybrider und monolithischer Integration. Die genannten Entwicklungsarbeiten werden zusammen mit Industriepartnern durchgeführt, um sie in möglichst kurzer Zeit in marktfähige Produkte zu überführen. Neben der optischen Nachrichtentechnik gibt es neue, zunehmend bedeutende Anwendungsfelder für optische/optoelektronische Komponenten in der Sensorik, Bio- und Medizintechnik sowie der Fahrzeugtechnik und Verkehrstelematik, für die das HHI Entwicklungen durchführt.

Das Geschäftsfeld „Elektronische Bildtechnik für Multimedia“ arbeitet an den Voraussetzungen für die Nutzung von Multimedia-Diensten in den digitalen Netzen der nächsten Generation. Die Kompetenzen liegen bei der Bildcodierung für Anwendungen, die sich vom Video-Handy bis zum Digitalen Kino erstrecken, in der robusten Übertragung über mobile Kanäle sowie bei der 2D- und 3D-Bildsignalverarbeitung. Es werden innovative Bildwiedergabetechniken entwickelt, die das gesamte Spektrum von der Darstellung virtueller und gemischt-realer Umgebungen, über tele-immersive Systeme, HDTV und 3DTV-Großbildprojektionen bis hin zu Multiview-Systemen und autostereoskopischen 3D-Displays abdecken. Darüber hinaus werden neuartige intuitiv nutzbare Mensch-Maschine-Schnittstellen entwickelt und untersucht, um die Gebrauchstauglichkeit und Nutzerfreundlichkeit künftiger mobiler und stationärer Endgeräte sicherzustellen.

Darüber hinaus bietet das Geschäftsfeld „Dienste und Unterstützung in Messtechnik und Entwicklung“ die Möglichkeit, Erfahrungen und Technik des Instituts für Messaufgaben und Entwicklung von Hard- und Software zu nutzen. Bei allen F&E-Aktivitäten des HHI steht die Verbindung zur Industrie und die Verifizierung der späteren Realisierbarkeit im Vordergrund.

Einige wichtige Ereignisse und große Erfolge aus dem Berichtszeitraum sollen hier heraus gehoben werden:

- Die bedeutendste Auszeichnung im Jahr 2004 erhielt die Abteilung Bildsignalverarbeitung: Den mit 10.000€ dotierten Joseph-von-Fraunhofer-Preis 2004 der Fraunhofer-Gesellschaft für herausragende wissenschaftliche Leistungen zur Lösung anwendungsnaher Probleme. Sie lieferten sowohl auf technischer Ebene als auch im Rahmen leitender Funktionen entscheidende Beiträge zum neuen internationalen Videocodierstandard H.264/AVC. Gegenüber dem bisherigen MPEG-2-Standard erzielt H.264/AVC eine 2- bis 3fach niedrigere Datenrate bei subjektiv gleicher Qualität. Das neue Verfahren wird unter anderem für zukünftige HDTV-Satellitenübertragungen und voraussichtlich weltweit in allen zukünftigen UMTS-Handys eingesetzt werden. Darüber hinaus erhielten die drei ausgezeichneten Wissenschaftler auch den ITG-Literaturpreis für eine Veröffentlichung über das von ihnen entwickelte Entropycodierverfahren CABAC (Context Adaptive Binary Arithmetic Coding), das Teil des H.264/AVC-Standards ist.
- Sehr große Aufmerksamkeit erzielte die erste mobile Gbit/s-Datenübertragung. In einem gemeinsamen Projekt haben die Fraunhofer-Institute HHI und MCI, die Siemens AG und die IAF GmbH am 30. November 2004 in Braunschweig eine breitbandige mobile Funkübertragung mit einer Brutto-Datenrate von 1039 Mbit/s demonstriert. Dafür wurde die bekannte OFDM-Technik, welche schon in einigen drahtlosen Standards verwendet wird wie z. B. DVB-T, 802.11a/g (WiFi) und 802.16 (WiMax), mit Mehrantennentechniken kombiniert, die auch als MIMO (Multiple-Input Multiple-Output) bekannt sind. Das System wurde auf dem 3GSM World Congress 2005 in Cannes von der Siemens AG erfolgreich vorgestellt. Auf der CeBIT konnten bereits die Link-Adaption und das Scheduling für MIMO Mehrnutzer Szenarien demonstriert werden und stellen damit ein Beispiel für die Arbeiten im Bereich der Cross-Layer-Optimierung dar.
- Zwei Highlights auf dem Gebiet der Photonik sind die Demonstration einer 640 Gbit/s-Datenübertragung über eine Glasfaserstrecke mit einer Länge von 160 km und die Realisierung einer Photodiode mit einer Bandbreite von 110 GHz, die zur Zeit von Systemherstellern evaluiert und von einer Partnerfirma in ein Produkt überführt wird.
- Nicht unerwähnt bleiben soll die erneute erfolgreiche Zertifizierung des Qualitätsmanagementsystems DIN EN ISO 9001:2000 im März 2005.

Die F&E-Arbeiten werden im Auftrag nationaler und internationaler Großunternehmen und KMUs, Netzbetreibern sowie der öffentlichen Hand, wie Land Berlin, Bund, DFG und EU, durchgeführt.



Herr Professor Dr. Joachim Hesse, der das Institut seit Mai 2002 für eine Übergangszeit leitete, hat Ende April 2004 sein Amt niedergelegt. Er hat in dieser Zeit das HHI erfolgreich in die Fraunhofer-Gesellschaft überführt. Die Mitarbeiterinnen und Mitarbeiter des HHI danken ihm auf diesem Wege für sein großes Engagement in der Übergangszeit und wünschen ihm für die Zukunft alles Gute.

Seit Mai 2004 nahm ein Geschäftsführungsgremium bestehend aus vier Abteilungsleitern die Institutsleitung wahr. Zum 1. April 2005 ist mit Herrn Dr. Hans-Joachim Grallert und Herrn Professor Dr. Dr. Holger Boche vom Vorstand der FhG die neue Institutsleitung des HHI berufen worden.

Als ein Institut der Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. ist uns Forschung und Entwicklung für industrielle Anwendungen ein selbstverständliches Anliegen. Der Erfolg eines Unternehmens steckt in den Köpfen seiner Mitarbeiter im Wissen über Produkte, Verfahren, Zusammenhänge. Die Leistungskraft des Instituts beruht auf der Kreativität und dem Optimismus unserer Mitarbeiterinnen und Mitarbeiter und der Unterstützung durch unsere zahlreichen Geschäftspartner und Förderer. Ihnen allen gilt unser besonderer Dank!

Insgesamt kann die aktuelle Situation wie folgt zusammengefasst werden:

- Das HHI hatte 2004 im Durchschnitt 250 Mitarbeiterinnen und Mitarbeiter.
- Mit den ca. 150 Projekten wurden im Jahr 2004 Erträge in Höhe von 11,6 Mio. € (siehe Bild 2) erwirtschaftet. Das getätigte Investitionsvolumen betrug in 2004 1,7 Mio.€.
- Das Institut genießt hohes internationales Ansehen in Wissenschaft und Industrie.
- Es verfügt über technisch hochwertige, teilweise einzigartige technologische Ressourcen.
- Es hat eine ausgewogene und hoch qualifizierte Mitarbeiterstruktur und ein gutes Betriebsklima mit kollegialer Zusammenarbeit der installierten Gremien.
- Das HHI kooperiert eng mit Universitäten; einige Institutsangehörige nehmen Lehraufträge wahr; zahlreiche Doktoranden, Diplomanden, studentische Hilfskräfte und Praktikanten werden an den Projekten beteiligt.

Das Geschäftsführungsgremium im Frühjahr 2005
Prof. Dr.-Ing., Dr. rer. nat. H. Boche, Dipl.-Ing. H. Mrowka,
Dr.-Ing. R. Schäfer, Dipl.-Ing. G. Walf

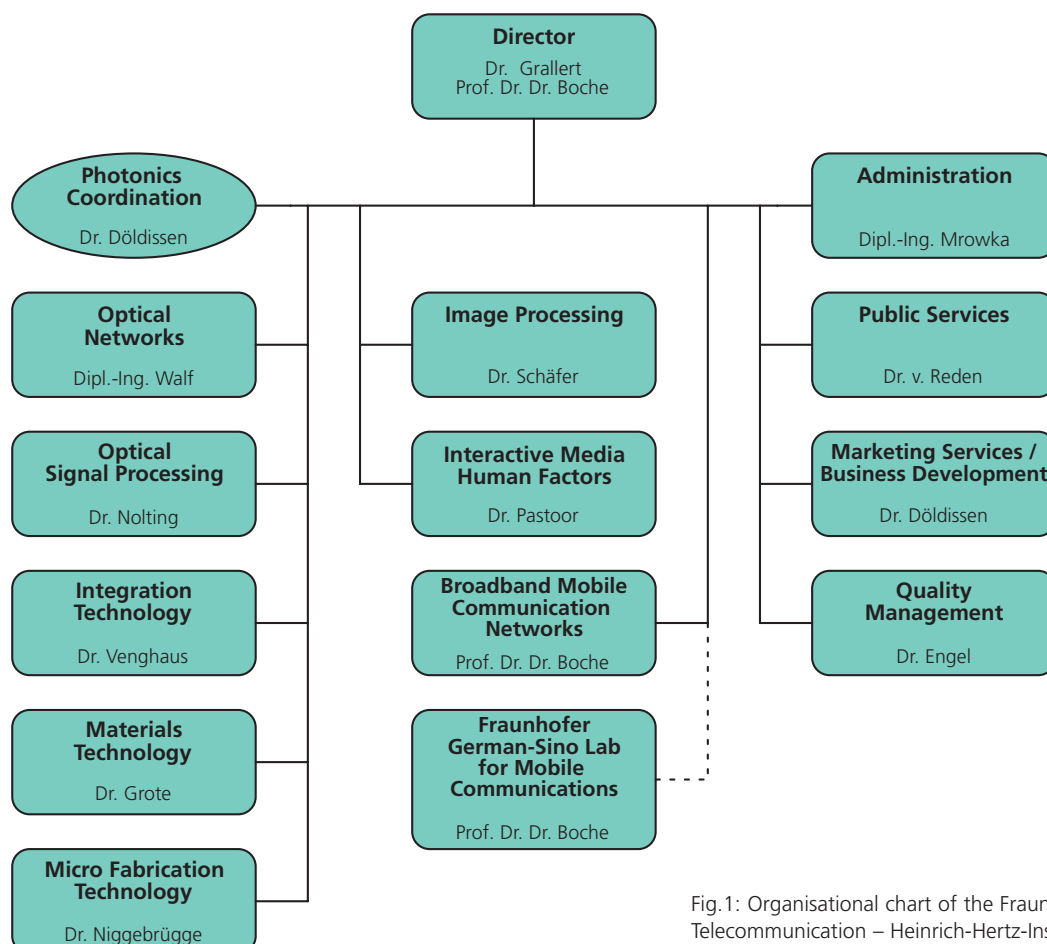


Fig.1: Organisational chart of the Fraunhofer-Institute for Telecommunication – Heinrich-Hertz-Institut. The various fields of activity are organised into departments

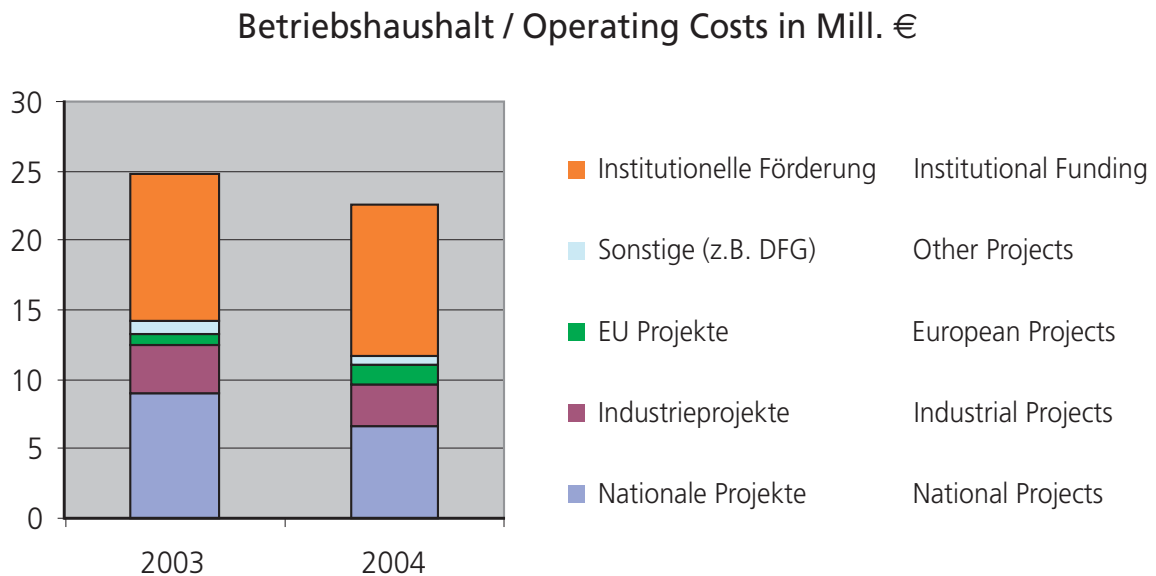


Fig. 2: Development of operating costs and sources of funding in 2003 and 2004

Innovations for the digital future!

Today's communication and information technology has brought about fundamental change in almost all areas of society, such as industry, labor, education, administration, health care, culture and entertainment. This becomes particularly apparent in the ever-growing use of the Internet and the rapid expansion of broadband mobile communications. In future, broadband will be a must for everybody in order to maintain and boost a nation's efficiency both on a national and on an international level. The tremendous pace of development in digital media, the Internet, PCs as well as digital devices, such as DVD players, camcorders and digital TV, is the driving force behind the development of broadband communication networks.

But we are just at the beginning of the transition to the information society, the very existence of which depends on the availability of state-of-the-art means of communication. Many of the possibilities offered by advanced IT solutions are only gradually unfolding in what is, so to speak, a continuously flowing development cycle. In much the same way as fast processors are the basis for the development of even faster processors, it is only the application of broadband services which gives us an idea of how the working environment of the future might look. Integrated videoconferencing and joint editing of documents over indefinite distances are today a matter of course in modern companies, just like the "follow the sun" principle where, for example, computer-based design documents are smoothly passed on by Asian designers to their European and US colleagues and back to Asian colleagues again. The efficiency of development and production processes can thus receive an enormous boost.

Innovations for this future – i.e. both in the field of state-of-the-art communications systems and in the field of digital media and services use – are at the heart of research and development work carried out by Heinrich-Hertz-Institut in its strategic business fields, i.e.

- communications networks
- electronic imaging technology for multimedia
- components technology
- development support

New technologies and transmission methods for better utilization of optical fiber transmission systems and for boosting the performance of photonic networks are developed and explored by the fixed and wireline approach of "communications networks" business field, dealing with networks from the core, to access and right through to the customer area. Focal areas include development work on low-cost systems based on polymer fibers (POF) as well as R+D work on very-high-capacity transmission systems in telecommunications and data communication networks where the available transmission band of the optical fiber is to be fully used. Important issues addressed in this context include increasing the data rate towards 1 terabit per second using optical time-multiplex technology, and wavelength multiplex technology in order to make full use of the fiber capacity, as well as dispersion compensation, non-linear effects, better modulation methods and optical signal regeneration. Besides purely physical/technical issues, other studies and developments deal with the management of photonic networks as well as the interaction of the protocol layers with the physical layer. Studies deal with optical



network nodes for line and burst switching, network switching behavior as well as transparency and performance monitoring.

The optical and opto-electronic components and modules needed for these networks are developed and manufactured by the "components technology" business field. The range covers all indium phosphide-based semiconductor components with key functions for optical transmission and signal processing. These include, for instance, lasers with broadband modulation capability for uncooled operation and use in metro and access networks, photo-diodes with a bandwidth of up to 110 GHz for use in high capacitive data networks, as well as optical semiconductor amplifiers and laser-based components for purely optical signal regeneration. R+D work on photonic crystals, i.e. in the nanotechnology range, is underway in order to develop new future function elements. Besides the active components, passive planar optical components are developed and manufactured, especially on a polymer basis. These components are manufactured at low cost and are hence particularly attractive for mass applications in optical access networks and in-house systems. Another focal point of work is the implementation of complex, opto-electronic IC with hybrid and monolithic integration. The above-mentioned development work is carried out together with industry partners in order to minimize time to market.

The mobile broadband systems develop and explore algorithms for multi-antenna systems, multi-carrier systems and CDMA systems and methods for resource management for both cellular mobile radio systems and for WLAN, as well as for QoS subscribers depending on the respective channel quality using new cross-layer optimization approaches. The special challenge in this context is to master the complex nature of these tasks, taking realtime requirements into consideration. In addition to these areas, new projects are being launched in the field of wireless ad-hoc systems, car-to-car communication, meshed networks and wireless sensor systems. Focal points of interest in this context include the optimization of transmission methods as well as aspects related to routing, scheduling and load balancing. The increased importance of integrated system optimization is reflected by the fact that access management projects were launched in 2005 together with industry partners, taking subscribers' mobility behavior into consideration. These projects also address architecture issues for different access systems. We have thereby significantly broadened the focus which was formerly exclusively placed on the physical layer.

The "electronic imaging technology for multimedia" business field is working on the preconditions for the use of multimedia services in the next generation of digital networks. Competence exists in the coding of images for

applications from video mobile phones to digital cinema, in the robust transmission through mobile channels, as well as in 2D and 3D image signal processing. Innovative image rendering techniques are being developed, covering the full range from the rendering of virtual and mixed real environments via tele-immersive systems HDTV and 3DTV large screen projection as well as multiview systems and auto-stereoscopic 3D displays. Furthermore, new human-machine interfaces designed for intuitive use are being developed and explored in order to ensure the suitability and user-friendliness of future mobile and stationary devices.

As "development support" we offer in addition access to infrastructural skill and equipment of the institute and its personnel.

Links with industry and verification of implementability are central aspects of all R+D activities pursued by HHI.

Some important results and major successes from the period under review which deserve special mention are reported below.

- The image signal processing department won the most important award in 2004: the Joseph-von-Fraunhofer prize 2004 awarded by Fraunhofer-Gesellschaft for outstanding scientific achievements for solving application-near problems. Both on a technical level and within the scope of managing functions, the department made key contributions towards the new international H.264/AVC video coding standard. Compared to the present MPEG-2 standard, H.264/AVC achieves a 2 to 3 times lower data rate with subjectively the same quality. The new method will be used, for instance, for future HDTV satellite transmissions and is likely to be used world-wide in all future UMTS mobile phones. Furthermore, the three prize-winning scientists also won the ITG Outstanding Paper Award for a publication on the CABAC (Context Adaptive Binary Arithmetic Coding) entropy coding method which was developed by them and which forms part of the H.264/AVC standard.
- The first mobile Gbps transmission met with great interest. In a joint project, the Fraunhofer Institutes HHI and MCI, Siemens AG and IAF GmbH demonstrated a broadband mobile radio transmission with a gross data rate of 1039 Mbps on 30 November 2004 in Braunschweig, Germany. For this purpose, the familiar OFDM technology which is already used in several wireless standards – such as DVB-T, 802.11a/g (WiFi) and 802.16 (WiMax) – was combined with multi-antenna techniques which are also known as MIMO (Multiple-Input Multiple-Output). The system was successfully demonstrated by Siemens AG at the 3GSM World Congress 2005 in Cannes, France. At the CeBIT, link adaptation and scheduling for MIMO



multi-user scenarios were already demonstrated, providing an example of the work carried out in the field of cross-layer optimization.

- Two highlights in the field of photonics are the demonstration of 640-Gbps data transmission through an optical fiber system measuring 160 km in length and the implementation of a photo diode with a bandwidth of 110 GHz which is currently being evaluated by system manufacturers and perfected to product maturity by a partner company.
- Another achievement that deserves mention is the repeated, successful certification of the quality management system according to DIN EN ISO 9001:2000 in March 2005.

The R+D work is carried out on behalf of large national and international companies as well as small and medium-sized enterprises, network operators and the public sector, such as the Federal Land of Berlin, the Federal Government, DFG and the EU.

Professor Dr. Joachim Hesse, who led the institute starting in May 2002 for an interim period, resigned from office in April 2004. During this term, he successfully integrated HHI into the Fraunhofer-Gesellschaft. The staff of HHI would like to thank him here for his commitment during the interim period and wish him all the best for his future.

Since May 2004, a board consisting of four heads of department led the institute.

Effective as of 1 April 2005, the Management Board of the Fraunhofer-Gesellschaft appointed Dr. Hans-Joachim Grallert and Professor Dr. Dr. Holger Boche new directors of HHI.

In our capacity as an institute of Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V., research and development for industrial applications are our prime and natural concern. A company's success is rooted in the minds of its employees and their knowledge of products, processes and contexts. The institute's performing power is based on our staff's creativity and optimism as well as support by our many business partners and sponsors. We would like to specially thank all of them!

The current situation can be generally summarized as follows.

- In 2004, HHI employed a staff of 250 on average.
- With around 150 projects, HHI generated revenue of € 11.6m (refer to Fig. 2) in 2004. The investment volume in 2004 totaled € 1.7m.
- The institute enjoys a high international reputation in the science and industry communities.
- It features technically advanced, sometimes even unique technological resources.
- The institute has a well-balanced and highly qualified staff structure and a good working atmosphere with a cooperative spirit of the bodies in place.
- HHI cooperates closely with universities. Some members of the institute teach at universities. Numerous post-graduates, pre-graduate students, student assistants and interns are involved in its projects.

The Management Board in spring 2005

Prof. Dr.-Ing., Dr. rer. nat. H. Boche, Dipl.-Ing. H. Mrowka,
Dr.-Ing. R. Schäfer, Dipl.-Ing. G. Walf

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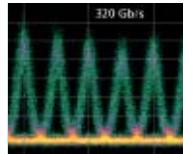
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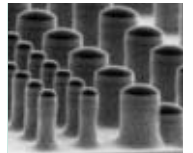
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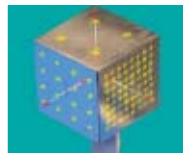
Image Processing

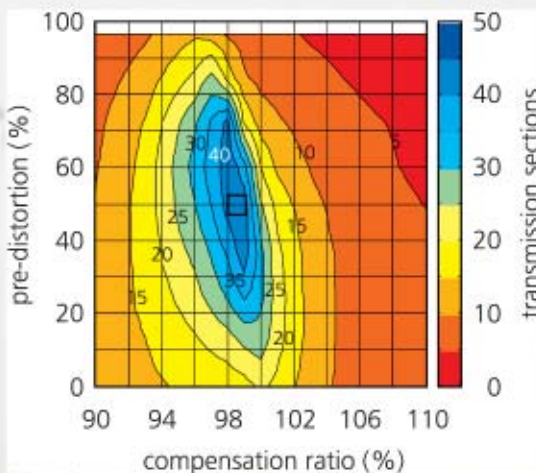
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Broadband Mobile Systems

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Photonic Networks and Systems

Photonic networks are the foundation of modern world-wide communication systems. They consist of optical fibre systems with optoelectronic or optical switching nodes. Compared to traditional copper-based and radio frequency systems, the spectral width of the fibre transmission band is 70 Terahertz and offers virtually unlimited transmission capacity; it has led to the creation of the global data super highway. Telephone calls and the worldwide exchange of e-mails, graphics, video and other data across the Internet have been available at affordable cost. The creation of this information super highway ensured the triumphant success of the Internet, which has become an indispensable tool for everybody.

Despite the economic downturn of the IT industry traffic still doubles every year. Private and business users increasingly demand bandwidth for faster Internet access. One major problem, however, is the currently insufficient broadband access forming a bottleneck between the network and the user. The copper-based DSL-technology with moderate transmission rates in the Mbit/s range can only be an intermediate step towards a truly broadband fibre access (Fibre to the Home, FTTH). In some countries such as Japan, Korea, and the USA, there are – often highly subsidised – programmes to implement FTTx access with over 100 Mbit/s line rates for the private subscriber and several Gb/s for the business user.

Above all, a cost reduction in all network areas is necessary to provide the user with bandwidth at acceptable costs. This goal could be achieved by making the present static network more flexible and by using network resources more efficiently. Also, photonic networks are a prerequisite for the realisation of broadband mobile communication systems. The photonic network layer is necessary for the broadband connection between the base stations. In future pico-cell broadband mobile communication systems, an intelligent combination of wireless channels, base stations and optical interconnections will be required.

Since the 1970's, the HHI has been actively involved in the research and development of optical transmission systems and networks in cooperation with the industry and network operators. The HHI is among the few select institutes worldwide which have worked in the field of optical telecommunications from its inception and contributed decisively to its progress.



The main goal of present R&D activities is the use of new technologies and transmission schemes to achieve an improved utilisation of optical fibre transmission systems and increased capacity of photonic networks. This strategy covers all network aspects from the core, metro and access to the customer network. The nature of these investigations ranges from R&D tasks to purely physical-technical issues but also covers the development and test of management techniques for photonic networks and the interaction between protocol and physical network layer. A further R&D activity is concerned with the implementation of optical transmission techniques for high capacity inter- and intra-machine communication.

In the area of transmission technology, the institute carries out developments of low-cost-systems based on polymer fibre (POF) and R&D tasks for high capacity transmission systems using the entire available transmission band of the optical fibre. In this context, other important areas of active R&D are transmission rates up to 1 Terabit per second using optical time multiplex techniques, the full spectral utilization of fibre capacity by wavelength division multiplexing (WDM), novel dispersion compensation techniques, investigation of non linear effects, higher level modulation techniques, Raman amplification and all-optical 3R-regeneration.

In the area of photonic networks, the R&D activities focus on the investigation of optical nodes, circuit and burst switching, switching behaviour of networks, transparent transmission and network performance monitoring. One essential aspect of this work is the investigation of access network solutions including FTTH and coarse WDM systems using low-cost transceivers.

At HHI, well equipped state-of-the-art laboratories are available, which allow experiments pushing the boundaries of present day technology. This is supported by the development of novel photonic components and enabling material technologies at HHI. A WDM fibre loop test bed is used for the experimental investigation of systems and networks with up to 32 wavelength channels in several wavelength bands (S, C, L) and at bit rates up to 44 Gbit/s, which can be extended to additional transmission bands. In another high-speed laboratory, transmission experiments of currently 640 Gbit/s are carried out with the future goal of 1 Tbit/s on a single wavelength. All these R&D efforts are supported by computer simulations using sophisticated simulation tools.

Photonische Netze und Systeme

Photonische Netze sind die Basis moderner weltumspannender Kommunikationssysteme. Sie bestehen aus optischen Glasfaserübertragungsstrecken und optoelektronischen oder optischen Vermittlungsknoten. Im Vergleich zu den traditionellen Übertragungsmedien auf Kupferbasis und zur Funktechnik bietet die Glasfaser mit einer Übertragungsbandbreite von 70 Tera-Hertz eine nahezu unbegrenzte Übertragungskapazität und ermöglichte in den vergangenen Jahren den Aufbau eines weltumspannenden Datenautobahnnetzes. Durch die Glasfaser ist es möglich, zu sehr geringen Kosten in alle Welt zu telefonieren und per Internet E-Mails, Bilder, Videos, Daten usw. mit jedem Punkt der Erde auszutauschen. Erst durch sie war der Siegeszug des Internets möglich, dessen Nutzung für Jedermann mittlerweile ein Muss ist.

Trotz des Einbruchs in der IT-Branche verdoppelt sich das Verkehrsaufkommen in den Netzen weiterhin jedes Jahr. Die Teilnehmer – private wie geschäftliche – verlangen nach mehr Bandbreite, um z. B. schneller im World Wide Web surfen zu können. Ein großes Problem stellen die noch fehlenden „Auffahrten“, d. h. der breitbandige Anschluss der Teilnehmer dar. Die DSL-Technik auf der Basis der bestehenden Kupferleitungen mit moderaten Übertragungsraten im Mbit/s-Bereich ist nur ein Zwischenschritt zum breitbandigen Glasfaseranschluss. In Ländern wie Japan, Korea und USA gibt es bereits zum Teil hoch subventionierte Programme zur Einführung des optischen Anschlusses mit Übertragungsraten von über 100 Mbit/s für private und mehrere Gbit/s für geschäftliche Teilnehmer.

In allen Netzbereichen ist noch eine erhebliche Kostenreduktion erforderlich, um den Teilnehmern die gewünschte Bandbreite zu akzeptablen Kosten zur Verfügung zu stellen. Dies soll u. a. durch eine Flexibilisierung der derzeit starren Netze und einer damit verbundenen besseren Nutzung der Netzressourcen erreicht werden.

Auch für die breitbandige Mobilkommunikation sind die photonischen Netze eine Grundvoraussetzung. Über sie werden die Basisstationen breitbandig miteinander verbunden. In zukünftigen pikozellularen breitbandigen Mobilfunknetzen ist ein intelligentes Zusammenwirken von Funkkanal, Basisstation und optischem Netz erforderlich.

Das HHI führt bereits seit den 70er Jahren intensive Forschungs- und Entwicklungsarbeiten in Kooperation mit Industrie und Netzbetreibern zu optischen Übertragungssystemen und Netzen durch. Es gehört damit zu den weltweit wenigen Institutionen, die seit dem Beginn der Forschung auf dem Gebiet der optischen Nachrichtentechnik agieren und maßgeblich zum Fortschritt beigetragen haben.



Wesentliches Ziel der derzeitigen F&E-Aktivitäten ist es, mit neuen Techniken und Übertragungsverfahren eine bessere Nutzung der Glasfaserübertragungsstrecken sowie eine Steigerung der Leistungsfähigkeit photonischer Netze zu erreichen. Hierbei werden Netze vom Core- über den Access- bis hin zum Customer-Bereich betrachtet. Neben F&E-Arbeiten zu rein physikalisch-technischen Fragestellungen werden Untersuchungen und Entwicklungen zum Management photonischer Netze sowie zum Zusammenwirken der Protokollebenen mit der physikalischen Ebene durchgeführt. Eine weitere F&E-Aktivität befaßt sich mit dem Einsatz von optischen Übertragungstechniken zur hochkapazitiven Inter- und Intra-Maschine-Kommunikation.

Auf dem Gebiet der Übertragungstechnik werden Entwicklungsarbeiten für Low-Cost-Systeme auf der Basis von Polymer-Fasern (POF) bis hin zu F&E-Arbeiten für hochkapazitive Übertragungssysteme durchgeführt, bei denen das gesamte zur Verfügung stehende Übertragungsband der Glasfaser genutzt werden soll. Steigerung der Übertragungsrates in Richtung auf 1 Terabit pro Sekunde mit Hilfe der optischen Zeitmultiplextechnik, Nutzung der Faserkapazität durch Einsatz der Wellenlängenmultiplextechnik, Dispersionskompensation, nichtlineare Effekte, höherwertige Modulationsverfahren, Ramanverstärkung und optische 3R-Regeneration sind wichtige Themen, die in diesem Zusammenhang bearbeitet werden.

Zum Thema photonische Netze erfolgen Untersuchungen zu optischen Netzknoten zur Leitungs- und Paket- bzw. Burstvermittlung, zum Schaltverhalten des Netzes, zur Transparenz und zum Performance-Monitoring. Einen wesentlichen F&E-Schwerpunkt stellen Untersuchungen zum kostengünstigen optischen Access-Netz dar.

Für die Untersuchungen stehen gut ausgestattete Labore zur Verfügung, die Experimente bis an die derzeitigen physikalischen und systemtechnischen Grenzen erlauben. Dies wird insbesondere auch durch die Entwicklung neuartiger photonischer Bauelemente und der dafür notwendigen Technologien im HHI ermöglicht. Mit einem WDM-Loop-Testbett können System- und Netzuntersuchungen mit bis zu 32 Wellenlängenkanälen in mehreren Wellenlängenbändern (S, C, L) und einer Datenrate von bis zu jeweils 44 Gbit/s durchgeführt werden. In einem Hochgeschwindigkeitslabor erfolgen zur Zeit Übertragungsversuche bei 640 Gbit/s mit der Zielrichtung auf 1 Tbit/s. Begleitet und gestützt werden die Untersuchungen durch Rechnersimulationen mit komplexen Simulationswerkzeugen.



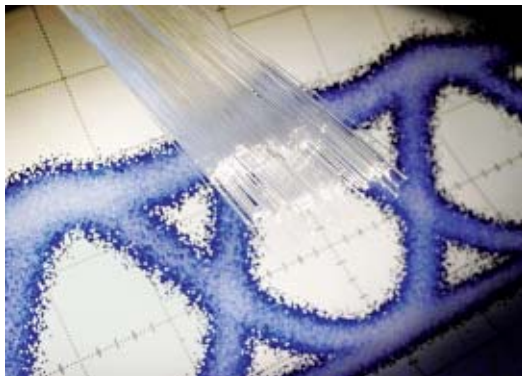
Photonic Networks and Systems

Optical Networks

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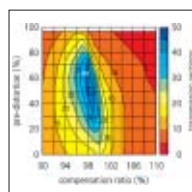
Optical fibres with a nearly unlimited bandwidth of 70 Terahertz are the transmission media for optical broadband communication networks



Implementation of photonic networks in all communication network areas for broadband for all: core, metro, access and indoor networks



Optical loop test bed for investigation and development of S-, C-, L-band wavelength division multiplex systems with transmission rates up to 40 Gb/s per channel



Simulation and design of photonic networks



DYNAMICALLY SWITCHED OPTICAL NETWORKS/OPTICAL BURST SWITCHING

The major characteristics of optical circuit, burst, and packet switching are discussed. Recent results on the scalability of optical burst switching nodes are presented.

Nach einer Darstellung der Charakteristika von optischer Leitungs-, „Burst“ und Paketvermittlung werden neue Ergebnisse zur Skalierbarkeit von optischen Burst-Schaltknoten präsentiert.

In order to be capable to efficiently serve all emerging highly dynamic traffic demands, new optical switching techniques, such as fast optical circuit switching (OCS), optical burst switching (OBS), and optical packet switching (OPS) have been proposed during the last years.

switching technology	granularity	utilization	complexity
circuit switching	coarse	poor	low
burst switching	moderate	moderate	moderate
packet switching	fine	high	high, not mature

Fig. 1: Comparison of the major characteristics of OCS, OBS, and OPS

Major characteristics of these three different switching technologies are summarized in Fig. 1. Fibres, wavelength bands or wavelengths are switched in a circuit switched WDM network. Optical circuit switching has thus the coarsest granularity. Packet switching has the finest granularity; In an OPS network the packets e.g. in the kByte range are switched optically. Burst switching has a granularity between circuit and packet switching. In an OBS network IP packets are aggregated to bursts with a size of e.g. several tens of kbytes. In comparison to OCS, OPS and OBS are both expected to better support dynamic traffic and to improve the utilisation of the network resources. The required switching complexity (e.g. switching

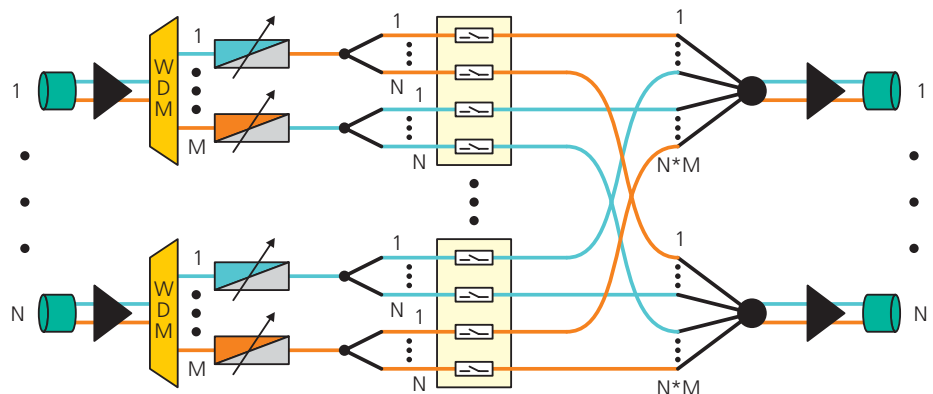


Fig. 2: Tune-and-select optical burst switching node

time, optical signal processing) of OBS is between OCS and OPS.

As optical bursts have a typical duration between a few μs and several $100\mu\text{s}$, the switching time of burst switching nodes should be well below $1\mu\text{s}$. Semiconductor optical amplifier (SOA) based switches with switching times in the ns range are well suited for this application. It was shown, that the so-called "Tune-and-Select" (TAS) switching node is a promising candidate for OBS (see Fig. 2). The optical switching node with SOAs as on/off gates introduces signal distortions because of amplifier noise, crosstalk of WDM channels, SOA gain saturation and dynamics.

The scalability analysis of the TAS OBS node was extended by considering SOA chirp and dispersion compensated transmission in addition to noise, crosstalk, SOA saturation and dynamics. The impact of NRZ and RZ modulation is compared, as there is different transmission behavior on the links and different dynamic response of the amplifiers on the RZ and NRZ signals.

Three different types of SOAs have been compared. The reference SOA is defined by a static gain versus current characteristic and a noise figure. It is used for (ideal) reference. The conventional SOA and the gain clamped SOA (GC-SOA) are used to describe real SOAs.

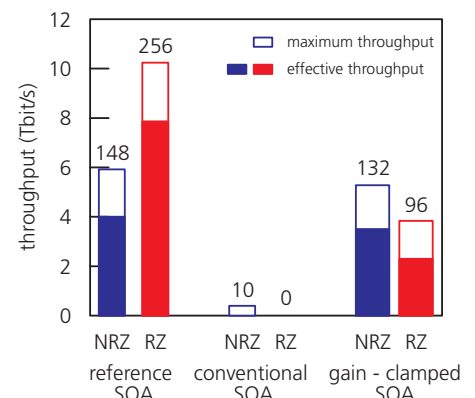


Fig. 3: Maximum number of wavelengths (10 Gbit/s), maximum and effective throughput of TAS nodes

Figure 3 shows the achievable maximum capacity and the effective throughput for a burst loss probability of 10^{-6} , for the three types of SOAs and for NRZ and RZ modulation format.

Conventional SOAs are not suitable to be used as switching gates, due to the high optical powers in the node. For NRZ modulation GC-SOAs only lead to slight decrease of the maximum size of the nodes, compared to reference SOA. RZ modulation is superior with the reference SOA, giving more room for degradations caused by the nodes. This advantage is lost for the GC-SOA because it reacts more strongly on RZ modulated signals than on NRZ modulated signals.

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HIGH-CAPACITY FREE-SPACE DATA TRANSMISSION FOR PROJECTION MASK-LESS LITHOGRAPHY

High-capacity free-space data transmission into the high-vacuum and high-voltage area of a Projection Mask-Less Lithography Tool was investigated. Data transmission via 12 channels operating in parallel with 1.4 Gbit/s each have been demonstrated. A transmission capacity of >36 Gbit/s will be accomplished in the next project phase.

Die optische Freistrahübertragung sehr großer Datenmengen in den Hochspannungs- und Hochvakuumbereich einer Maskenlosen Lithografie-Anlage wurde untersucht. In einem Demonstrator wurden 12 parallele optische Kanäle mit je 1,4 Gbit/s realisiert und untersucht. Im nächsten Schritt soll die Übertragungskapazität auf >36 Gbit/s erweitert werden.

The project on Projection Mask-Less Lithography Technology was started in January 2004 by R&D teams of the IMS Nanofabrication (Austria), Leica Jena, IMS Jena, FhG-ISiT, FhG-HHI, FhG-IOF, IMS-chips, EQUIcon (Germany) and Philips-ETG (The Netherlands) in co-operation with MEDEA+.

The FhG-HHI is responsible for the specification and the design of a demonstrator for the optical data transfer comprising a high-speed real-time data buffer (Stripe Buffer – cf. page 78), an optical data path, an optical receiver and a de-multiplexer for the transmitted optical data. The objectives of the optical data transfer are the generation and optical transmission of the pixel data stream to the Aperture Plate System (APS)

The high-capacity optical data path is intended to be realized by means of an optical free-space transmission system with 36 parallel beams. The light beam information is detected by a photo-

diode array and converted into electric signals.

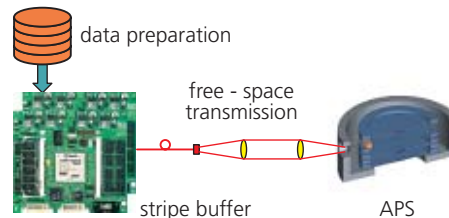


Fig. 1: Optical data transfer

In order to realize the optical Data Transfer Demonstrator, commercially available receiver and transmitter modules (Infineon PAROLI-Modules) with 12 parallel optical channels and an optical imaging system using two lenses have been used.



Fig. 2: Photography of the free-space optical transmission system using a 12-channel transmitter and receiver

Figure 2 shows a photograph of the accomplished optical test setup. The free-space parallel optical interconnect was designed to bridge a distance of approx. 30 cm. Specially designed aspheric lenses have been developed to image the 850 nm multimode (MM) emitters of the transmitter (12 VCSELs which are connected to 12 fibers) onto an array of photodiodes.

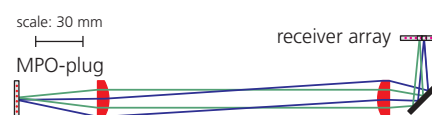


Fig. 3: Optical transmission path with mirror

To analyze the transmission path, the light emitted from the 12 MM-fibers (core diameter 62,5 µm) was imaged onto the receiver photodiodes via the lens system (Fig. 3) and a mirror located underneath the R_x -module (Fig. 2).

The results of the transmission experiments using 12 channels with a data rate of 1.4 Gbit/s each and a NRZ modulation (PRBS $2^{15}-1$) are depicted in Figure 4. The measurement results of the Bit-Error Ratio (BER) of each transmitted channel in dependence on the received optical power at the receiver are summarized in the Figure.

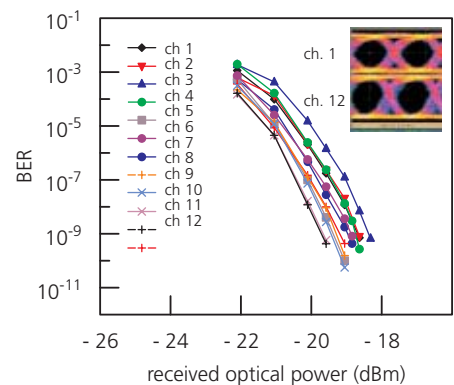


Fig. 4: BER-measurements (12 channels with 1.4 Gbit/s each) and eye diagrams

Additionally, the eye diagrams of the most critical two outer channels 1 and 12 are depicted. All channels show a BER < 10^{-9} for a mean optical power at the receiver of less than -18 dBm. Since the mean optical power of each channel which can be expected at the receiver is approx. -10 dBm, an error-free transmission can be ensured, assuming a transmitter output power of -5 dBm and an optical free-space link loss of 5 dB.

Based on the achieved results it can be concluded, that this imaging system can be applied to transmit data rates of >40 Gbit/s if the number of channels is increased. This data rate is sufficient to proof the concept of the Mask-Less Lithography. The optical inter-channel cross-talk is very low and of no influence on the BER. Long term measurements over >60 hours have shown that error-free transmission can be achieved. Even in case of higher ambient temperatures of up to 90 °C only negligible degradations on the BER was observed.

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USING CWDM IN OPTICAL ACCESS NETWORKS

CWDM is a potential technique for optical access networks based on single mode fibres. Design studies and investigations of low-cost solutions show promising prospects in terms of high capacity provision and upgrading of channel bit rates.

Vorstellbar ist ein Einsatz der CWDM-Technik in optischen Zugangsnetzen, die auf Single-Mode-Fasern basieren. Design-Studien und Untersuchungen zur kostengünstigen Bereitstellung hoher Übertragungskapazitäten und zur Bitraten-Erhöhung sind viel versprechend.

Since fibres are to be deployed in the access network area, flexibility in provision of data rates, future proof solutions, and upgradeability are issues for research. Coarse wavelength division multiplexing (CWDM) is seen as a technique to meet such demands. In the course of R&D projects on national and European scale, low-cost solutions for CWDM access networks are developed and tested at HHI's lab for optical access networks. The work is based on scenarios like

- single fibre point-to-point links, e.g. for provision of high transmission capacity to network nodes located in subscribers' vicinity or to high-end customers,
- high capacity distribution using only few fibres and optical add-drop multiplexers along residential streets,
- provision of bandwidth via two-stage passive optical network architectures.

The CWDM wavelength grid was originally defined for metro network applications. As shown in Fig. 1, it consists of eighteen 20 nm wide channels within the range between 1260 and 1620 nm. Conceptually, this approach is optimized for the use of uncooled

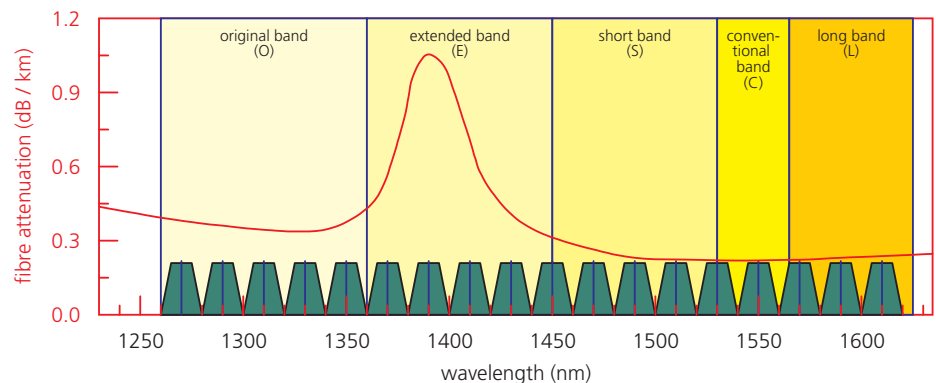


Fig. 1: CWDM channel allocation and typical loss characteristics of standard single mode fibre

and cost-efficient transceivers based on standard directly modulated lasers (DML) that can provide the desired high optical output power, however at the expense of shorter system reach due to fibre dispersion and laser chirp. For access networks distances of up to 20 km are of special interest. Concerning transmission reach it is mainly important to investigate the wavelength regions where fibre loss is high, (Fig. 1, O & E bands). Additionally, chromatic dispersion may limit the reach at high bit rates if compensation is avoided due to cost reasons. Thus, C & L bands were in the focus of related investigations. As an example, Fig. 2 shows the wavelength spectrum after multiplexing signals of 6 CWDM channels.

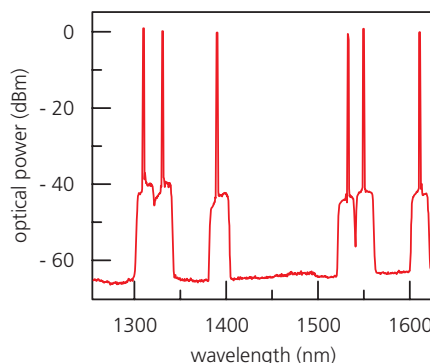


Fig. 2: CWDM spectrum after multiplexing of 6 channels under test

It has been shown that power margins allow for simple passive optical networks in the access domain with use of the entire CWDM band, as far as bit rates per channel are below 2.5 Gb/s. However, since fibre infrastructure is to last for much longer than a decade,

system upgradeability is also of utmost importance. It has been shown that channels can be easily upgraded up to 10 Gb/s using DMLs without any dispersion compensation. Although (as is shown in Fig. 3) chromatic dispersion limits reach in the L band region, it is expected that several kilometres (sufficient in many cases) could be covered even on these channels.

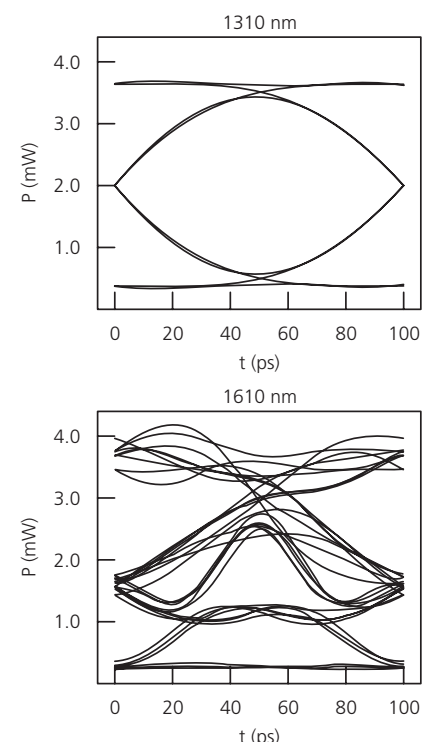


Fig. 3: Calculated eye diagrams for 10 Gb/s transmission over 20 km standard single mode fibre using DML

The facilities of HHI's lab for optical access networks are available for studies and testing on customer's demand.

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40 GBIT/S S-BAND TRANSMISSION

The increasing demand on transmission capacity fosters the exploration of further transmission bands, such as the S-band. For the first time, an 8×40-Gbit/s wavelength division multiplexed (WDM) signal has been transmitted over installed fibre in the 1499 nm to 1504 nm wavelength region using novel S-band EDFAs.

Die steigende Nachfrage nach Übertragungskapazität fördert die Erschließung weiterer Übertragungsbänder wie das S-Band. 40 Gbit/s WDM-Übertragungsexperimente mit 8 Kanälen im Wellenlängenbereich von 1499 nm bis 1504 nm wurden erstmalig unter Verwendung neuartiger S-Band-EDFA über verlegte Fasern durchgeführt.

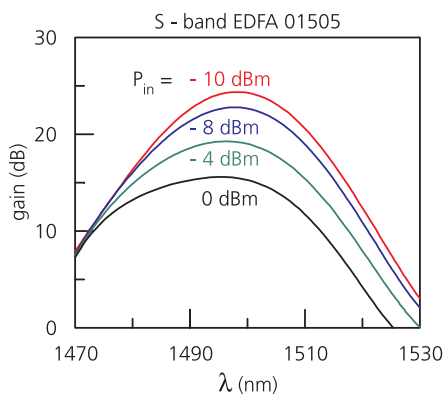


Fig. 1: Measured gain characteristic of an S-band EDFA

For future upgrade of transmission systems, the opening up of new wavelength regions is important. Besides the established L-band (1565 nm–1625 nm), the S-band (1460 nm–1530 nm), which also lies in the low loss region (< 0.25 dB/km) of silica-based fibre, is the candidate on the short wavelength side of the conventionally used C-band for this purpose. In general, system performance and achievable transmission distance depend on properties of the applied optical amplifiers. So far, Thulium-doped fluoride and Raman fibre amplifiers have been investigated for the S-band. More recently, a new approach for S-band amplification

using Erbium-doped silica fibre has been achieved (s. Fig. 1) that promises high output power, low noise and high gain characteristics.



Fig. 2: Installed fibre link (77 km SSMF), which was directly connected to the test-bed at HHI

For the first time, an 8×40 Gbit/s transmission was carried out over installed SSMF spans in the network of Deutsche Telekom AG (from HHI to Zeuthen) using S-band EDFAs (s. Fig. 2).

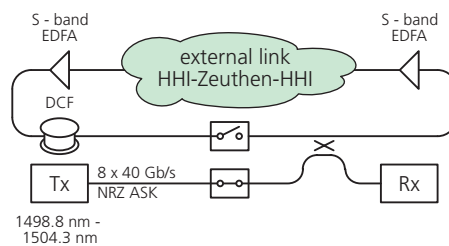


Fig. 3: Setup of the recirculating loop experiment using installed fibre infrastructure

The external link HHI–Zeuthen–HHI, with a total length of 77 km, was directly connected to the recirculating loop testbed located at HHI (s. Fig. 3). The fibre loss of the whole link was measured to be 25 dB. This high loss of the installed fibre and its connectors corresponds to approximately 130 km spans of ideally spliced SSMF and presents therefore a challenge for 40 Gbit/s non-Raman based transmission. The chromatic dispersion was postcompensated at the receiver using dispersion compensating fibre (DCF).

The transmission performance of an 8×40-Gbit/s-NRZ-ASK WDM-signal was evaluated. Eye diagrams for back-to-back and after two recirculations are shown in Fig. 4 for the outer channels.

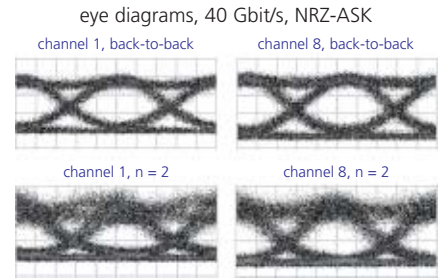


Fig. 4: Eye diagrams for back-to-back and after two recirculations for the outer channels

The variation of the Q-factor was measured across the S-band channels after the transmitter and for up to three recirculations (s. Fig. 5). Error-free transmission ($Q > 15.6$ dB, $BER < 10^{-9}$) was obtained for up to 2 recirculations (154 km) for all channels with a small variation in the Q-factor of ≈ 0.5 dB.

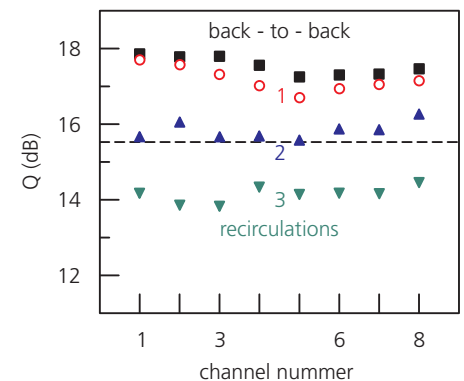


Fig. 5: Measured Q-factor vs. channel number for a different number of recirculations

System experiments have shown the great potential of S-band EDFAs to open up the 1460 nm–1530 nm wavelengths region for capacity enhancements in future optical transmission systems.

The S-band EDFAs were provided by Lightwave Electronics, USA.

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POLYMER OPTICAL FIBRES FOR INDOOR AND SHORT-REACH TRANSMISSION

Polymer optical fibres (POFs) are a promising transmission media for indoor and short-reach communication systems. They allow easy handling, have a small required space, are immune to electrical interference, and have sufficient bandwidth for such applications. The HHI investigates POF communication systems for bit rates up to a few Gb/s.

Polymerfasern sind ein viel versprechendes Übertragungsmedium für Inhaus- und Kurzstrecken-Kommunikationssysteme. Sie sind einfach handhabbar, besitzen einen geringen Platzbedarf, sind unempfindlich gegenüber elektro-magnetischen Störungen und haben für diese Anwendungen eine ausreichende Bandbreite. Das HHI untersucht POF-Übertragungssysteme mit Bitraten bis zu mehreren Gb/s.

POFs can be manufactured from different polymer materials, where typically polymethyl methacrylate (PMMA) is used. The attenuation characteristics of PMMA are depicted in Fig. 1.

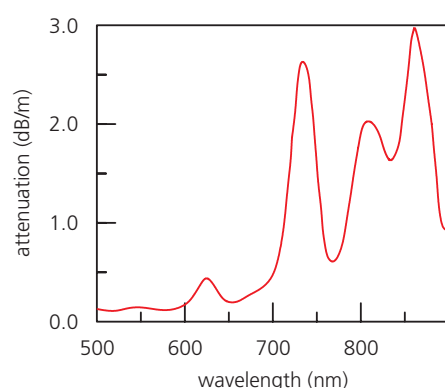


Fig. 1: Spectral attenuation for polymethyl methacrylate (PMMA)

It can be seen that PMMA has good attenuation properties for visible light with a minimum of ~ 0.1 dB/m at 570 nm (green light). High-speed transmitters at this wavelength are currently

in development and not yet commercially available. Therefore transmitters at the attenuation minima around 650 nm (~ 0.2 dB/m) and 780 nm (~ 0.6 dB/m) are mostly used. Low-cost components such as LED (transmission speeds up to a few 100 Mb/s) and Vertical Cavity Surface Emitting Laser (VCSEL), with a transmission speed up to a few Gb/s, are offered at these wavelengths.

There exists a wide variety of POF types depending on their application. The Standard POF type has a core diameter of 1 mm, and a numerical aperture (NA) of 0.5 which enables a low-loss coupling of light source and fibre. On the other hand this relatively large NA complicates the coupling of fibre and broadband detector, and limits the bandwidth-length product (B·L) to a moderate value of $40 \text{ MHz} \times 50 \text{ m}$. When higher B·L values are needed, some specialised fibre types are available (see Tab. 1).

POF-Type	Available Bandwidth (at 50 m)
Step-Index (Standard)	40 MHz
Low-NA	200 MHz
Multi-Step-Index	500 MHz
Multi-Core	500 MHz
Graded-Index	> 4 GHz

Tab. 1: Bandwidth-length product for different polymer fibre types

Low-cost Si-PIN-Photodiodes with a quantum efficiency up to 0.8 A/W are used as receivers for POF systems. These diodes are available for bandwidths up to 2 GHz. Unfortunately, with the increase of maximum bandwidth the diameter of the active area decreases. While a 500 MHz-diode has a diameter of ~ 0.8 mm, which allows for a direct fibre-diode coupling, a 2 GHz-diode has a diameter of just 0.1 mm. Such small diodes bring about considerable costs, because an optical lens is needed to convert the large fibre diameter (1 mm) to the small diameter of the active area (0.1 mm).

In processing of a customer request a 2 Gb/s short-reach transmission over 5 m of Multicore-POF (MC-POF) was investigated at HHI. A 780 nm VCSEL, a Si-PIN photo diode, and a transimpedance amplifier were used for this application. The VCSEL-POF coupling for such a trial is shown in Fig. 2 (here, using a 662 nm VCSEL for better visibility).

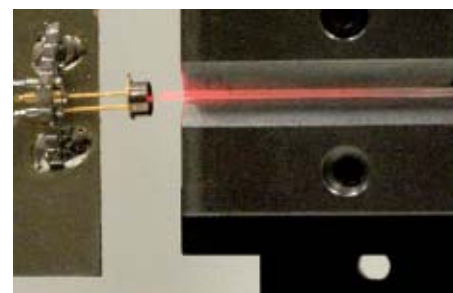


Fig. 2: VCSEL – POF coupling on a free-space workbench (wavelength $\lambda = 662 \text{ nm}$)

The well-defined eye diagram for this error-free transmission at the receiver is depicted in Fig. 3. The slightly visible pulse distortion is not caused by the MC-POF itself, but originates, in this case, from bandwidth limitation of the optical receiver.

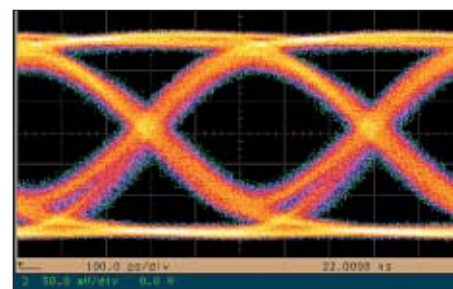


Fig. 3: Eye diagram at the receiver for an error-free 2 Gb/s transmission over 5 m MC-POF

For indoor communication techniques (i.e. Ethernet, Firewire) the newly-available graded-index POFs allow transmission speeds up to 1 Gb/s over about 100 meters.

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MARGINS AND TOLERANCES IN 40-GBIT/S-NRZ-ASK METRO- NETWORKS

Despite the increased system requirements, cost efficient deployment of 40-Gbit/s-NRZ-ASK transmission in legacy 2.5-Gbit/s and 10-Gbit/s metro networks is feasible from the technical point of view, when polarisation mode dispersion is not the limiting factor.

Trotz der erhöhten Systemanforderungen ist aus technischer Sicht ein kosteneffizienter Einsatz einer 40-Gbit/s-NRZ-ASK Übertragung in bestehenden Metro-Netzwerken möglich, solange die Polarisationsmodendispersion nicht der begrenzende Faktor ist.

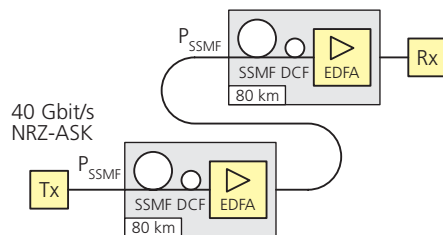


Fig. 1: Investigated optical transmission section for $N \times 40$ -Gbit/s-NRZ transmission for usage in metropolitan area networks

Due to the widespread introduction of broadband access technology and the rapid growth in high-speed communication services, today's metropolitan area networks (MANs) will lag behind the foreseeable bandwidth demands. To overcome this bottleneck, a cost efficient capacity enhancement of the currently deployed $N \times 2.5$ -Gbit/s and $N \times 10$ -Gbit/s WDM systems will be inevitable. Although several new modulation formats are proposed for usage in long-haul systems, in metro networks 40-Gbit/s-NRZ-ASK is still the simplest and, therefore, most cost efficient modulation format. But due to the higher bit-rate per channel, their margins and parameter tolerances are typically tighter in comparison to the already installed systems. For instance the requirement for the optical signal-to-noise ratio is 6 dB higher for

40 Gbit/s systems as for 10-Gbit/s systems. Moreover, chromatic dispersion limits uncompensated 40-Gbit/s-transmissions over standard single mode fibre (SSMF) to 4 km that is 16 times tighter than for 10 Gbit/s.

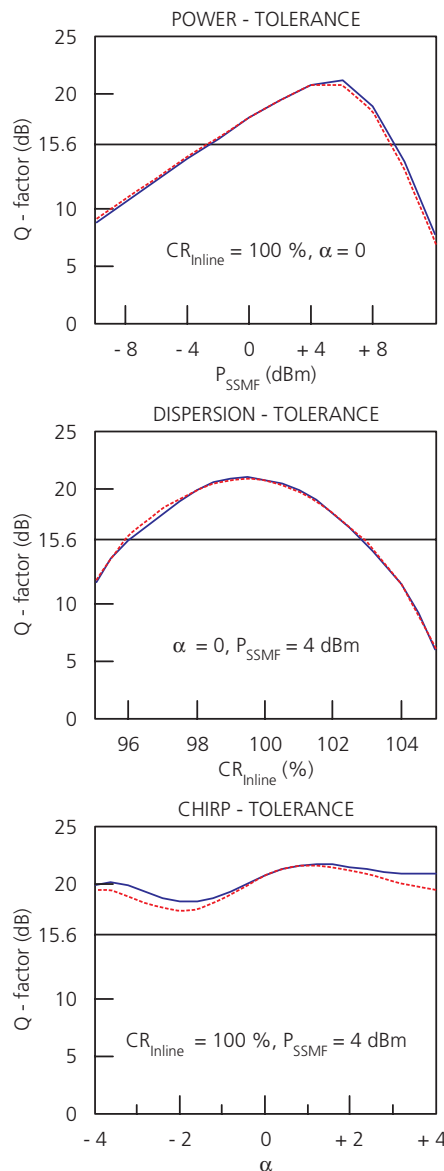


Fig. 2: Simulated tolerance of system performance against varying operating conditions, starting from nominal operating point: $P_{SSMF} = 4$ dBm, $\alpha = 0$, $CR_{Inline} = 100\%$. Solid lines show 1×40 -Gbit/s-NRZ-ASK, dotted lines show 5×40 -Gbit/s-NRZ-ASK transmission

To evaluate 40-Gbit/s transmission in MANs, transmission sections of 80 km SSMF (Fig. 1) have been investigated. For cost reduction no EDFA is employed between SSMF and dispersion compensating fibre (DCF). Numerical simulations have been carried out

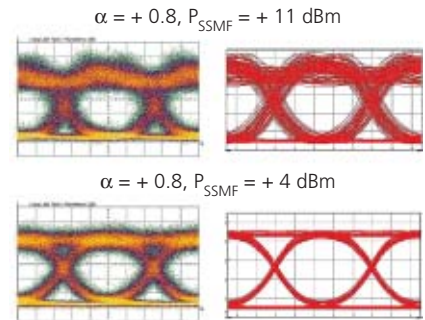


Fig. 3: Comparison of measured (left) and simulated (right) eye diagrams for different alpha-factors and SSMF launch powers

using the VPItransmission-Maker™ to investigate Q-factor versus the launch power into the SSMF (P_{SSMF}), the inline compensation ratio (CR_{Inline}) of the chromatic dispersion and the chirp-factor of the Mach-Zehnder modulator (α) at the transmitter Tx. Fig. 2 shows exemplarily the tolerances for the three parameters around an selected optimal operating point of $P_{SSMF} = 4$ dBm, $CR_{Inline} = 100\%$ and $\alpha = 0$. The simulations were verified by selected experiments, (see Fig. 3 and Fig. 4) and have shown a good agreement over a wide range of parameter variations.

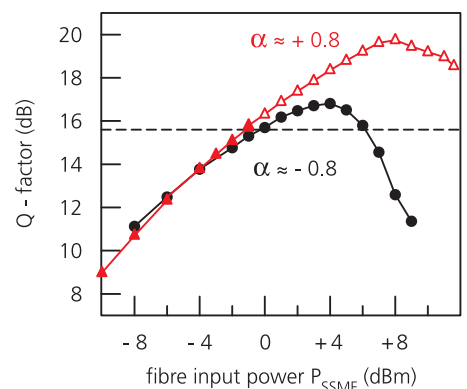


Fig. 4: Measured Q-factors versus fibre launch power into the SSMF for different alpha-factors of the transmitter's Mach-Zehnder-Modulator

With optimised system parameters, Q-factors of 20 dB were obtained experimentally, which provide a system margin of 4.4 dB, assuming a target Q-factor of 15.6 dB. The application of FEC can further increase the system margin and/or relax the system requirements.

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160 GBIT/S TRANSMISSION SYSTEM WITH LONG-TERM STABILITY

Using the of "RZ-DPSK" modulation format, the 160 Gbit/s transmission system could be operated with the stability that is necessary for the application in deployed transmission systems. HHI offers the components that are needed to upgrade a 40 Gbit/s DPSK system to 160 Gbit/s.

Unter Verwendung des „RZ-DPSK“ Modulationsformates erreicht die 160 Gbit/s Datenübertragung die Stabilität, die für den Einsatz in praktischen Übertragungssystemen notwendig ist. Das HHI bietet die Komponenten an, die für die Aufrüstung eines 40 Gbit/s DPSK Systems auf 160 Gbit/s notwendig sind.

Currently, 10 Gbit/s systems are state-of-the-art, and 40 Gbit/s systems will be deployed in the near future.

Although transmission systems with 160 Gbit/s and beyond have been realised in laboratories, up to now these systems were not appropriate for deployed systems because of the limited stability.

The "RZ-DPSK" modulation format showed a clear advantage in the transmission of 160 Gbit/s per wavelength channel, as was described in the last Annual Report (p. 23). With RZ-DPSK, the phase of the optical pulses is used to code the binary information instead of the amplitude. The recent focus of our work was to prove the reliability of this 160 Gbit/s transmission system. Some additional components are required to upgrade a 40 Gbit/s DPSK system. The key components are a pulse source, a clock recovery for the synchronisation of the receiver and a demultiplexer for extracting the channels from the multiplexed signal. These subsystems have been realised in a compact housing. They consume less power and space and are easier to operate than the traditional laboratory equipment.

Together with the Berlin-based companies u²t Photonics and SHF Communications, the components were presented at the "European Conference on Optical Communication" (ECOC) in Stockholm. They were utilised in a live 160 Gbit/s transmission over 80 km fibre in the exhibition hall, demonstrating the applicability of the system outside the laboratory. At the TeraBit Laboratory in Nuremberg, a collaboration between Lucent Technologies and HHI, it was shown that the components can also upgrade a commercial 40 Gbit/s transmission system.



Fig. 1: One of the compact units for a 40 to 160 Gbit/s upgrade (160 → 40 Gbit/s demultiplexer)

We proved the stability of the 160 Gbit/s system in a 320 km transmission experiment.¹ The advantage of the DPSK modulation format is evident from BER measurements. Stable semiconductor devices for the pulse source, the optical gate and the clock recovery enabled a long-term measurement (10 h) that was only limited by slow drift effects in the laboratory system owing to the absence of automatic feedbacks. For more than 5 h, no error was measured without re-adjusting and without FEC.



Fig. 2: The live demonstration in Stockholm

The use of FEC would further improve the system margin. A PMD-compensator was not required in these measurements because of the high quality of the SLA/IDF fibre link.

The actual installed fibre links contain some fibre sections with high polarisation mode dispersion (PMD). Therefore, high bit rates require a compensation of the PMD. Together with our partners Adaptif Photonics, the Technical University Hamburg-Harburg (TUHH), and Deutsche Telekom, an adaptive and dynamic compensator was successfully tested in a 160 Gbit/s transmission over deployed fibre with high PMD for the first time.²

These results suggest that data rates of 160 Gbit/s per channel are applicable to deployed systems.

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¹ Ferber et al., Electron. Lett. 41, 200 (2005)

² Kieckbusch et al., OFC'04, Los Angeles, PDP31 (post-deadline)

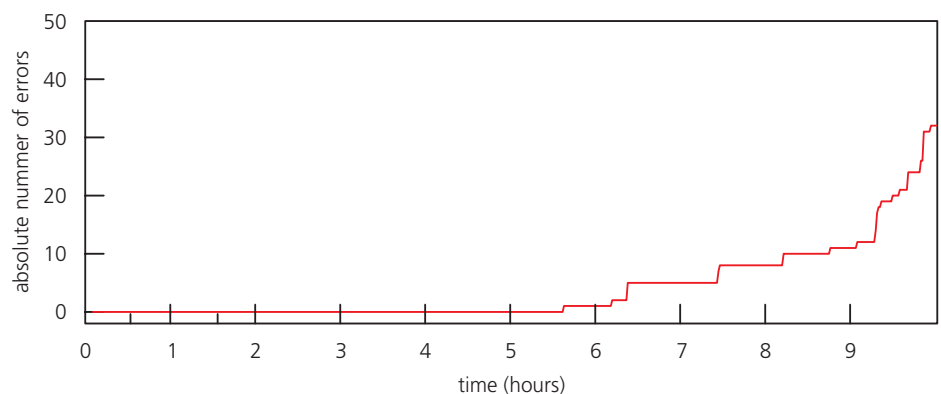


Fig. 3: Long-term error recording in a 160 Gbit/s RZ-DPSK transmission over 320 km



SINGLE-CHANNEL 640 GBIT/S TRANSMISSION OVER A 160 KM FIBER LINK

A 640 Gbit/s data signal with the modulation format differential phase shift keying (DPSK) and with alternating polarization was transmitted over a 160 km fiber link. Key components like an optical clock-recovery for 320 Gbit/s and a fast optical demultiplexer, both developed at HHI, enabled error-free operation.

Ein 640 Gbit/s Datensignal mit DPSK-Kodierungsformat (Differential Phase Shift Keying) und alternierender Polarization wurde über eine 160 km-lange Faserstrecke übertragen. Die in diesem Experiment eingesetzten Schlüsselkomponenten, eine Takt-rückgewinnung für 320 Gbit/s und ein optisches Demultiplexer, wurden beide am HHI entwickelt.

Internet, video-on-demand and other applications increase significantly the network traffic worldwide. To ensure sufficient transmission capacity, the TDM (Time Division Multiplexing) data rate per wavelength channel can be enhanced, e. g. by using the Optical TDM (OTDM) technique. HHI already succeeded in transmitting a 160 Gbit/s DPSK signal over a 240 km fiber link with high-stability (see Annual Report 2003). The use of the modulation format DPSK with balanced detection, improves the receiver sensitivity and thus relaxes the OSNR requirements.

Recently, HHI showed that this system could be upgraded to the higher TDM bit rate of 640 Gbit/s. Challenges for higher bit rate systems are the clock-recovery (CR), which synchronizes the receiver to the incoming data signal, and the demultiplexer, which selects one 40 Gbit/s channel of the 16 TDM-channels of the 640 Gbit/s TDM signal.

Fig. 1 shows the experimental setup of the 640 Gbit/s DPSK transmission experiment with alternating polarization. The data pulse source in the transmitter as well as the pulse source driving the demultiplexer (DEMUX) were two 40 GHz Fiber Lasers, enabling low jitter pulse trains. The data pulses were compressed to a Full Width Half-Maximum (FWHM) of 0.7 ps by transmitting the 40 Gbit/s data signal over a Dispersion-Shifted Highly Nonlinear Fiber. Polarization multiplexing was used to generate a 640 Gbit/s data signal.

Fig. 2 shows the 640 Gbit/s data signal before the transmission link. The eye diagrams were measured with an optical sampling system (including a DPSK demodulator) based on a Kerr-gate (temporal resolution ~1 ps). The eyes reveal the good temporal separation and uniformity of the OTDM channels.

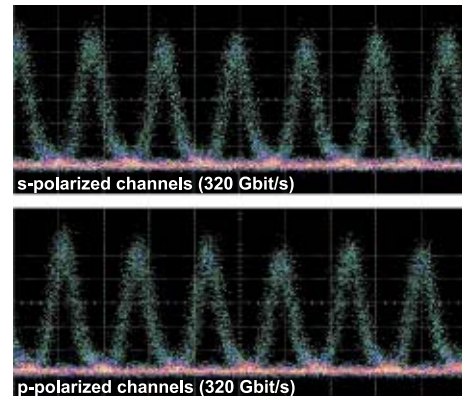


Fig. 2: Both bit-interleaved polarization channels of the 640 Gbit/s data signal (back-to-back) after DPSK-demodulation, measured with an optical sampling system

After transmission through a 160 km fiber link comprising of Super Large Area (SLA) and Inverse Dispersion Fiber (IDF), the 640 Gbit/s signal with alternating polarization was first demultiplexed to 320 Gbit/s using a polarization filter. The demultiplexer from 320 Gbit/s to 40 Gbit/s was a Nonlinear Optical Loop Mirror interferometer (NOLM), comprising two optical couplers and a piece of DS-HNLF kindly provided by Fujitsu Labs. The velocity of nonlinear effects in such a fiber allows processing at very high speed. The NOLM was used for the first time as a demultiplexer for DPSK signals.

The 40 Gbit/s signal at the output of the demultiplexer was sent to a 40 Gbit/s DPSK receiver consisting of a DPSK to OOK demodulator (based on a Mach-Zehnder interferometer with a differential delay of 25 ps) and a balanced receiver. Error-free operation was achieved for all sixteen 40 Gbit/s OTDM channels.

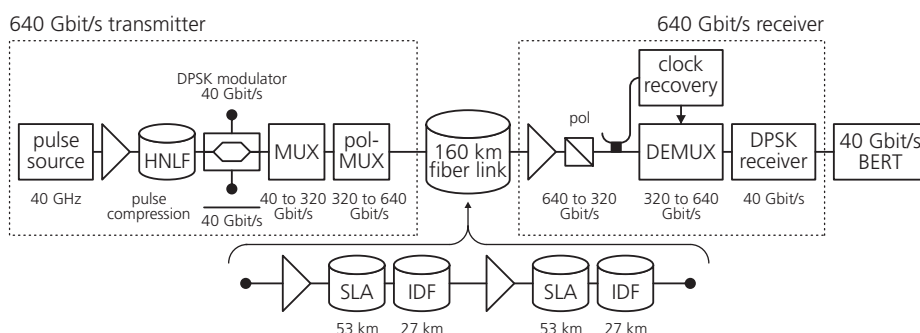
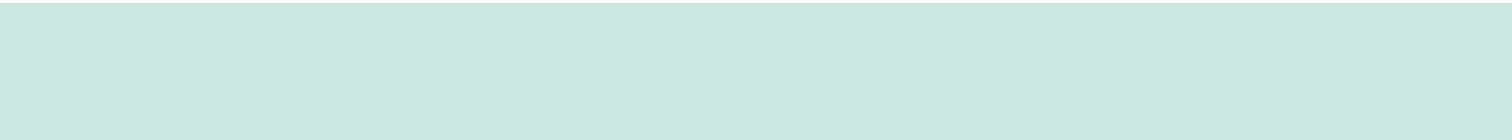
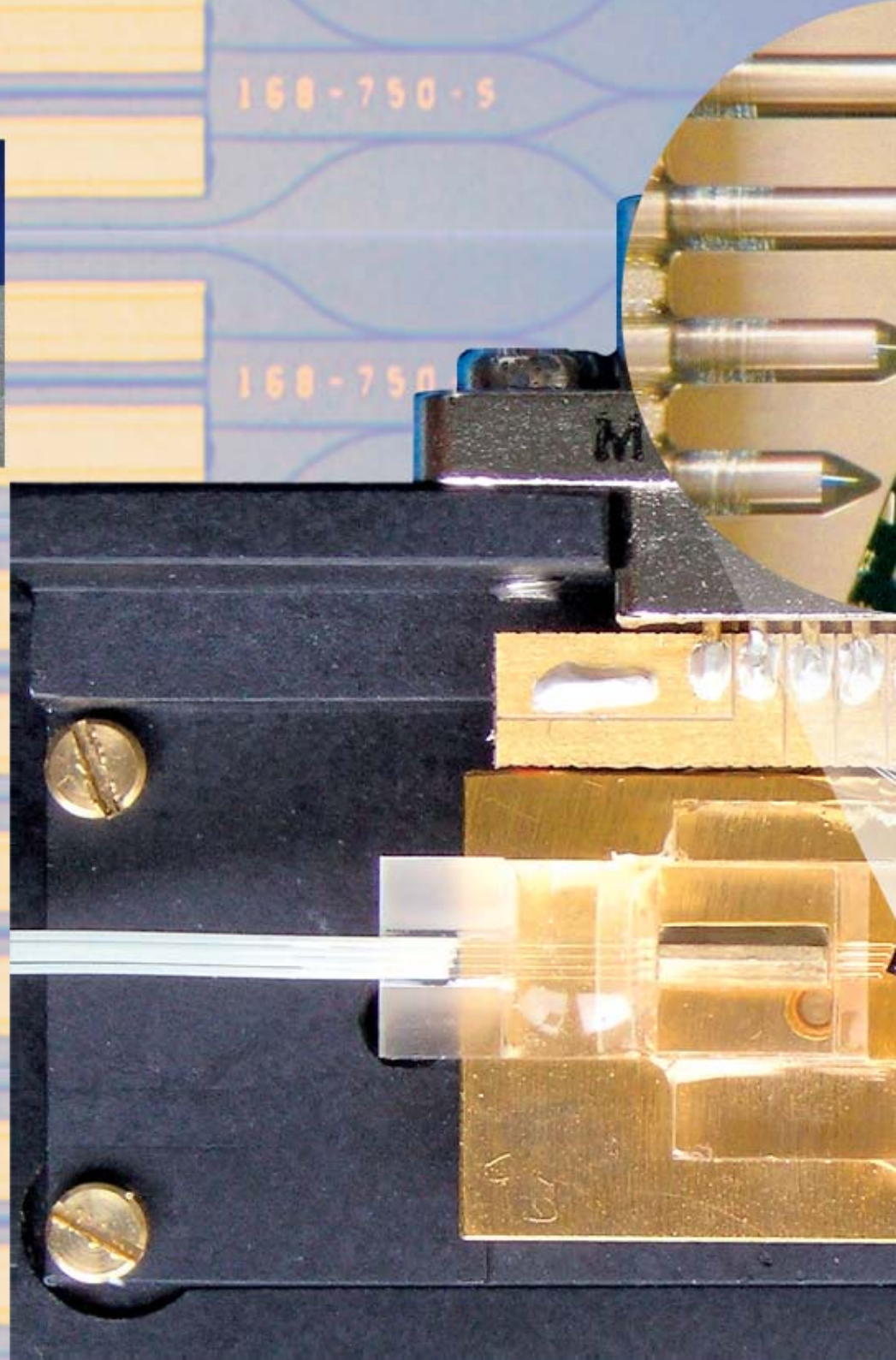


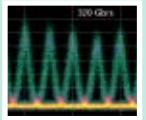
Fig. 1: Experimental setup

The transmission experiment was performed in cooperation with a research group of Fujitsu Laboratories. This leading-edge technology would be impossible without the support of the public institutions, like BMBF and DFG. The transfer to the practical application is greatly driven by the support of our industrial partners worldwide.

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Photonic Components

Fibre optic (photonic) communication networks represent one corner stone of today's global economy, and optoelectronic/photonic devices, microelectronics and micro system technologies are key elements of photonic networks. These devices are enabling components for the internet and for mobile communication systems as well, where the individual base stations are linked and connected to the world wide web via fibre optic techniques.

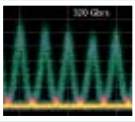
Data traffic still grows at a rate of about 100% per year, and the possibility to transport an ever increasing amount of data at constant or even lower cost depends on the availability of optoelectronic devices with continuously improved characteristics and decreasing prices of the corresponding chips.

The focus of optoelectronic device development has recently changed to a certain extent: Single channel bit rates beyond 160 Gbit/s and beyond are considered less promising, and as a consequence component development aiming at such high single channel bit rates and optical signal processing as well are receiving significantly less funding, and this is particularly true for industry-supported research. This is a very general trend and it is irrespective of the fact that high quality experiments on 160 Gbit/s single channel transmission are still being reported on key conferences such as OFC or ECOC. On the other hand, 100 Gbit/s-Ethernet is attracting considerable interest with a particular focus on robust systems and low cost at the same time.

In contrast to the reduced interest in single channel bit rates beyond 40 Gbit/s there is an increased interest in advanced modulation formats at 40 Gbit/s. These might eventually be supplemented by forward error correction (FEC) algorithms, which have raised the performance of 10 Gbit/s systems significantly and could bring about similar advantages at 40 Gbit/s provided the electronics required is available at sufficiently low cost.

Another general trend has kept the momentum it already had in the past: the development of devices, which enable lower overall system cost (comprising operation, administration, and maintenance). This includes the development of

- devices for uncooled operation, in particular lasers for 10 Gbit/s direct modulation
- hybrid subsystems on SiO₂-, silicon-on-insulator- (SOI), or polymer compact optical boards plus optoelectronic devices with monolithic integrated spot size transformer, which provide sufficiently wide tolerances for passive alignment, and
- polymer-based low-cost devices such as wavelength multiplexers/demultiplexers or optical switches.



Photonic bandgap (PBG) structures are expected to enable the design of devices with completely new functionalities or, alternatively, light emitters or WDM devices, which are much more compact than traditional semiconductor lasers or wavelength-selective devices for example. Consequently such devices are still an attractive research topic, although the commercialisation of PBG-based devices has been restricted to corresponding ('holey') fibres so far.

Optical chip-to-chip interconnects as a means to overcome expected bottle necks with electronic chip-to-chip interconnects have attracted large amounts of research funds internationally (USA, Japan, Korea, Europe), while Germany is lagging behind and HHI is trying in close cooperation with other German partners to raise money for such research.

The actual device development performed at HHI is along these internationally prevailing lines. Device and subsystem development is typically implemented in close cooperation with SMEs, and it is frequently supplemented by transmission and systems experiments, which are carried out with different focus in different groups at HHI. The high level of performance of HHI's device development is reflected by the fact that HHI's corresponding groups/departments have been particularly successful with project proposals within the sixths framework of the European Commission. HHI is partner in one Network of Excellence, in four different STREPs and HHI is even the coordinating partner in two of them.

A selection of typical and relevant research projects are described in more detail on the following pages, where the limited space excludes the complete coverage of all projects.

During 2004 attempts and initiatives to commercialise the results of earlier research projects have been intensified. Life experiments performed within the OFC- or ECOC-related exhibitions constitute one corresponding example, and these demonstrations experienced strong international interest. Invited talks at these conferences can be considered as supporting and accompanying measures. Other projects/initiatives were based on HHI's own experience in systems-related measurements or on proven cooperations with external partners.

In the past HHI researchers had developed chips for specific all-optical signal processing functionalities within different research projects, and various research groups worldwide had expressed their interest in obtaining corresponding modules. As a consequence HHI has developed such modules and sold a limited number of them. The modules offer unique properties and could eventually lead to the (step-wise) introduction of all-optical techniques into commercial systems, once their potential has been investigated and assessed in different research labs.

After the IT-related euphoria of recent years has vanished, more realistic cost and profit estimates have led many companies to a reduction of their technological capacities. Variants have been down-sizing, transfer to low-labour cost environments, outsourcing, or complete shut-down and keeping a design-competence only, and these measures have been implemented by SMEs and Global Players as well. HHI still has a complete InP technology line comprising epitaxy, planar technology, packaging and module technology. HHI's facilities also comprise versatile and comprehensive characterisation and measurement equipment, which enables thorough investigations on a chip or module level and in systems tests as well.

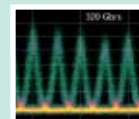
The close cooperation between systems and components engineers and the steady improvement of the technological skill and experience in such wide an area is unique within Germany and places HHI among the leading institutions within Europe. This is a prerequisite for securing continuing success in the area of photonic components and systems, where raising research funds has become increasingly difficult, and competition is tough and margins for commercial products are small. Under such circumstances HHI with its resources and its expertise as well is a strong and reliable partner, which enables cooperating SMEs to acquire or hold key positions worldwide.

Photonische Komponenten

Optoelektronische Bauelemente in Kombination mit Glasfasernetzen, Mikrosystemtechnik und Mikroelektronik bilden das Rückgrat faseroptischer Kommunikationssysteme, welche wiederum ein wesentliches Fundament der heutigen in globalem Maßstab eng vernetzten Wirtschaft bilden. Photonische Komponenten sind die technologische Voraussetzung für das Internet und die Mobilkommunikation, deren Basis-Stationen durch ein leistungsfähiges optisches Netz verbunden werden.

Die zu transportierenden Datenmengen haben seit Jahren hohe Wachstumsraten (+100% pro Jahr). Eine wesentliche Voraussetzung für das Ziel, immer mehr Daten zu immer niedrigeren Kosten weltweit transportiert zu können, ist die Verfügbarkeit optoelektronischer Bauelemente mit immer weiter verbesserten Leistungsmerkmalen bei gleichzeitig fallenden Bauelement-Kosten.

Die Akzente bei der Entwicklung optoelektronischer Bauelemente haben sich im vergangenen Jahr im Vergleich zur Zeit davor weiterhin in bestimmten Grenzen verschoben: Die wirtschaftliche Bedeutung von Einzelkanal-Übertragungsraten jenseits 100 Gbit/s wird zunehmend skeptischer beurteilt, mit der Folge, daß die Entwicklung von Komponenten für höchste Bitraten ebenso wie für die optische Signalver-



arbeitung von industrieller Seite wesentlich zurückhaltender gefördert wird. Dieser Trend gilt, auch wenn auf wichtigen Tagungen (ECOC, OFC) nach wie vor über Transmissionsexperimente mit 160 Gbit/s-Einzelkanal-Bitraten berichtet wird. Zunehmendes Interesse findet dagegen das 100 Gbit/s-Ethernet mit dem Schwerpunkt der gleichzeitigen Entwicklung robuster und preiswerter Systemkomponenten.

Einen zunehmende Bedeutung haben die höherwertigen Modulationsverfahren erfahren, die den wirtschaftlichen Einsatz von 40 Gbit/s-Systemen stark voranbringen können, ggf. unterstützt von Forward Error Correction (FEC) Verfahren, die bei 10 Gbit/s-Systemen zu enormen Leistungssteigerungen geführt haben.

Die Forderung, Bauelemente zu entwickeln, deren Einsatz zu niedrigeren Gesamtkosten im System führt, hat einen unverändert hohen Stellenwert. In die entsprechenden Entwicklungskategorien fallen:

- Bauelemente, insbesondere Sendelaser für ungekühlten Betrieb und Direktmodulation bis zu 10 Gbit/s
- hybride Subsysteme auf der Basis von auf SiO₂-, SOI- oder Polymer-Wellenleiter-basierenden optical boards, die für moderate Justagetoleranzen (Feldweitentransformator) und möglichst geringe Modulgröße konzipiert sind
- preisgünstige Komponenten (z.B. WDM-Bauelemente, optische Schalter) auf Polymerbasis

Bauelemente auf der Basis photonischer Kristalle, die z.T. extrem kompakte Strukturen oder auch völlig neuartige Funktionalitäten ermöglichen, sind weiterhin ein aktuelles FuE-Thema, auch wenn der Sprung zur kommerziellen Verwertung bisher nur bei Fasern mit entsprechenden Strukturierungen gelungen ist („holey fibres“).

Schließlich haben optische Chip-zu-Chip-Verbindungen im vergangenen Jahr einen erheblichen Zuwachs an Aufmerksamkeit gefunden. Entsprechende Arbeiten, die dazu dienen, einen vorhersehbaren Engpaß bei den elektrischen Chip-zu-Chip-Verbindungen zu überwinden, werden in den USA, in Japan, Korea, aber auch in Europa bereits intensiv gefördert. In Deutschland geschieht das dagegen noch nicht im erforderlichen Umfang, und deshalb bemüht sich das HHI zusammen mit anderen Partnern in Deutschland, diese Thematik als einen künftigen Förderschwerpunkt zu verankern.

Die Bauelement-Entwicklungen am HHI orientiert sich an den genannten Entwicklungslinien. Die Entwicklungen erfolgen einerseits in enger Kooperation mit Firmen, in der Mehrzahl KMUs, andererseits wird die Bauelement-Entwicklung in der Regel in System-Tests eingebunden, die am HHI in verschiedenen Gruppen und mit unterschiedlicher Fragestellung durchgeführt werden. Die hohe Qualität der FhG-HHI Bau-

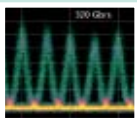
element-Entwicklung spiegelt sich auch in der Tatsache wieder, daß das HHI innerhalb des sechsten Rahmenprogramms der EU in vier verschiedenen Projekten (STREPs) und in einem Network of Excellence vertreten ist und in zwei Projekten sogar die Rolle des Koordinators wahrnimmt.

Eine repräsentative Auswahl von entsprechenden Arbeiten wird auf den folgenden Seiten genauer beschrieben, Vollständigkeit ist wegen des begrenzten Raumes nicht möglich.

Im Jahr 2004 wurde in einigen Bauelement-Gruppen verstärkt begonnen, das in den letzten Jahren erarbeitete Know How auch zu vermarkten. Dazu wurden Life-Experimente erfolgreich auf den wichtigen Konferenzen OFC und ECOC präsentiert, die die Aufmerksamkeit einer interessierten weltweiten Öffentlichkeit fanden. Begleitet wurden diese Marketing-Maßnahmen durch begleitende „Eingeladene Vorträge“ im wissenschaftlichen Rahmen. Es wurden Projekte mit öffentlichen und privaten Mitteln gestartet, in denen am FhG-HHI vorhandene Erfahrung auf dem Gebiet der System-Messungen in Zusammenarbeit mit anderen Gruppen genutzt wurden. Ferner wurden Anstrengungen unternommen, spezielle Komponenten, für die Interessenbekundungen anderer Labore vorlagen, gezielt für einen entsprechenden Verkauf herzustellen. Dabei handelt es sich um Prototypen, die am HHI entwickelt wurden und für die das HHI z. Zt. ein Alleinstellungsmerkmal hat. Zukünftige Berichte (auf Konferenzen, in Zeitschriften) über FuE-Ergebnisse, die unter Einsatz dieser vom HHI gelieferten Komponenten oder Module möglich wurden, werden die Vermarktung weiterer Komponenten und Subsysteme fördern.

Nachdem die Euphorie auf dem IT-Markt weitgehend verfliegen ist, haben realistische Kosten- und Gewinnabschätzungen viele Firmen dazu veranlaßt, – angefangen von den start-ups bis zu den großen „global players“ – ihre Technologie-Kapazitäten zum Teil drastisch zu reduzieren, zu verlagern oder sogar vollkommen ‚fabless‘ zu werden. Das HHI verfügt nach wie vor über eine komplette InP-Technologie-Linie, angefangen von der Epitaxie über die planare Prozessierung, stets begleitet von einer umfangreichen Meßtechnik, bis zum Aufbau einer begrenzten Anzahl von Modulen für System-Tests innerhalb und außerhalb des Hauses.

Das Zusammenspiel zwischen Systemarbeiten, Komponentenentwicklung und permanenter Verbesserung der Materialtechnologie ist einzigartig in Deutschland und führend in Europa. Dies stellt den Schlüssel für erfolgreiche Arbeiten auf dem schwierigen Markt und dem schnell veränderlichen Forschungsgebiet der Photonischen Netze und Komponenten dar. Das HHI ist damit vor allem für start-ups (weiterhin) ein wichtiger, verlässlicher und leistungsfähiger Partner, der es den kooperierenden Firmen ermöglicht, weltweit Spitzenpositionen zu erwerben bzw. zu verteidigen.



Photonic Devices

Optical Signal Processing

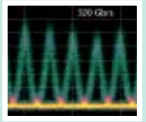
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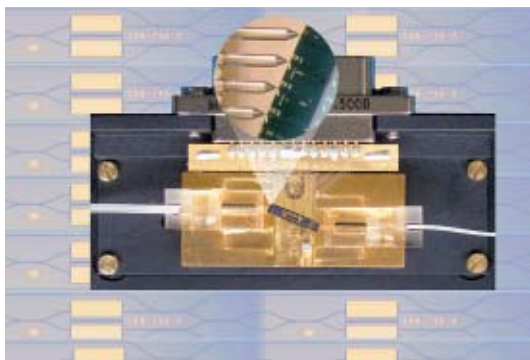
Micro Fabrication Technology

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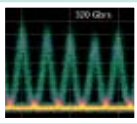
The background shows a processed InP wafer with rows of MZI-SOA structures. In the middle a single MZI-SOA chip is mounted on a heat sink and is connected to multi-fiber-arrays. The inset gives an enlarged view of the coupling of the fiber-array to the MZI-SOA.



Unit for high bitrate clock recovery (CR 160)



Laboratory setup of a phase stabilized optical data multiplexer



LASER DIODES WITH INTEGRATED BRAGG REFLECTOR

Aiming at a cost-effective "on-wafer" fabrication of laser diodes with a high-reflectivity facet, InGaAsP/InP ridge waveguide lasers have been realized that incorporate a monolithic external Bragg-reflector.

Mit dem Ziel, eine kostengünstige „on-wafer“ Verspiegelung von Lasern zu realisieren, wurden InGaAsP/InP „Ridge-Waveguide“ Laserdioden mit integriertem Bragg-Reflektor entwickelt.

For many applications the back side facet of a laser diode has to be highly reflective in order to increase the usable optical power at the front facet. Prominent examples are transmitter lasers with large slope efficiency, gain chips for fiber-grating lasers, and pump lasers for optical amplifiers. Conventionally, the high reflectivity (HR) is accomplished by depositing a periodic stack of dielectric layers of different refractive indices on the respective laser facet. This process needs to be applied to bars cleaved from the processed wafer. With a 2"-wafer containing e. g. 10,000 laser diodes, typically some 150–200 bars have to be coated which has a significant impact on the overall device costs.

To reduce those costs, a suitable "on-wafer" HR coating technique would be desirable. One approach for such a parallel coating process is to apply a metallization, in conjunction with an insulating film, to the previously dry-etched back facet. A nearly 100% reflectivity can be obtained this way, however, it impedes the use of a monitor diode for output power control of the laser.

We have pursued an alternative method employing an integrated etched Bragg reflector (BR). This design not only renders possible to adjust the reflectivity but also to monolithically integrate additional device structures.

The BR-gratings investigated are etched through the complete heterostructure. Due to the large contrast of refractive index between the grating teeth and the air gaps a high reflectivity can be obtained already with a very small number of grating periods in the range of 3 ... 10. In Fig. 1 a calculated reflectivity spectrum is displayed for a representative structure.

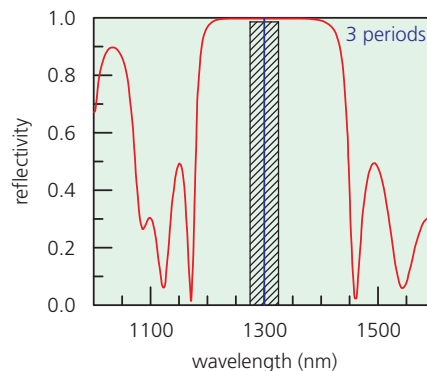


Fig. 1: Calculated reflectivity spectrum for a 3-period, 3rd order InGaAsP/air Bragg mirror; dashed region indicates temperature drift of Fabry-Perot laser diode from -40 °C to +85 °C

Experimentally, the BR technology has been applied to Fabry-Perot (FP) type 1300nm-RW-InGaAsP/InP lasers. Third order BR gratings were defined by

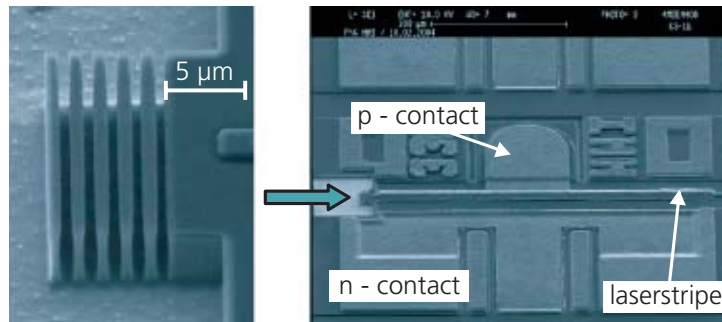


Fig. 2: Top view of RW laser diode with integrated Bragg reflector

electron beam lithography and etched using an adapted chlorine-assisted ion beam etching (CAIBE) process. Fig. 2 shows a REM image of the fully processed RW-laser featuring top-side contacts for both the p- and n- electrode. In this particular case a 5-period BR grating (left) was employed having a total length of only 8 μm.

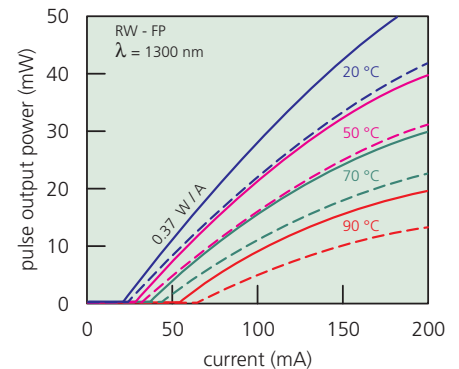
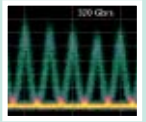


Fig. 3 : P-I characteristics of an InGaAsP/InP-RW-laser diode (cavity length: 300 μm); broken lines: both facets as cleaved; solid lines: as-cleaved/integrated Bragg reflector

A comparison of the output power characteristics of a standard as-cleaved RW-FP-laser and the developed RW-FP-BR-laser (Fig. 3) clearly confirm the high-reflection behaviour of the integrated BR-mirror. From these curves an effective reflectivity of about 75% can be deduced which has proven to be independent of the operation temperature.

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1.3 μm SIPBH FABRY-PEROT LASERS

1.3 μm buried heterostructure Fabry-Perot (FP) lasers with integrated semi-insulating InP:Fe current blocking layers have been developed and fabricated for applications in commercial, 10 GHz external cavity pulse laser sources.

1,3 μm Fabry-Perot (FP) Laser mit semi-isolierenden InP:Fe Stromblockierungsschichten wurden entwickelt und hergestellt. Die Laserstrukturen werden nach Fertigstellung als aktive Elemente in kommerziell erhältlichen, hybrid aufgebauten 10 GHz PulsLasern mit externem Resonator eingesetzt.

Planar Buried Heterostructure (PBH) lasers, which contain a semi-insulating InP:Fe current blocking layer, are thought to have the potential of better high frequency characteristics than those containing conventionally regrown pnp-InP layer sequences. Thus, SIPBH laser structures are preferably chosen as basic building blocks in high speed optical semiconductor (pulse) laser components (SIPBH: Semi-insulating Planar Buried Heterostructure).

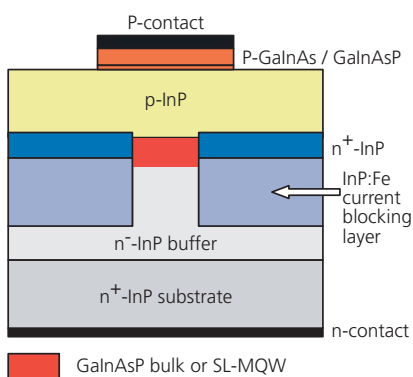


Fig. 1: Schematic cross-section of a SIPBH laser structure consisting of a semi-insulating InP:Fe current blocking layer

1.31 μm bulk SIPBH FP lasers have been developed and fabricated for implementation into commercially available, wavelength tunable 10 GHz external cavity pulse sources for applications in optical sampling components

or transmission set-ups (cf. Fig. 2 and www.u2t.de). After laser chip processing and mounting a saturable absorber will be integrated by ion implantation to complete the required active building block for mode-locked laser operation.



Fig. 2: Commercially available 10 GHz external cavity pulse laser source consisting of FhG-HHI's implanted 1.31 μm SIPBH FP bulk laser ("TMLL1310", u2t Photonics AG, www.u2t.de)

The critical process steps within SIPBH laser fabrication are the preparation of the etched laser stripe prior to the selective area MOVPE regrowth of the semi-insulating InP:Fe layer and the MOVPE growth itself. A not optimized technology at this stage will cause unwanted leakage currents later during laser operation, which deteriorate the device performance (e.g. increased laser threshold, strong decrease of laser efficiency with increasing injection current). Based on the preparation and regrowth procedure developed at FhG-HHI, a reproducible fabrication of 1.31 μm SIPBH FP bulk lasers was achieved as well as it was already demonstrated for 1.55 μm SIPBH bulk and MQW FP lasers before (cf. Annual Report 2003).

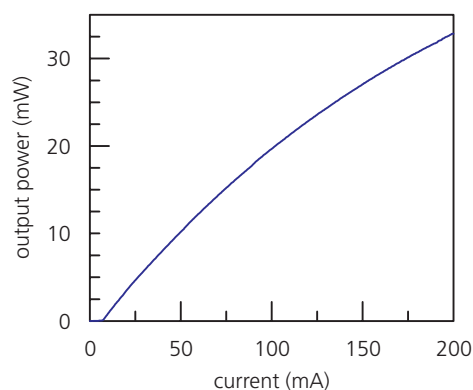
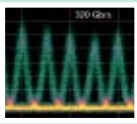


Fig. 3: Optical output power vs. injected laser current at the front facet of a typical 1.31 μm SIPBH bulk Fabry Perot (FP) laser (laser length: 300 μm , laser width: 1.0 μm , laser facets as cleaved, pulsed operation at room temperature)

Fig. 3 shows a typical L-I characteristic of a 300 μm long laser device. The threshold currents of all fabricated lasers are in the range of 7.0 ± 0.5 mA at room temperature. Optical output powers of 18.5 ± 1.5 mW (at 100 mA gain current) and 31 ± 3 mW (at 200 mA) are obtained at one laser facet.

The wavelength tunable 10 GHz mode-locked laser finally emits optical pulses with a width of less than 1.5 ps and low timing jitter values down to 50 fs (cf. Fig. 2 and www.u2t.de).

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VERY HIGH FREQUENCY 1550NM-BH-LASER DIODES

Using InGaAsP/InGaAlAs as active medium 1550 nm -BH-FP-laser diodes have been developed that exhibit a very large modulation bandwidth of 18 GHz (20 °C) and >10 GHz (90 °C) at fairly low bias currents.

Durch Verwendung aktiver InGaAsP/InGaAlAs-Schichten wurden mit 1550 nm BH-FP-Lasern sehr große Modulationsbandbreiten von 18 GHz (20 °C) und >10 GHz (90 °C) bei niedrigen Betriebsströmen erreicht.

Emerging optical transmission applications, including uncooled 10/12.5 Gbit/s operation at ambient temperatures up to 85 °C and even beyond, 10 Gbit/s fibre grating lasers, very high-frequency analogue transmission, and potentially also >10 Gbit/s optical chip-to-chip-interconnects require laser diodes that provide large modulation bandwidths $\gg 10$ GHz – to be achieved at bias currents as low as possible! With InP-based lasers (1550 nm), we demonstrate that using active quantum well medium composed of InGaAsP/ InGaAlAs can make a great difference.

With conventional 1550 nm laser diodes incorporating InGaAsP/InGaAsP-QWs the high speed performance is mainly limited by the large valence band discontinuity between well and barrier (about 60 % of the band gap difference) that leads to slow hole carrier transport across the QW layers. This behaviour is significantly improved using InGaAlAs/InGaAlAs QWs, but optimum conditions are obtained when employing a combination of both materials to form an InGaAsP/InGaAlAs QW structure (barrier = InGaAlAs). Here the valence band discontinuity favourably makes up only 22 % of the bandgap difference, leaving 78 % to the conduction band discontinuity.

After optimising the epitaxial growth and material quality of InGaAsP/InGaAlAs-QW-structures designed for 1550 nm emission, buried heterostructure (BH)-FP-lasers incorporating pn-blocking layers and surface n-contacts to facilitate RF measurements were fabricated. Despite the presence of Al containing layers bearing oxidation risks in the BH process high performance lasers have been achieved.

Coated lasers show low threshold currents of some 6 mA at room temperature and 20 mA at 90 °C in conjunction with high optical output powers. (Fig. 1).

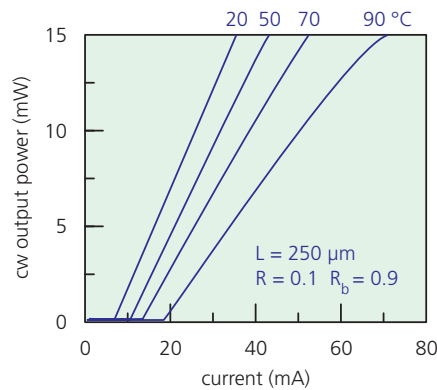


Fig. 1: Output power characteristics of a 250 μm long BH-FP-laser

RIN measurements confirm the superior frequency behaviour of these lasers compared with respective standard InGaAsP/InGaAsP-BH-lasers, characterized by a substantial increase of the slope of the relaxation frequency vs $\text{current}^{0.5}$ dependence, D^* , from 1.6 GHz/ $\text{mA}^{0.5}$ to 3.1 GHz/ $\text{mA}^{0.5}$ (Fig. 2).

Along with this, these lasers exhibit a very large modulation bandwidth. In Fig. 3 the frequency response at 20 °C is depicted. At room temperature more than 18 GHz modulation bandwidth is obtained at a bias current of 70 mA, and 10 GHz at only 15 mA (incl. threshold current).

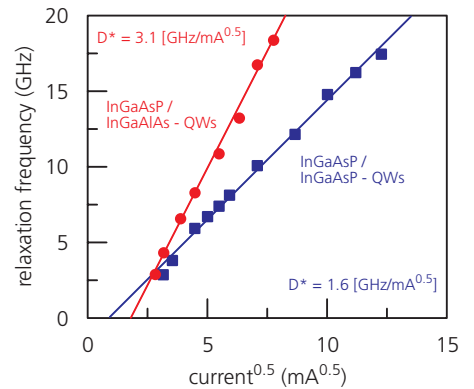


Fig. 2: Relaxation frequency in dependence of operation current for InGaAsP/InGaAlAs- and InGaAsP/InGaAsP-QW-BH-FP-lasers

At 90 °C, 10 GHz modulation bandwidth is achieved at about 45 mA.

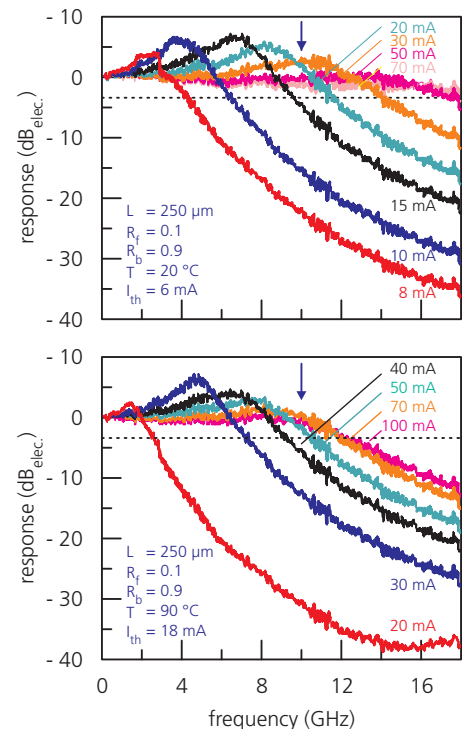
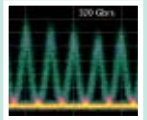


Fig. 3: Frequency response at 20 °C (top) and 90 °C (bottom)

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1 M. Möhrle, L. Mörl, A. Sigmund, A. Suna, F. Reier, and H. Roehle, "InGaAsP/InGaAlAs 1.55 μm strain-compensated MQW BH lasers with 12.5 GHz cut-off frequency at 90 °C", International Semiconductor Laser Conference 2004, Matsue, Japan, paper WB 2



LOW NOISE 40 GHz PULSE SOURCE OEIC

Optimized, low noise 40 GHz mode-locked laser pulse sources, designed to be used in high data rate transmission systems, are demonstrated. The monolithically integrated lasers are based on semi-insulating planar buried hetero-structure (SIPBH) GaInAsP/InP technology. The pulse sources have been optimized with respect to low amplitude noise and shortest pulse lengths.

Es wurden optimierte, rauscharme 40 GHz modengekoppelte Laser-Pulsquellen für die Anwendung in hochbitratigen Übertragungssystemen demonstriert. Die monolithisch integrierten Laser basieren auf dem GaInAsP/InP Materialsystem und der Technologie planar vergrabener und semi-isolierender Blocking-schichten. Die Pulsquellen wurden bezüglich geringen Amplituden-rauschens und kürzester Pulslängen optimiert.

The monolithically integrated mode-locked laser OEICs are designed to be used as Return to Zero pulse sources for high bit rate transmission within one single channel for datacom or telecom applications. The benefits of this pulse source are compactness, robustness and low cost.

The implementation of SIPBH technology based on Fe doping into an integration process for the GaInAsP/InP material system has been the pre-

requisite for fabrication of monolithic lasers for hybrid mode-locked operation at 40 GHz. The OEIC comprises 4 sections in active and passive material, as shown in Fig. 1. The different sections are needed for mode-locking operation and can additionally be used for tuning or trimming the parameters of the emitted laser pulses. This concept results in a higher fabrication yield. The OEIC has a footprint of only 0.35 mm².

Simple driving schemes for tuning of repetition frequency and emission wavelength at the same time have been successfully proven¹, however, they were applicable only up to 80 Gbit/s data rate after multiplexing.

This limitation was mainly given by high levels of amplitude noise. Amplitude noise is due to the simultaneous occurrence of Q-switching and mode-locking. Q-switching could be suppressed successfully by optimizing the laser design, in particular by balancing the saturation behavior of the gain and absorber section. As a result of an improved processing, which takes into account the required balancing, the amplitude noise has been reduced down to 0.8 – 2.5% (shown by the pulse trace in Fig. 2) while keeping the generated pulse widths low within the range of 1.2 – 2 ps. A compilation of the most relevant data of the redesigned pulse source is given in Tab. 1. It turns out, that the performance meets already the requirements for 100 Gbit/s and/or 160 Gbit/s applications.

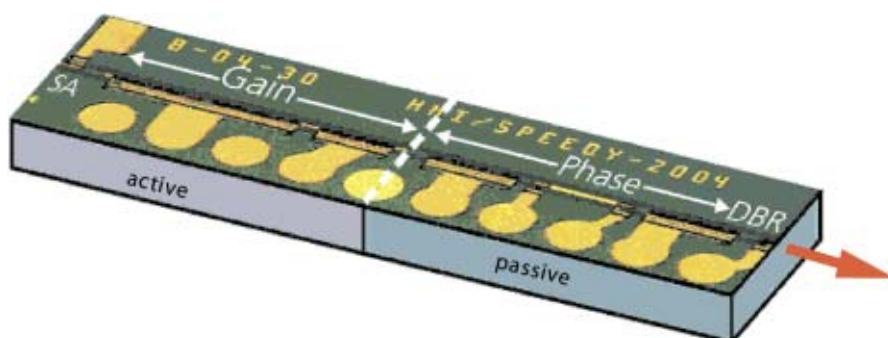


Fig. 1: View photograph of a monolithic mode-locked laser OEIC

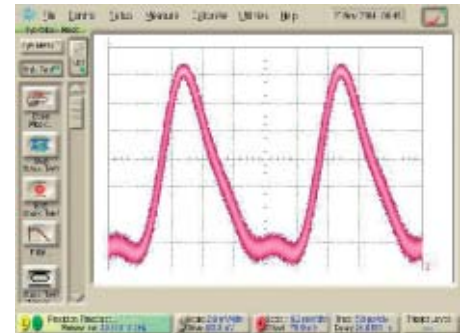


Fig. 2: Pulse trace of pulse source, representing low amplitude noise (< 1.2%), repetition frequency of 39.812 GHz

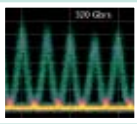
Repetition rate	39.5 .. 39.82 GHz
Repetition rate tuning/locking bandwidth	200 .. 300 MHz
Pulse width	1.2 .. 2 ps
Amplitude noise	0.8 .. 2.5%
Timing jitter	150 .. 250 fs
Time bandwidth product	0.40 .. 0.50
Power (in fiber)	-3 .. 0 dBm
Emission wavelength	1550 .. 1555 nm

Tab. 1: Performance data of low noise, hybridly mode-locked laser

This work has been supported by the Federal Ministry of Education and Research under grant 01 BP 070 and the State of Berlin under grant Terabit Optics Berlin 10017603

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¹ R. Kaiser, B. Hüttel, C. Kindel, H. Stolpe, H. Heidrich, S. Fidorra, W. Rehbein, S. Ritter, and G. Jacumeit, "Effects of On-chip Wavelength Tuning on Pulse and Noise Characteristics of Monolithic Mode-locked 40 GHz SIPBH DBR Lasers", Proc. of IEEE 19th Internat. Semiconductor Laser Conf. 2004, Matsue, Japan, p. 95



40 GBIT/S OPTICAL 3R REGENERATOR FOR ASYNCHRONOUS DATA PACKETS

All-optical 3R signal regeneration (Re-amplification, Re-timing, Re-shaping) is a key function in future scalable packet switched WDM networks. In comparison to the synchronous point-to-point transmission, the regenerator operates in asynchronous mode under more critical conditions: The incoming packets are uncorrelated in time to each other and the wavelength can vary. Thus, the recently developed optically clocked 3R regenerator (OC-3R) has been evaluated for 40 Gbit/s asynchronous PRBS packet streams.

Rein-optische 3R Signalregeneration (Re-amplification, Re-timing, Re-shaping) gehört zu den Schlüsselfunktionen zukünftiger Paketgeschalteter WDM Netze. Im Vergleich zu einer synchronen Punkt-zu-Punkt Übertragung arbeitet der Regenerator im asynchronen Betrieb unter viel schwierigeren Bedingungen: Die ankommenden Pakete sind zueinander in ihrer Zeitlage unkorreliert und ihre Wellenlänge kann variieren. Der neu entwickelte optisch getaktete 3R Regenerator (OC-3R) wurde deswegen mit 40 Gbit/s asynchronen PRBS Paketströmen untersucht.

The wavelength preserving optically clocked 3R regenerator is based on two compact semiconductor components (Fig. 1). Clock recovery is performed by a three section self-pulsating PhaseCOMB-laser that synchronises all-optically to the injected data signal. The clock signal periodically modulates the gain of the ultra-long SOA (UL-SOA) resulting in re-timing and re-shaping of the degraded data signal.

One technique for processing of asynchronous packets is to add a preamble with synchronisation bits. However, the

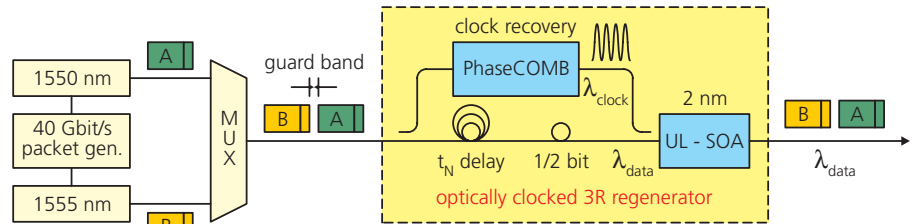


Fig. 1: Scheme of the OC-3R regenerator operated in asynchronous packet data streams

degraded preamble must be swapped by a new one after each regeneration stage resulting in sophisticated logical circuits. Due to the special locking characteristics of the PhaseCOMB clock, the OC-3R scheme can process asynchronous packets without an additional preamble.

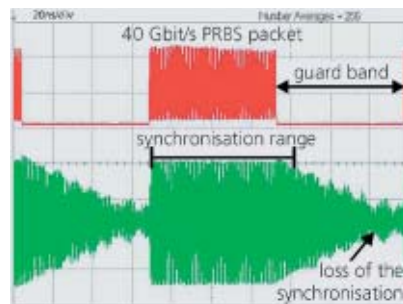


Fig. 2: Locking behaviour of the PhaseCOMB-laser

In the experiment, a 40 Gbit/s PRBS packet (3000 bits) at 1550 nm (Fig. 2, upper trace) was launched into the self-pulsating laser. The lower trace of Fig. 2 shows the corresponding clock signal of the PhaseCOMB-laser, measured in the average mode of the sampling oscilloscope. The instantaneous increase of the clock amplitude at the packet head shows ultra-fast locking (within 3 ns), and the slow decrease of the amplitude at the packet end indicates a long holding of the synchronisation for more than 10 ns after the packet end.

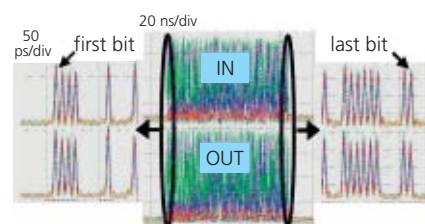


Fig. 3: PRBS packet at OC-3R input and the regenerated output data packet without loss of any bit at head or end

Next, the PRBS packet was injected into the OC-3R and analysed at the regenerator output (Fig. 3). It is obvious, that the first bit as well as the last bit of the data packet are processed without distortions.

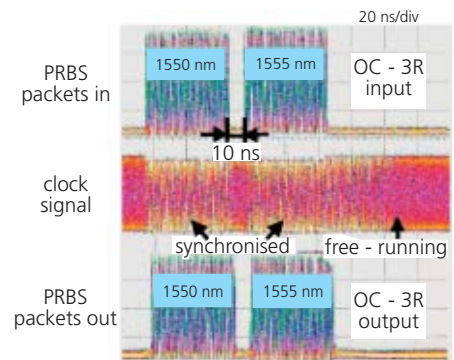
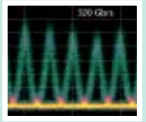


Fig. 4: OC-3R operation in 40 Gbit/s asynchronous WDM packet data streams

The asynchronous operation of the OC-3R was investigated in a stream of data packets with alternating wavelength and various guard band lengths. Fig. 4 shows in the upper trace two 40 Gbit/s packets at 1550 nm and 1555 nm respectively. Both signals were multiplexed and launched into the regenerator (Fig. 1). The guard band was reduced down to 10 ns. Even for this very small time interval the optical clock synchronises ultra-fast to the respective incoming packets (Fig. 4, middle trace). The data packets are processed in the OC-3R without any bit losses (Fig. 4, lower trace). Thus, the OC-3R regenerator fulfils excellently the requirements of dynamically reconfigurable asynchronous all-optical WDM networks.

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¹ J. Slovak et al., ECOC 2004, Stockholm, Sweden, Paper We2.5.7



HIGH-POWER 14XX NM BH-LASER DIODES

InP-based BH-type pump laser diodes (1450 nm) have been developed that deliver 0.7 W single transversal mode CW output power and stable, low-divergence far-fields.

InP-basierte Pumplaserdioden (1450 nm) mit BH-Struktur wurden entwickelt. Die Laser liefern Ausgangsleistungen > 0.7 W und zeigen schmale, stabile Fernfelder.

Raman amplification has gained a lot of attention in recent years as a powerful technique for optical amplification in fiber-optic networks. Occurring in the standard transport fiber itself Raman amplification is applicable basically to any wavelength region, in contrast to doped fiber amplifiers. For Raman amplification of optical data signals in the 1500–1600 nm range pump lasers are required that emit at wavelengths some 100 nm below, i.e. in the 1400–1500 nm region (14xx pump lasers). High pump powers of several hundreds of mW, even up to more than 1 W, are desired, and to achieve amplification over a broader spectrum a multiple pumping wavelength scheme has to be used, demanding suitable power combiners with low insertion loss.

We have developed 14xx nm pump lasers with a Buried-Heterostructure (BH) design which promises superior performance with respect to low threshold current, high slope efficiency, and optical mode stability even at high pump currents. A large optical cavity design was adopted involving a quaternary cladding layer in the n-type region to minimize optical cavity losses.

Fig. 1 shows that fairly high cw output powers of more than 0.7 W at room temperature have been obtained with

these laser devices. Such levels were achieved when mounting the laser chips p-side down with In solder which is, however, not compatible with telecom applications.

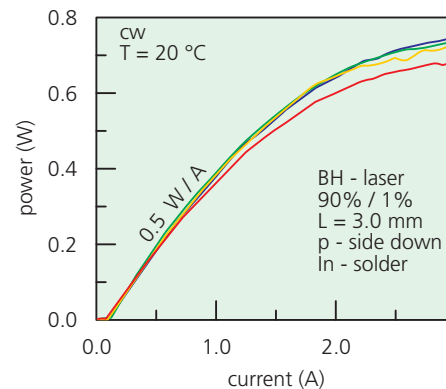


Fig. 1: Output power of 1450 nm BH-FP power laser diodes mounted with In solder (performed at Fraunhofer IAF)

Use of the accepted AuSn solder and AlN heatsinks was found to considerably reduce the output power to about 0.4–0.5 W (Fig. 2). This finding proves the mounting technology to be at least as crucial for the laser performance as an optimized device design.

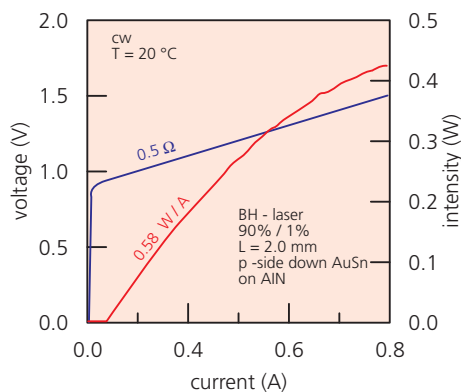


Fig. 2: P-I-V characteristics of laser diodes soldered with AuSn on AlN submount

The light output is transversal single mode as seen from spectral and far-field measurements (Fig. 3, 4). The far-field patterns behave perfectly stable over the whole power range and exhibit beam angles of 12°/18° (FWHM) with an M²-factor of < 1.5.

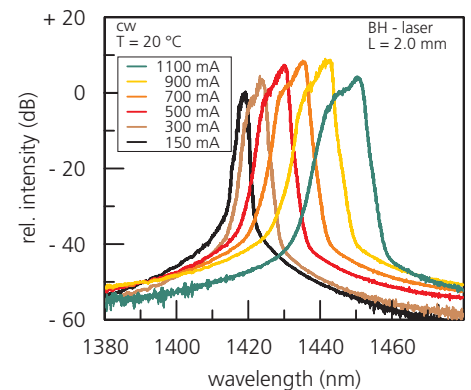


Fig. 3: Optical spectra as function of drive current

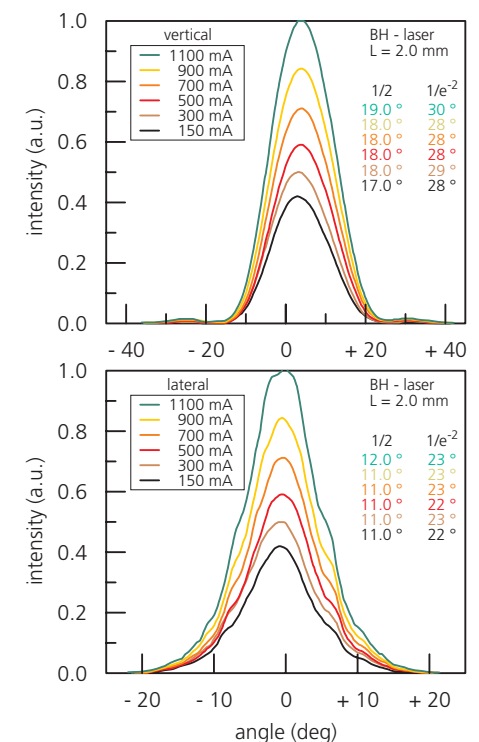
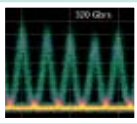


Fig. 4: Farfield patterns

Using these laser chips, high optical coupling efficiencies to standard monomode fibers or to planar-light-wave-circuit based pump combiners (AWG, MZI) may be guaranteed. The slope efficiency of 2 mm long devices is as high as 0.58 W/A when coated 90% / 1% and remains at 0.50 W/A for a length of 3 mm, proving the low absorption loss of the layer structure.

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PMD MITIGATION AT 40 GBIT/S USING AN ALL-OPTICAL 3R REGENERATOR

The polarization mode dispersion (PMD) is one of the most serious obstacles facing high-bitrate fiber optic communication systems today. It can degrade the performance of 40 Gbit/s transmission links and also result in severe system outages. Optical 3R-regenerators are an alternative way that can make significant contributions in terms of mitigation the PMD in a cost saving way. Recently a novel semiconductor based all-optical 3R regenerator preserving the original data wavelength was developed and patented by FhG-HHI. This optically clocked regenerator was successfully demonstrated at 40 Gbit/s for the mitigation of PMD.

Die Polarisationsmodendispersion (PMD) stellt heute eine der größten Herausforderungen in hochratigen faserbasierenden Datenübertragungssystemen dar. Schon bei einer Datenrate von 40 Gbit/s kann sie zu massiven Einschränkungen der Übertragungsqualität und damit zu folgenschweren Systemausfällen führen. Optische 3R Regeneratoren sind ein alternativer Ansatz um den Einfluß der PMD entscheidend und kostengünstig zu minimieren. Dazu wurde im FhG-HHI ein neuartiger auf Halbleiterbauelementen basierender, wellenlängenerhaltender optischer 3R Regenerator entwickelt und patentiert. Dieser wurde bei einer Datenrate von 40 Gbit/s bezüglich der Verringerung der PMD erfolgreich getestet.

Fig. 1 shows the scheme of the optically clocked 3R regenerator (OC-3R). It needs only two compact semiconductor devices for operation, the Phase COMB-laser and an ultra long SOA (UL-SOA). The PhaseCOMB-laser synchronises all-optically even on the degraded 40 Gbit/s RZ PRBS data signal

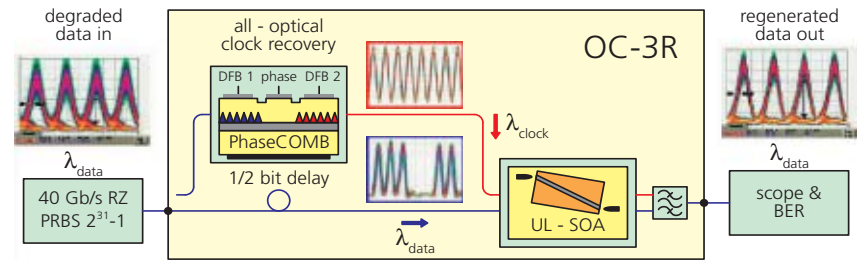


Fig. 1: Scheme of the OC-3R regenerator

and extracts a 40 GHz sinusoidal low jittered clock signal. Both, the clock signal and the 40 Gbit/s data signal are delayed by half a bit relative to each other and are launched into the second device, the ultra long SOA. The clock trace modulates periodically the gain in the UL-SOA and defines its saturation conditions. The incoming data pulses are re-timed and re-shaped while transmitting the regenerator. As a result a clear open eye on the data wavelength with improved Q-factor and reduced timing jitter is obtained.

Since PMD mitigation has proven a difficult task, it is of great interest to verify the PMD mitigation potential of the OC-3R regenerator. Hence a 40 Gbit/s RZ data signal with $2^{31}-1$ bit sequence was intentionally degraded by a PMD emulator which comprises an average differential group delay (DGD) of 10.2 ps corresponding to 40% of the bit period at 40 Gbit/s (Fig. 2 upper trace).

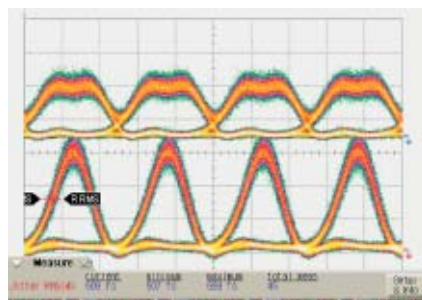


Fig. 2: PMD impact on OC-3R regenerator

The lower trace in Fig. 2 shows a clearly opened RZ eye which is obtained at the regenerator output. It is evident that the OC-3R regenerator retimes and reshapes the signal quality significantly. The broadened data pulses with FWHM of about 21 ps are reshaped to an RZ signal with 50% duty cycle and FWHM of 12.5 ps. In addition the high

jitter of the data input signal (900 fs) is reduced down to 509 fs which is related to the excellent retiming function of the PhaseCOMB-laser applied for all-optical clock recovery. Due to the stable low jittered clock pulses a pulse shaping in the UL-SOA is performed. Summing up there is a negligible impact of PMD distortions on the OC-3R regenerator.

The good results for PMD mitigation by the OC-3R were also confirmed by BER-measurements. A negative penalty of 2.5 dB was obtained for an PMD degraded data signal with an average DGD of 10.2 ps (Fig. 3).

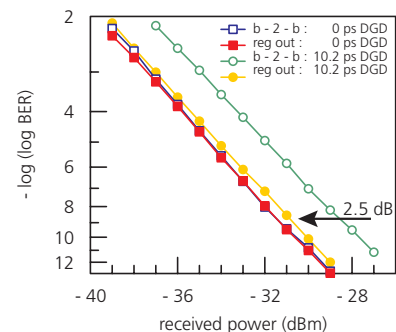


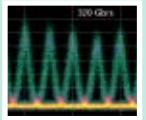
Fig. 3: BER analysis of PMD distortion

Thus the OC-3R shows high reliability and robustness against distortions of the data signal induced by time fluctuation and by PMD distorted pulse broadening. This verifies the OC-3R concept as a promising solution for future all optical signal processing networks. Hereto the compact and cost effective semiconductor based structure will pave the way to the market.

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1 Bornholdt et al., Electron. Lett. 40, pp. 192–194 (2004)

2 Bornholdt et al., OFC 2005, OTuO6



100 GHz PHOTODETECTORS – COMPONENTS TO MANAGE THE EVER INCREASING DATA TRAFFIC IN OPTICAL COMMUNICATIONS

Ultrafast longhaul fiber transmission and 100 G ethernet are leading applications to manage the ever increasing data traffic in optical communications. Therefore we optimised a photodetector OEIC for bandwidths of up to 110 GHz, as part of a family of ultrafast photodetectors and photoreceivers. We packaged the OEICs into modules and operated them at data rates of up to 160 Gbit/s.

Die höchstbitratige Übertragung über Weitverkehr-Glasfaserstrecken und das 100 Gbit/s Ethernet sind führende Anwendungen, um dem stetig steigenden Datenverkehr über optische Verbindungen den Weg zu ebnen. Hierfür haben wir im Rahmen der Entwicklung ultraschneller Photodetektoren und Photoempfänger, einen Photodetektor-Chip für Bandbreiten bis zu 110 GHz optimiert. Die Chips wurden in Module verpackt und bei Datenraten bis zu 160 Gbit/s betrieben.

The photodetector (PD) chip comprises a pin photodiode, a spot-size converter for effective fibre-chip coupling, a biasing network, and a $50\ \Omega$ termination resistor. This termination resistor was applied to provide a good signal integrity. The evanescently coupled photodiode with an active area of $5 \times 20\ \mu\text{m}^2$ and an InGaAsP/InGaAs heterostructure absorption layer stack is located on top of a semi-insulating ($5 \times 10^7\ \Omega\text{cm}$) optical waveguide stack¹.

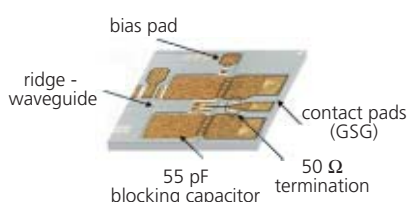


Fig. 1: Micrograph of the photodetector chip including a bias-T at the cathode and 50 Ohm termination

The viewgraph of the chip is given in Fig. 1 which shows the photodiode p-mesa, coupled via an optimised air-bridge to the $50\ \Omega$ terminating resistance. The RF output signal is fed by a coplanar waveguide taper to the contact pads, which are compatible to 110 GHz on-wafer probing heads. The bandwidth of these new detector chips was proven by heterodyne measurements to be 110 GHz.



Fig. 2: Photograph of the PD module with fibre pigtail and 1 mm output connector

The devices are assembled in standard housings equipped with a fibre pigtail and a 1 mm coaxial output connector². Fig. 2 shows a photograph of a finished PD module. The DC responsivity of the PD module amounts to 0.63 A/W with a polarization dependant loss of only 0.64 dB at $1.55\ \mu\text{m}$ wavelength. The frequency characteristic of the photodetector module was determined by an optical heterodyne measurement setup up to 120 GHz, see Fig. 3.

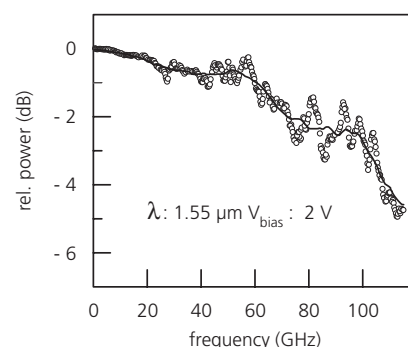


Fig. 3: Relative frequency response of a PD module measured at +2.3 dBm optical input power incl. smoothed curve

We observe a smooth decay of 2 dB up to 70 GHz and a -3 dB bandwidth of 100 GHz.

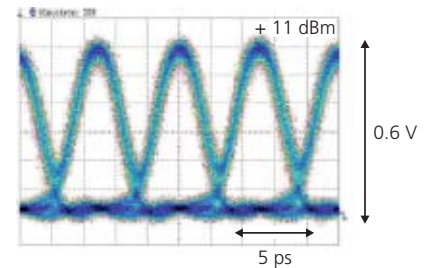


Fig. 4: Electrical 80 Gbit/s RZ eye pattern at +11 dBm optical input power detected by the photodetector module at 2.5 V reverse bias, x-axis: 2.5 ps/div, y-axis: 100 mV/div

By using optical time domain multiplexing techniques we generated 80 Gbit/s and 160 Gbit/s return-to-zero (RZ) modulated data streams (PRBS) with 2^7-1 pattern length. In Fig. 4 the optical input power was adjusted to +11 dBm, resulting in an average photocurrent of 8 mA.

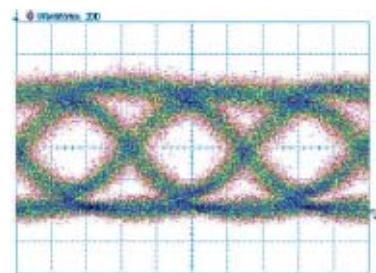


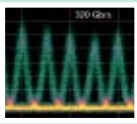
Fig. 5: Detected eye pattern under 160 Gbit/s RZ excitation at +11 dBm optical input power, $V_{\text{bias}} = 2.5\ \text{V}$; x-axis: 2 ps/div, y-axis: 100 mV/div

The detected RZ eye pattern is clearly opened with negligible saturation effects. The eye opening exceeds 0.5 V peak voltage at a moderate reverse bias of 2.5 V. Fig. 5 shows the detected 160 Gbit/s RZ data stream for +11 dBm optical input power. Due to the limited bandwidth of the sampling head and the photodetector module we observe an RZ-to-NRZ conversion. The eye opening is still remarkable with an amplitude that amounts to 0.3 V.

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¹ H.-G. Bach et al.: InP-Based Waveguide-Integrated Photodetector with 100 GHz Bandwidth, invited paper in IEEE Journal of Selected Topics on Quantum Electronics on Photodetectors and Imaging, Vol. 10, No. 4 (2004), pp. 668–672.

² A. Beling et al.: Highly Efficient pin Photodetector Module for 80 Gbit/s and Beyond, Tech. Digest Optical Fiber Commun. (OFC 2005), Anaheim, CA, USA, paper OFM1, March 6–11, 2005.



PLANAR INGAAS PHOTODIODES WITH VERY LOW DARK CURRENTS – CHIPS FOR IR SENSORS

We developed a family of planar InGaAs pin photodiodes for sensor applications and for low-cost optical transmission systems. The photodiodes, made by a cost-efficient process, exhibit very low dark currents. The devices are adaptable to varying customer requirements concerning characteristics like responsivity and cut-off frequency. We fabricated discrete diodes with diameters from 20 μm to 3 mm as well as photodiode arrays.

Am FhI HHI wurde eine ganze Gruppe von planaren InGaAs-pin Photodioden für die Sensorik und für optische Low-Cost Übertragungssysteme entwickelt. Die Photodioden, erzeugt in einem kostengünstigen Prozess, zeichnen sich durch sehr niedrige Dunkelströme aus. Die Komponenten können unterschiedlichen Kundenanforderungen hinsichtlich Charakteristika wie Responsivität und Grenzfrequenz angepasst werden. Es wurden Einzeldioden mit Durchmessern von 20 μm bis 3 mm und auch Photodiode-Arrays hergestellt.

For photodetectors in sensor applications high responsivities and very low dark currents are of crucial importance. Moreover for industrial customers a simple and inexpensive wafer fabrication process with a high yield is of major interest.

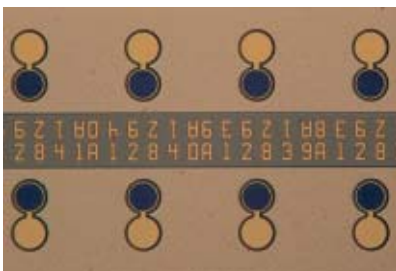


Fig. 1: 4×2 diode array with 250 μm pitch size

Therefore we designed a versatile set of photomasks allowing us to fabricate

discrete diodes with diameters from 20 μm up to 3 mm and arrays of up to 16×2 elements with a pitch of 250 μm (Fig. 1). It gives us the possibility to adapt the devices to the customers needs. For example we can apply a somewhat more complex processing schemes to increase the cut-off frequency or to change the configuration of electrical connections from back side to front side contacts, enabling also flip-chip bonding.

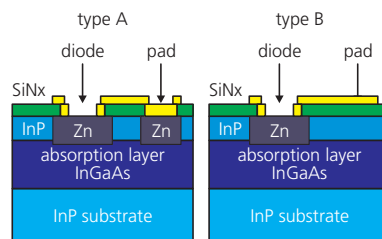


Fig. 2: Schematic drawing of the photodiode type A and type B

All processing schemes have a selective Zn diffusion with a silicon nitride mask in common. The silicon nitride remains on the wafer surface serving as a passivation layer for the pn-junction. As shown in figure 2 for type A diodes the signal pad is located on a Zn diffused region which shows a voltage dependent stray capacity similar to that of the photodiode. In type B diodes the signal pad is placed on a dielectric layer making the stray capacity independent of the applied voltage. If in addition a thick BCB layer is used to isolate the signal pad the stray capacity is significantly reduced. With this process we obtain extremely low dark current densities of 300 pA/mm² (Fig. 3) and a responsivity of 1.05 A/W at 1550 nm.

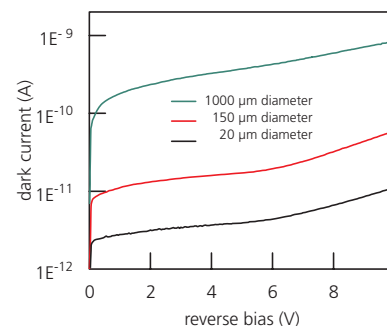


Fig. 3: Dark current of three planar photodiodes of type B with 20 μm , 150 μm , and 1000 μm diameter

For applications in the GHz region part of the devices were provided with a contact pattern suitable for microwave interconnections (Fig. 4), also allowing on-chip RF measurements. Type A diodes with a 3 μm thick undoped absorption layer show already cut-off frequencies of up to 6 GHz at -5 V bias (Fig. 5) although they have a rather large stray capacitance and their series resistance has not yet been optimized.



Fig. 4: Planar photodiode with RF-suitable contact pattern (ground and signal pads on front side)

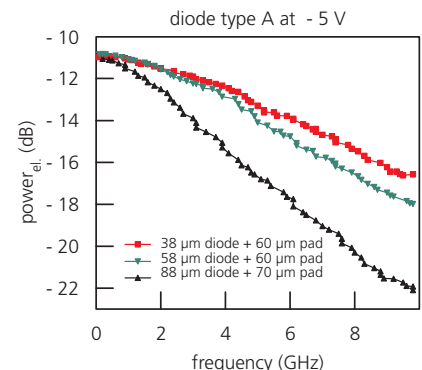
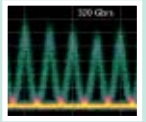


Fig. 5: Cut-off frequencies of photodiode type A with different diameters

At present work is done to reduce the stray capacity of the signal pad and the series resistance. From simulations we expect cut-off frequencies of 12 GHz for diodes with an active area diameter of 32 μm .

Part of this work was done in cooperation with EPIGAP Optoelektronik GmbH (Berlin).

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HIGH-BIT RATE MZI MODULATORS FOR ON-OFF-KEYING AND PHASE-MODULATION FORMATS LIKE DPSK

The evolution of the Internet to an integrated platform for data and voice (VoIP) and even unified messaging (UM) is in full progress. And the Ethernet platform shows a high potential for cost savings. Even more, if the ethernet standard could be extended from local area networks (LAN) to wide area network (WAN) interconnects. The key-component for this is a long range, high speed modulator, based on a Mach-Zehnder-Interferometer (MZI)-structure. With this design, the modulator is suited not only for standard on-off-keying modulation, but also for enhanced new modulation schemes like Carrier Suppressed RZ (CS-RZ) or Differential Phase Shift Keying (DPSK).

Die Entwicklung des Internet zu einer gemeinsamen Plattform für Daten- und Sprachverbindungen (VoIP) sowie „Unified Messaging“ (UM) ist in vollem Gange. Das Ethernet bietet darüber hinaus ein hohes Kostensenkungspotential, und dies um so mehr, wenn es vom ursprünglichen Bereich der lokalen Netzwerk-Infrastruktur (LAN) auf die Nutzung im Weitverkehrsbe- reich (WAN) ausgedehnt werden könnte. Eine Schlüsselkomponente hierfür ist ein auf einer Mach-Zehnder-Interferometer (MZI)-Struktur basierender schneller Modulator für große Reichweiten. Aufgrund seines Wirkungsprinzips ist er nicht nur für die aktuellen Standardmodulationsverfahren, sondern auch für die neuen Phasenmodulationsverfahren wie CS-RZ oder DPSK einsetzbar.

The modulator is based on InP and integrated with an optical spot size converter (SSC) for low insertion loss. It features 30 nm optical bandwidth, low driving voltage, small footprint and

stable operation over time. The modulator operates in a balanced push-pull configuration for low-chirp.

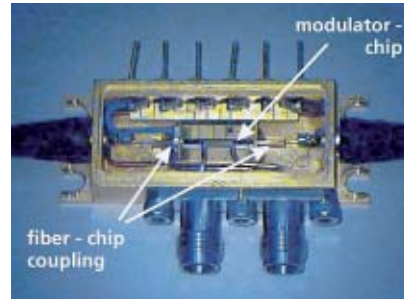


Fig. 1: 40 GHz MZ-Modulator; built up in a specially designed evaluation package

To achieve the high data rates, the modulator has a travelling wave electrode (TWE) (Fig. 2). One can see the two TWE electrodes which are designed as microstrip lines, where the overall impedance can be matched to $50\ \Omega$ by the capacitive load (active-waveguides in Fig. 3) of the distributed electrodes on the MZ arms.

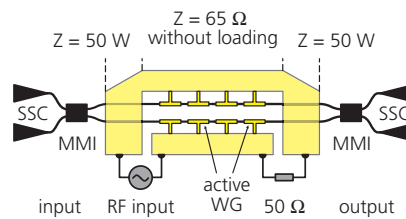


Fig. 2: Schematic layout of an MZI based modulator with capacitively loaded travelling wave electrodes

Details of the fabricated structure are shown in Fig 3 obtained with a scanning electron microscope (SEM). One can see the $4\ \mu\text{m}$ high, gold plated electrodes and the air-bridges to the $2\ \mu\text{m}$ wide active waveguides in the MZI-area.

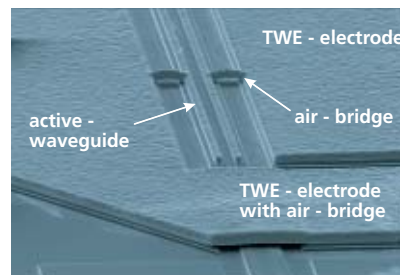


Fig. 3: SEM-picture of an MZI sector with capacitively loaded TWE's via air-bridge contacts

The electro-optical (EO) response of this device is shown in Fig. 4. The

optical output signal is transferred to the electrical domain using a high speed photodiode (u2t) and is measured with an electrical spectrum analyser. It shows a 2 dB bandwidth at 50 GHz which is the limit of the actual measuring setup. The relevant 3 dB bandwidth is estimated to 58 GHz using the electrical S21 parameter measurement. Furthermore high frequency simulations of this device show that actually planned optimisation steps should lead to a frequency response as high as 90 GHz.

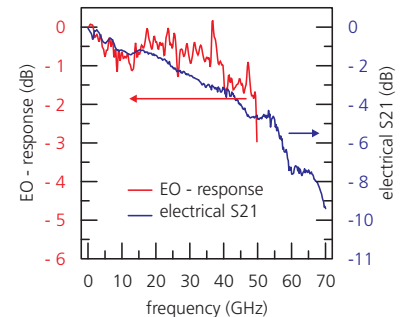


Fig. 4: Electro-optical (EO) response and electrical S21 parameter

A hybrid integration of the modulator and a driver-IC in one package (Fig. 5) and the possibility for the monolithic integration shows the potential for cheap and stable modulator-modules.

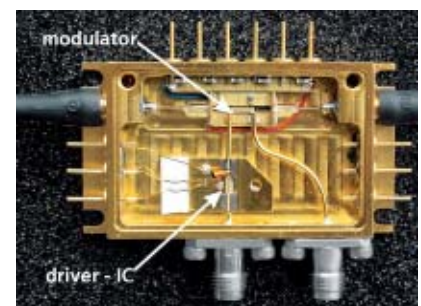
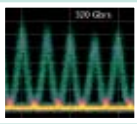


Fig. 5: Modulator-module with hybrid integrated driver-IC

With this design concept much higher bit rates are possible, approaching 100 Gbit/s in the near future. Furthermore the possibility for the monolithic integration of complex transmitter-structures for the enhanced modulation formats like DPSK and DQPSK will give this technology an additional drive.

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SMALL-SIZE POLYMER COMPONENTS FOR ACCESS NETWORKS

Very compact arrayed-waveguide grating (AWG) and optical add-drop multiplexer (OADM) chips have been fabricated using super-high refractive index contrast triazine containing polymers. The size of the four-channel AWG was only $10 \times 3 \text{ mm}^2$, and the insertion loss 3 dB.

Für Anwendungen in zukünftigen optischen Breitbandzugangsnetzen wurden kompakte optische Multiplexer (AWG, OADM) auf Basis triazinhaltiger Polymere mit hohem Brechzahlkontrast realisiert. Die Einfügedämpfung eines $10 \times 3 \text{ mm}^2$ großen 4-Kanal AWGs beträgt nur 3 dB.

Fibre-to-the-home (FTTH) represents the ultimate broadband environment and is being deployed at an accelerated rate in many countries now. A key issue for FTTH systems is the availability of inexpensive optical devices for optical access networks, such as optical splitters, multiplexers / demultiplexers, and optical add/drop multiplexers (OADM). Fig. 1 illustrates a scenario for the use of OADMs in future FTTH systems. Each OADM drops and adds signals at one wavelength, and the system capacity can be readily expanded by inserting additional OADM components.

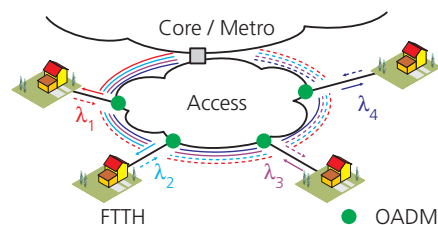


Fig. 1: OADM application in FTTH systems

Optical polymer waveguide devices are attractive for implementing such components because they offer to use fairly simple and low temperature fabrication processes and low cost packaging based on passive alignment. A crucial

cost factor is the number of chips that can be produced per wafer. This number is solely determined by the refractive index contrast, Δn , of the waveguide materials used. Higher Δn values not only result in smaller designs but would also counteract the propagation losses, thus yielding a compact, low-loss device.

Using novel triazine containing polymers that feature a super-high refractive index contrast of $\Delta n = 0.020$ and a propagation loss of 0.3 dB/cm @ $\lambda = 1.55 \mu\text{m}$, small-size devices for access network applications have been realized. Among these were 4- and 8-channel AWGs and OADMs with a channel spacing of 1200 GHz and 600 GHz , respectively. The chip size of the 4-channel AWG was only $10 \times 3 \text{ mm}^2$, rendering possible to place 150 pieces on a $4''$ wafer or 400 elements on a $6''$ wafer. The insertion loss amounted to be 3 dB , and the crosstalk was below -25 dB . The 8-channel AWG measures $13 \times 4.5 \mu\text{m}^2$, and the figures for the insertion loss and the crosstalk were 3 dB and -28 dB , respectively.

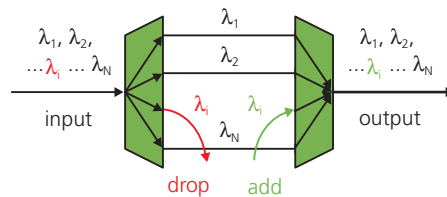


Fig. 2: Basic structure of an OADM

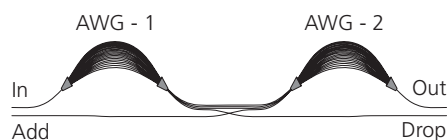


Fig. 3: Mask layout of a 4-channel OADM

The basic structure and the mask layout of a passive OADM are depicted in Figs. 2 and 3. It consists of two cascaded AWGs acting as wavelength demultiplexer at the input (AWG-1) and multiplexer at the output (AWG-2). The incoming optical signals carried by wavelength λ_1 are dropped at the first output port of AWG-1 (drop port). In fact, any port and any number of chan-

nels can be dropped and added as long as it is less or equal to the OADM channel number. The add signals at λ_1 are fed into the first input port of AWG-2 (add port). The demultiplexed input signals except the drop signals, together with the add signals at λ_1 , are launched into the input ports of AWG-2 to form the common output data stream of the OADM.

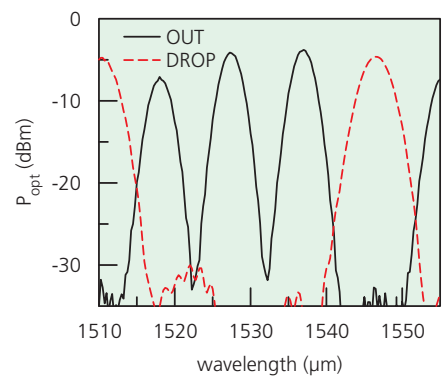


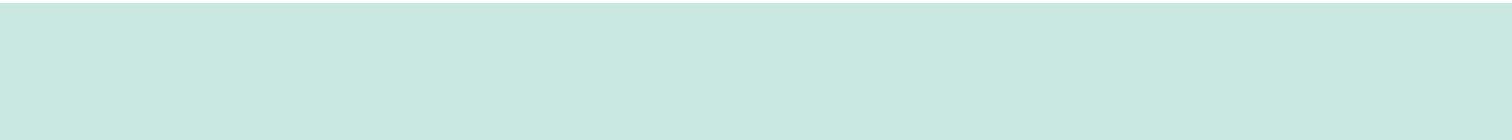
Fig. 4: Measured transfer characteristics: 4-channel OADM (1200 GHz)

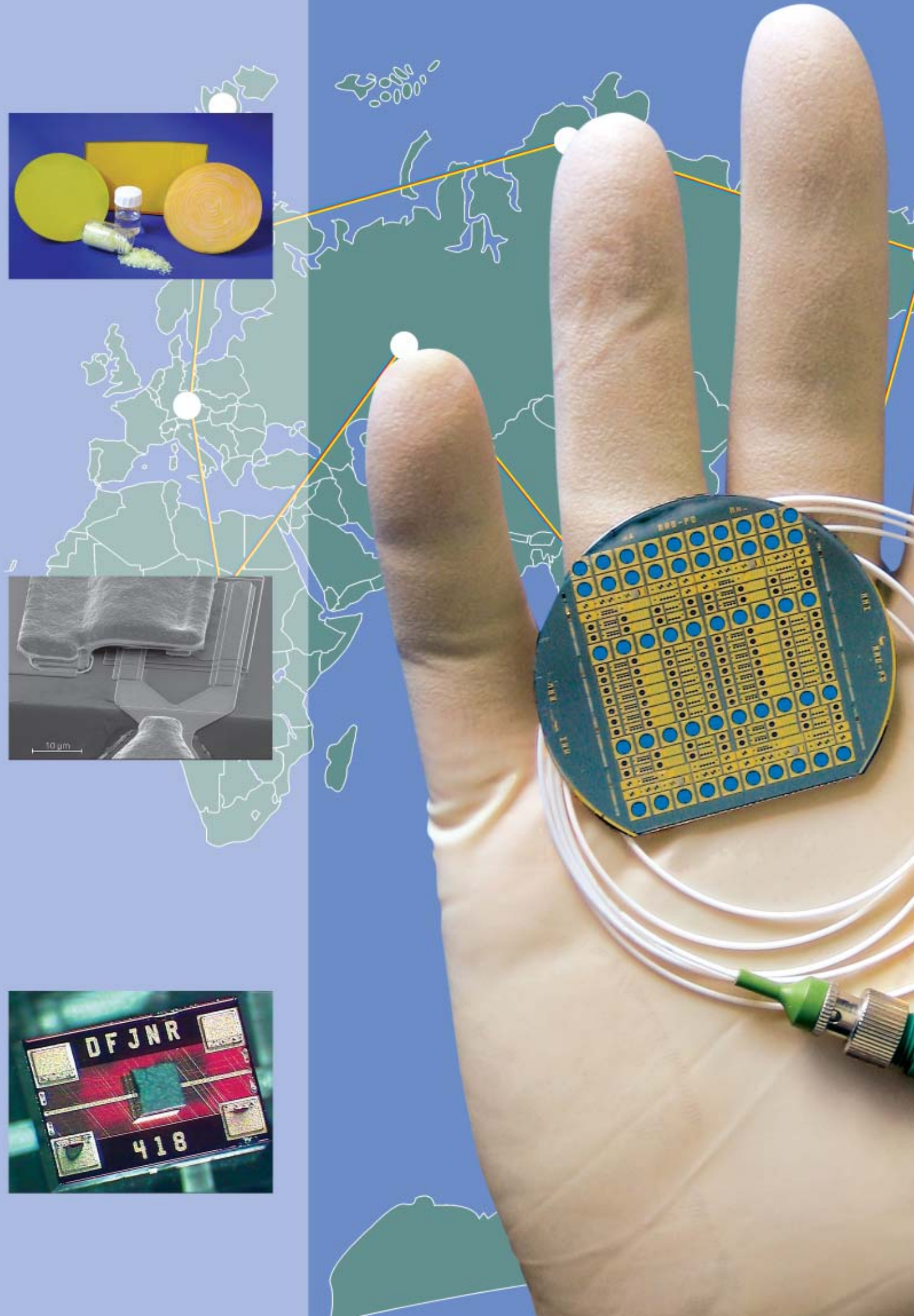
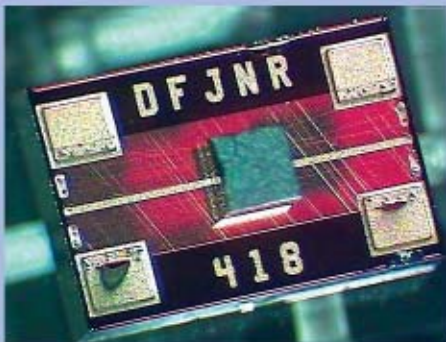
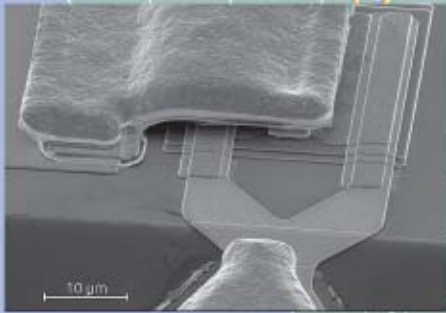
For the 4-channel OADM, the measured insertion loss was 3.8 dB and the crosstalk $< -25 \text{ dB}$, as shown in Fig. 4. The chip size for this device was only $18 \times 2.5 \text{ mm}^2$. For the 8-channel OADM, the insertion loss and crosstalk were 4.5 dB and $< -25 \text{ dB}$, respectively, and the chip dimensions $22 \times 4 \text{ mm}^2$. Fig. 5 displaying a 4-channel AWG and OADM highlights the compactness of those chips.



Fig. 5: Small size all-polymer components: 4-channel AWG (top), 4-channel OADM (bottom)

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Technologies for Photonic Components

'All in one hand, from wafer to module' – this is the guideline of our materials, processing, and assembly technologies. A solid base of profound know-how, long time experience, and modern technical equipment places us in a position to successfully develop and fabricate advanced photonic and optoelectronic components.

The chain of processes starts with epitaxial layer growth. For this purpose we run a number of MOVPE systems enabling the growth of the whole spectrum of InGaAsP and InGaAlAs layers based on InP. We achieve a high purity of the material and thus a very low background doping level. The conduction type and, in a wide range, the carrier concentration are adjusted by controlled addition of appropriate dopants. The techniques for the fabrication of quantum well structures, which are an indispensable part of many optoelectronic devices, have been established. Moreover, we have developed methods for the regrowth on topological surfaces and for selective epitaxy with high morphological quality. Besides MOVPE we use MBE for exploratory work, presently focused on the growth of Sb-containing compounds and of quantum dot structures. Our materials technology is backed by characterization techniques like X-ray diffractometry, photoluminescence, Hall measurements, electrochemical C-V profiling of carrier concentration, and SIMS.

Subsequently the photonic devices are formed from the 'raw material' of the epitaxial layers. For the definition of the micro patterns we use optical contact printing and in particular electron beam lithography, if structures with nanometer dimensions like Bragg gratings or transistor gates are required. Photomasks, which we design using professional CAD tools, are also fabricated by our state-of-the-art electron beam lithography system. For the transfer of patterns into the semiconductor surface as well as into dielectric and metal layers we improved in particular techniques of ion beam and plasma etching to a high level of performance. With these dry etching techniques, supported by in situ process monitoring, a precision in the nanometer range is achieved. They for instance make it possible to generate ramp profiles for optical mode transformation, which considerably facilitates fibre-chip coupling. Additional techniques complementing the front-end processing include diffusion doping, deposition of insulating and metal layers, and electroplating of interconnections. The in-line process control is, amongst others, accomplished by scanning electron microscopy, atomic force microscopy and ellipsometry.





PHOTONIC DEVICE TECHNOLOGIES

In the back-end area an automatic wafer tester, lapping and polishing equipment for wafer thinning as well as semi-automatic tools for separating the chips by scribing or sawing are available. Finally, the chip facets can be coated with anti-reflection or high-reflection layers by means of sputter deposition.

In addition to the semiconductor technology we operate a laboratory for the fabrication of polymer-based photonic devices like switching matrices and filters and for the development of a platform for low-cost hybrid integration of active and passive components. Besides silicon and glass we utilize polymer substrates on which devices with very low temperature sensitivity are fabricated. By closely cooperating with the Fraunhofer IZM where novel, 'tailored' optical polymers are synthesized, we take advantage of the progress made in materials development.

After their completion the chips have to be mounted in modules to make them ready for use in systems. Our assembly technology aims at a high degree of flexibility as devices of very different shape and functionality have to be connected optically and electrically to their environment. A focus of our activities is fibre-chip coupling, where we have established robust low-loss solutions for one- and two-sided connections of both single fibres and fibre arrays. Furthermore we design and fabricate electrical interconnections suitable for the transmission of very high frequency signals (up to about 120 GHz).

At present the 'evolution' of our device technology is geared to the fact that system suppliers are signalling an increasing demand for robust, reliable optoelectronic components of medium performance class, featuring long lifetime and low production and operation cost. On the other hand the interest in high-end components and therefore in forefront research activities has somewhat decreased. Consequently we primarily work on the maturing of our technological processes with respect to reproducibility, wafer uniformity, yield and ageing stability. As an example in the past year we conducted a series of experiments to reduce the defect density in epitaxially grown layers, which resulted in a considerable improvement of the chip yield. Furthermore we look for possibilities to simplify individual processing steps or whole process sequences in order to make them more cost-efficient. At the same time a variety of alternative techniques and methods is available for the support of new R&D topics.

Our material, wafer and chip technologies are implemented in such a way that they form a complete processing line, which is subject to a quality management system. On this processing line we develop application-specific devices for industrial partners and also fabricate the devices as prototype series of small volume. By doing so HHI has become an important partner for small- and medium-sized manufacturers of photonic and optoelectronic components on a national and an international scale as well. Moreover we offer individual services according to customer specifications such as wafer epitaxy, photomask making, development and manufacturing of micro-optical devices, and module assembly.



Technologien für photonische Komponenten

„Alles in einer Hand, vom Wafer bis zum Modul“ - unter dieser Devise stehen unsere Material-, Prozess- und Aufbautechnologien. Ein solides Fundament aus profundem Know-How, langjährigen Erfahrungen und moderner technischer Ausrüstung versetzt uns in die Lage, erfolgreich innovative photonische und optoelektronische Komponenten zu entwickeln und herzustellen.

Am Anfang der Prozesskette steht die Materialherstellung durch Epitaxie. Hier verfügen wir über mehrere MOVPE-Anlagen, mit denen Schichten aus dem gesamten Spektrum von InGaAsP- und InGaAlAs-Materialien, basierend auf InP, gewachsen werden. Wir erreichen eine hohe Reinheit der Schichten und damit niedrigste Hintergrunddotierungen, durch kontrollierte Zugabe von Dotierstoffen werden der Ladungsträgertyp und in weiten Bereichen die Ladungsträgerkonzentration gezielt eingestellt. Die Techniken zur Erzeugung von Quantum Well Strukturen, ein unabdingbarer Bestandteil vieler optoelektronischer Bauelemente, sind etabliert. Darüber hinaus wurden Verfahren entwickelt zum Überwachsen strukturierter Oberflächen und zur selektiven Epitaxie mit hoher morphologischer Qualität. Neben der MOVPE führen wir explorative Arbeiten mittels MBE durch, derzeit fokussiert auf die Erzeugung von Sb-haltigen Materialien und von Quantenpunktstrukturen. Die Materialherstellung wird unterstützt durch eine Reihe von Charakterisierungsverfahren wie Röntgen Diffraktometrie, Photolumineszenz, Hall-Messung, elektrochemische C-V-Dotierungsprofilmessung und SIMS.

Aus dem „Rohmaterial“ der Epitaxie-Schichten werden die photonischen Bauelemente geformt. Zur Definition der Mikrostrukturen dient optische Kontaktlithographie sowie Elektronenstrahl-Lithographie, wenn es, wie bei Bragg-Gittern und Transistor-Gates, um Dimensionen im Nanometerbereich geht. Mit der Elektronenstrahl-Lithographieanlage, die sich auf dem neuesten Stand der Technik befindet, stellen wir außerdem Photomasken her, deren Layout wir mit unserem professionellen CAD-System erstellen. Für die Übertragung der Strukturen in die Halbleiteroberfläche sowie in dielektrische und metallische Funktionsschichten haben wir insbesondere Ionenstrahl- und Plasma-Ätzverfahren zur hohen Leistungsfähigkeit gebracht. Diese Trockenätzverfahren lassen sich mit Hilfe von In-Situ-Prozesskontrolle mit Nanometer-Genauigkeit anwenden und ermöglichen z.B. die Erzeugung von Rampenprofilen für die optische Modentransformation zum Zweck einer verbesserten Faser-Chip-Kopplung. Der Frontend-Bereich wird vervollständigt durch lokale Dotierungsdiffusion, Deposition von Isolator- und Metallschichten und galvanische Leiterbahnverstärkung. Zur In-Line Prozesskontrolle sind u.a. Rasterelektronenmikroskopie, Atomic Force Mikroskopie und Ellipsometrie vorhan-

den. Im Backend-Bereich stehen uns ein automatischer Wafer-Prober, Läpp- und Poliereinrichtungen zum Abdünnen der Halbleiterscheiben sowie Halbautomaten zur Chip-Ver-einzelung mittels Spalten und Sägen zur Verfügung. Abschließend werden in einem Sputter-Depositionsprozess die Chip-Facetten ver- und entspiegelt.

In Ergänzung zur Halbleitertechnologie betreiben wir ein Labor zur Herstellung photonischer Polymer-Bauelemente wie Schaltmatrizen und Filter und für die Entwicklung einer Plattform für eine kostengünstige hybride Integration aktiver und passiver Komponenten. Neben Silizium und Glas verwenden wir Polymer-Substrate, auf denen Bauelemente mit sehr geringer Temperaturempfindlichkeit realisiert werden. Durch eine enge Kooperation mit dem Fraunhofer IZM, an dem neuartige, „zugeschnittene“ optische Polymere synthetisiert werden, profitieren wir unmittelbar von den Fortschritten an der Materialbasis.

Nach ihrer Fertigstellung müssen die Chips in Modulen aufgebaut werden, um sie in Systemen einsetzen zu können. Unsere Aufbau- und Verbindungstechnik ist in erster Linie auf hohe Flexibilität ausgerichtet, da Bauelemente von sehr unterschiedlicher Form und Funktionsweise optisch und elektrisch mit der Umwelt zu verbinden sind. Ein Schwerpunkt der Aktivitäten ist naturgemäß die Faser-Chip-Kopplung; hier haben wir verlustarme, stabile Lösungen für ein- und beidseitige Anbindungen, für den Anschluss von Einzelfasern und Faser-Arrays entwickelt. Darüber hinaus besitzen wir ein umfassendes Know-How auf dem Gebiet elektrischer Hochfrequenz-Verbindungen (bis ca. 120 GHz).

Die „Evolution“ unserer Bauelemententechnologie orientiert sich derzeit an der Tatsache, dass seitens der Systemausrüster ein wachsender Bedarf an robusten, zuverlässigen optoelektronischen Komponenten des mittleren Leistungssegments mit hoher Lebensdauer und möglichst niedrigen Herstellungs- und Betriebskosten besteht. Demgegenüber ist das Interesse an High-End Komponenten und damit an einer Vorlaufforschung etwas zurückgetreten. Konsequenterweise arbeiten wir kontinuierlich an der Ausreifung unserer technologischen Prozesse unter den Kriterien der Reproduzierbarkeit, Wafer-Uniformität, Chip-Ausbeute und Alterungsstabilität. Beispielsweise wurde im vergangenen Jahr ein Versuchsprogramm zur Reduzierung der Defektdichte in Epitaxie-Schichten durchgeführt, was zu einer deutlichen Verbesserung der Ausbeute führte. Weiterhin untersuchen wir die Möglichkeiten, einzelne Verfahrensschritte oder ganze Prozessfolgen zu vereinfachen und somit kostengünstiger zu gestalten. Zugleich steht uns für neue FuE-Themen eine Anzahl von alternativen Verfahren und Methoden zur Verfügung.



PHOTONIC DEVICE TECHNOLOGIES

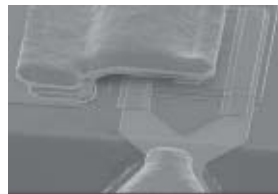
Unsere Material-, Wafer- und Chip-Technologien sind als vollständige Prozesslinie implementiert und unterliegen einem Qualitätsmanagementsystem. Die auf dieser Linie entwickelten Komponenten stellen wir für unsere Industriepartner auch in Prototyp-Kleinserien her. Das HHI ist in dieser Rolle ein wichtiger Partner mittelständischer Hersteller von photonischen und optoelektronischen Komponenten im nationalen und internationalen Bereich geworden. Darüber hinaus bieten wir einzelne technologische Dienstleistungen nach Kundenspezifikationen an wie Wafer-Epitaxie, Photo-maskenherstellung, Entwicklung und Herstellung mikro-optischer Elemente und von Modulaufbauten.



– All in one hand, from wafer to module –
We run a complete line of materials, processing, and assembly technologies to develop photonic components for optical communication systems.



Polymer substrates and waveguide materials – The basis of low-cost photonic devices.



Micro bridge as part of a high-speed photodiode built by means of sophisticated lithographic processing and electroplating.



InP-Based photonic device flip-chip bonded to 100 GHz microstrip line on multilayer thin film carrier (developed in cooperation with Fraunhofer IZM).



Photonic Device Technologies

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ULTRA-SHORT T-GATES – AN EXAMPLE FOR HIGH RESOLUTION ELECTRON BEAM LITHOGRAPHY

The fabrication of ultra-short T-gates for High Electron Mobility Transistors (HEMTs) is a strong challenge for the fineness and precision of the technology employed for pattern definition. To meet these requirements we use a state-of-the-art electron beam lithography system that unites the capabilities of flexible and highly accurate generation of structures down to the nanometer range and the fast and reproducible production of photomasks and reticles.

Die Herstellung von extrem kurzen T-Gates für High Electron Mobility Transistoren (HEMTs) stellt eine große Herausforderung dar an den Feinheitsgrad und die Präzision der zur Strukturdefinition eingesetzten Technologie. Um diesen Anforderungen gerecht zu werden, benutzen wir ein auf dem neuesten Stand der Technik befindliches Elektronenstrahl-Lithographiesystem, das die Möglichkeiten der flexiblen und hochpräzisen Generierung von Strukturen bis in den Nanometerbereich und die schnelle und reproduzierbare Fertigung von Photomasken und Reticles vereinigt.

At the FHI HHI electron beam lithography (EBL) is the key technology for the generation of high resolution structures written directly on substrates and for the fabrication of photomasks. Our Leica EBPG5000plus system is a modern Gaussian beam vector scan system. It is equipped with a thermal field emitter and can be operated at three different accelerating voltages of up to 100 kV. Featuring a minimum address increment of 1.25 nm and a maximum deflection frequency of 50 MHz the system has proven that structures down to a size of 10 nm can be produced at a reasonable speed.

The high precision and extreme overlay accuracy of the system is used for generating the critical T-gate level of HEMTs. We apply a two-step EBL process with two resist layers. First the head section of the gate is opened in the top resist (Fig. 1a), a second step patterns the 'foot' in the bottom resist (Fig. 1b) thus defining the gate length. The process follows a scheme already described in the literature¹.

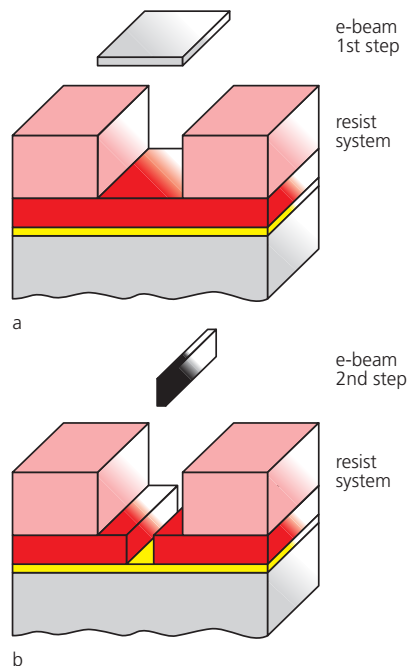


Fig. 1: Schematic drawing of the two step EBL process for T-shaped gates

We take advantage of the strong differences in the clearing doses of the employed resists (ZEP and UV88) (cf. Fig. 2) and the fact that the developer used for the top resist does not affect the bottom resist layer and vice versa. The removal of residuals left from the top layer is facilitated by an additional lift-off resist.

The benefits of the two-step process are that head and foot of the gates are defined independently of each other and that during the EBL step forming the gate foot only a very thin resist layer has to be exposed. That means that beam spreading effects due to forward and backward scattering are reduced. Fig. 3 shows an AFM image of the resist profile.

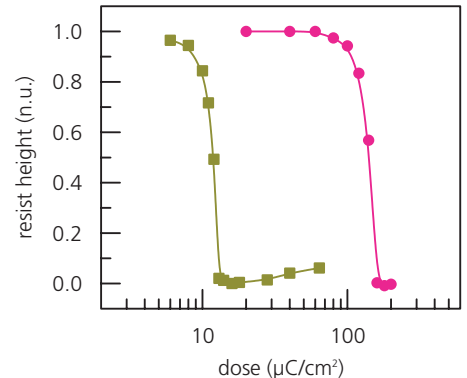


Fig. 2: Gradation curves of ZEP and UV88 resist

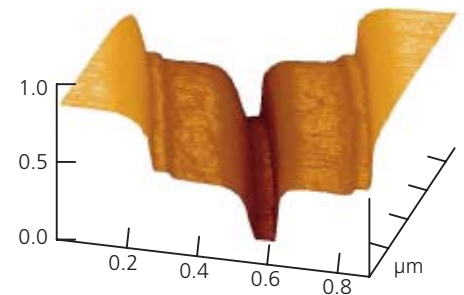


Fig. 3: AFM image of a T-shaped resist profile

We found that gate lengths of down to 50 nm can be achieved (Fig. 4). In the future the drawback of a rather time consuming EBL procedure may be alleviated by introducing a mix-and-match technology. There the head is opened by optical lithography and the gate length defined by high resolution EBL.

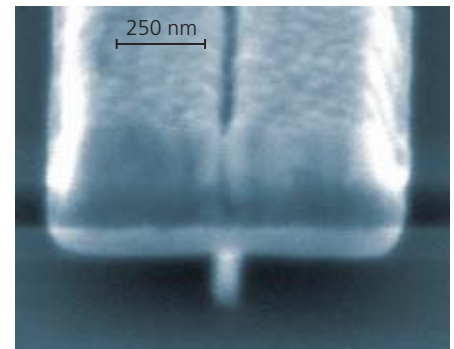


Fig. 4: SEM image of a T-shaped gate

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¹ Y. Chen et al., Microelectronic Engineering 73 74, 2004, pp 662 665



PLANAR SELECTIVE MOVPE GROWTH

A chlorine-assisted MOVPE selective regrowth process has been developed that provides excellent surface planarity even with very high (> 5 μm) ridge structures.

Es wurde ein Chlor-unterstützter MOVPE-Epitaxieprozess entwickelt, der das selektive Anwachsen von hohen (>5 μm) Mesastrukturen mit hervorragender Planarität erlaubt.

Because of their superior performance potential buried heterostructure designs are widely applied to InP based photonic components – namely lasers, optical amplifiers, electrooptical modulators. Such structures consist of narrow mesa stripes forming the active part of the device. For electrical and optical confinement reasons these mesa structures need to be laterally regrown with pn-doped or semiinsulating InP material. For such a selective regrowth step, metalorganic vapour epitaxy (MOVPE) is the epitaxial technique of choice to avoid any deposition on top of the masked mesa area. Under usual conditions, however, excessive growth takes place at the mesa edges yielding all but planar surfaces (Fig. 1) required for successful and reliable device processing. The thicker the regrown layer, the more detrimental this effect.

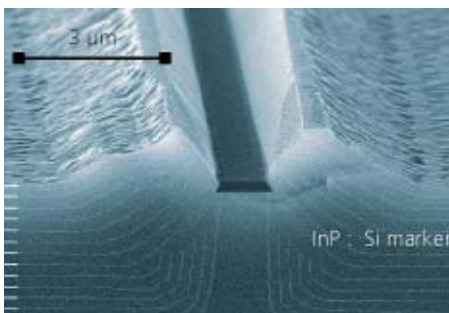


Fig. 1: Regrowth of an etched ridge structure using "normal" MOVPE growth conditions

Addition of halides to the MOVPE gases is known to be capable of substantially suppressing the excess edge growth. We have investigated chlorine using the organic precursor tertiarybutylchloride (TBCl) that has been successfully introduced for in-situ etching of InGaAsP material in an MOVPE reactor previously. A particular aim of this study was to achieve planar regrowth even with very high ridge structures (> 5 μm) as needed e.g. for very low-capacitance electro-optic modulator devices.

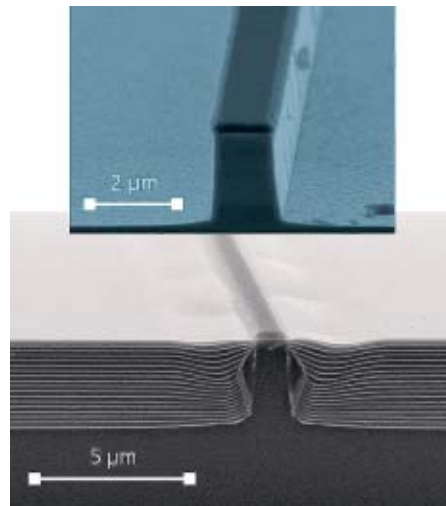


Fig. 2: Planar regrowth achieved by using TBCl in the MOVPE process; InP with doped marker layers; reactive ion etched ridge shown on top

Fig. 2 highlights the effectiveness of the Cl-assisted growth process. In this example, a 3 μm high and about 1.5 μm wide mesa stripe, in this case formed by reactive ion etching, was regrown to result into a perfectly planar surface. The growth evolution has been visualized by doped marker layers. Such a planarization effect was obtained independent of the shape of the etched ridge. The achievable surface morphology essentially proved to be affected by the growth temperature and the TMIn/TBCl ratio used. These MOVPE parameters also have a strong impact on the growth rate itself, as shown in Fig. 3.

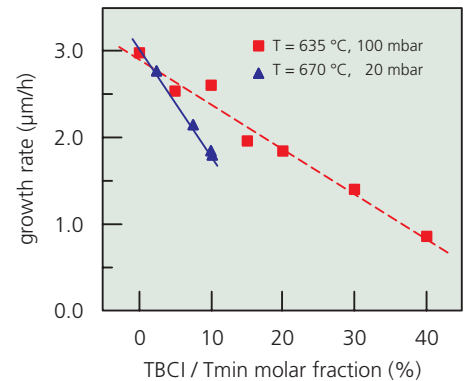


Fig. 3: Effect of TBCl on growth rate of InP layers

Fig. 4 shows I/V characteristics of a reversed biased modulator device incorporating a 5 μm high and 100 μm long active mesa stripe that was laterally regrown with semi-insulating Fe-doped InP. The excellent quality of the regrown interfaces that is achievable with an optimized procedure is evidenced by the low reverse current of around 2×10^{-7} A at bias voltages of as high as -10 V.

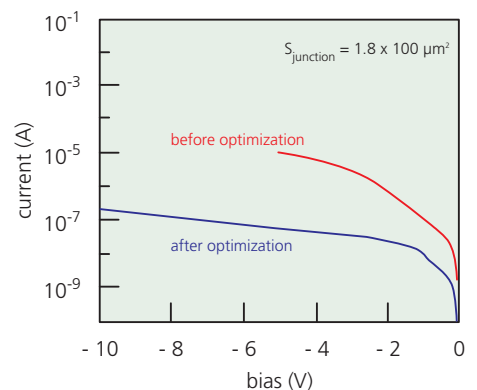


Fig. 4: Reverse current of a modulator structure regrown with a 5 μm thick Fe-doped InP layer

This work was conducted in the frame of the Alcatel Research Partnership Programme.

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1 A. Paraskevopoulos, D. Franke, P. Harde, S. Gouraud (7), M. Le Pallec (7), F. Alexandre (7) "Planarised selective regrowth of semi-insulating InP by LP-MOVPE using Tertiarybutylchloride for high-speed modulator devices", Proc. 16th Int. Conf. on Indium Phosphide and Related Materials (IPRM'04), Kagoshima (JP), paper TuB-3-4



DRY ETCHING – NANO-PRECISE PATTERNING

The development and fabrication of advanced photonic devices based on InP requires flexible, with nanometer precision acting dry etching techniques for pattern transfer into the semiconductor material. To this end reactive ion etching (RIE) in a plasma as well as physical and chemically assisted ion beam etching (IBE/CAIBE) are employed at the FHI HHI. With the aid of *in situ* process control methods an accuracy of 10 nm in etch depth is obtained.

Die Entwicklung und Herstellung leistungsfähiger photonischer InP-Bauelemente erfordert flexible, im Nanometerbereich präzise arbeitende Trockenätzverfahren zur Strukturübertragung in das Halbleitermaterial. Am FHI HHI werden hierfür sowohl reaktive Ionenätzung im Plasma als auch physikalische und chemisch unterstützte Ionenstrahlätzung eingesetzt. Mit Hilfe von *in situ* Prozesskontrollen können Ätztiefen mit einer Genauigkeit von 10 nm eingestellt werden.

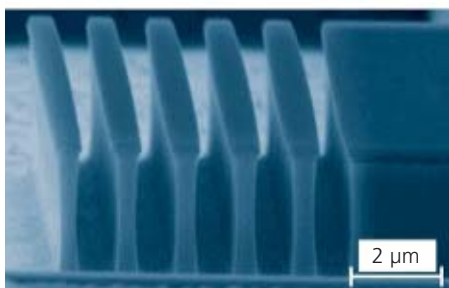
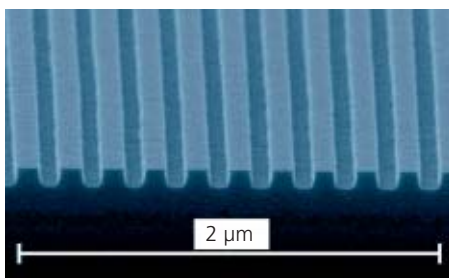


Fig. 1a: DFB laser gratings patterned by RIE, Fig. 1b: External Bragg reflector of an RW laser etched by CAIBE

The gratings of DFB lasers are etched to a depth of typically 60 nm by using RIE, resulting in the desired rectangular profile (Fig. 1a). Here a process with an etch rate as low as 10 nm/min is employed. On the other hand for the formation of external Bragg reflectors with a depth of larger than 4 µm (Fig. 1b) a CAIBE process with a high etch rate of about 500 nm/min is used.

Planar Photonic Crystal structures are a very promising approach for miniaturizing photonic devices. The key to their fabrication is the generation of very narrow and deep voids. For typical devices with a hole diameter of 240 nm aspect ratios of more than 10 were achieved (Fig. 2).

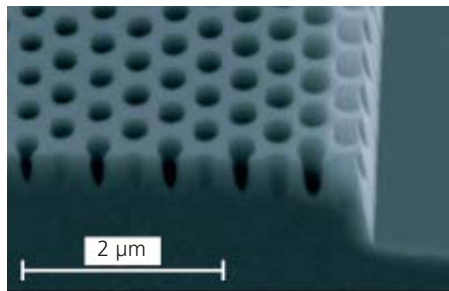


Fig. 2: Triagonal Photonic Crystal structure etched in InP

Ion beam etching processes are capable of forming sloped sidewalls in semiconductor materials (see Fig. 3) with tilt angles that are adjustable in a fairly wide range. This opens the way to novel device functionalities like vertical emission of laser light.



Fig. 3: Sloped sidewalls formed in InP by physical ion beam etching

Curved waveguides with small radii require smooth and vertical sidewalls for low-loss beam propagation.

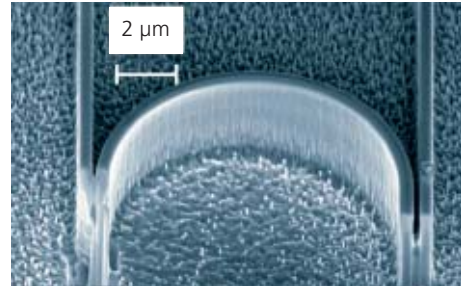


Fig. 4: Ring resonator with waveguide couplers etched by CAIBE in InGaAsP/InP (REM picture by courtesy of IHQ, University of Karlsruhe)

A CAIBE process is applied to form ring structures of 10 µm diameter with closely coupled waveguides (Fig. 4). The trench between ring and waveguide is less than 200 nm wide and about 1 µm deep. The ridges with a height of 3 µm exhibit smooth and nearly vertical sidewalls.

To achieve nanometer scale precision in etch depth endpoint detection by mass spectrometry and ellipsometry is used. As an example Fig. 5 shows the mass spectrometer signal taken during RIE of an InGaAsP MQW layer stack. The phosphorus content of the etch products and thus of the layer being actually removed is monitored. Layers with a thickness of only 10 nm are clearly resolved.

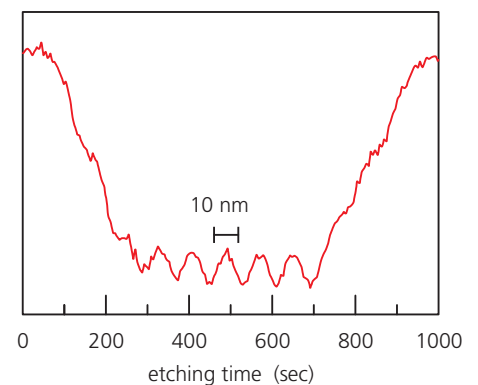


Fig. 5: Mass spectrometer signal of phosphorus-containing etch products recorded during RIE through an MQW layer stack

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FLIP-CHIP ADAPTED OEICs FOR ECONOMIC APPLICATION SPECIFIED OPTICAL BOARD SET-UPS

An essential cost reduction in the set-up of optical modules and optical boards demands the application of self-aligning flip-chip mounting of optoelectronic ICs (OEICs) on the optical platform. The basic tools for this technique have been developed and demonstrated in CWDM lasers.

Eine entscheidende Kostenreduktion in der Fertigung von optischen Modulen und von optischen Boards setzt den Einsatz der selbstjustierenden Flip-Chip-Montage der optoelektronischen ICs (OEICs) auf der optischen Leiterplatte voraus. Die wesentlichen „Werkzeuge“ für diese Technik wurden entwickelt und an ersten CWDM-Lasern demonstriert.

Optical modules and optical boards for Giga-scale data communication demand single mode operation of the devices. The economic set-up of such units require reliable optical interfacing of the planar hybridly mounted laser and detector OEICs with micrometer accuracy. Essential tools for OEIC-interfacing have been developed.

Multiple solder bumps fabricated by using sputter deposition of the accurate eutectic $\text{Au}_{80}\text{Sn}_{20}$ alloy are generating the forces for self-alignment during reflow between the OEIC and the board (cf. Fig. 1). The bumps can be located on the OEICs or on the board as well.

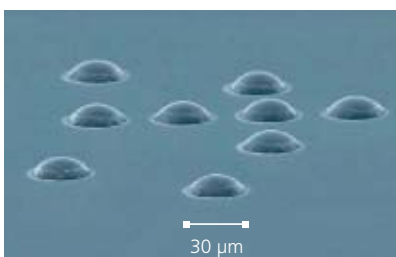


Fig. 1: Reflowed eutectic $\text{Au}_{80}\text{Sn}_{20}$ Bumps for self-alignment

The bump dimensions can be varied in a wide range. Especially, if low topographic differences are required on the optical board the bump height can be scaled down into the micrometer range.

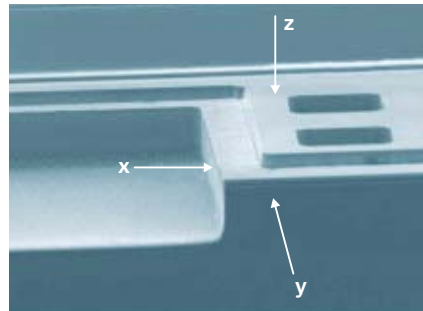


Fig. 2: Vertical and lateral alignment stops for passive alignment with submicron accuracy

Three-dimensional micrometer precision of the optical interface is given by pulling the OEIC against integrated alignment stops fabricated on the OEIC and board level to achieve submicron accuracy (cf. Fig. 2).

Optical spot size converters are integrated e.g. in the single mode laser device to guarantee -1 dB alignment tolerances of $\pm 1 \mu\text{m}$ butt coupled to single mode fibres or single mode optical board waveguides.

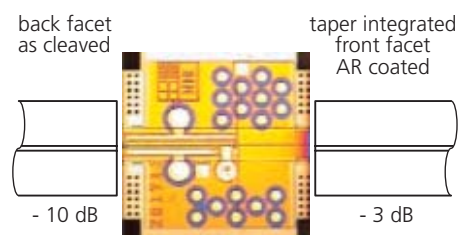


Fig. 3: SMF-butt coupling losses of a flip-chip adapted DFB-laser at the back facet (as cleaved) and the taper integrated front facet (AR coated)

As an example Fig. 3 shows the achieved butt coupling losses to a single mode fibre (SMF) at the untapered back facet and the tapered front facet of a laser. With integrated taper the interface losses resulted in -3 dB, which is an improvement of 7 dB compared to the untapered case.

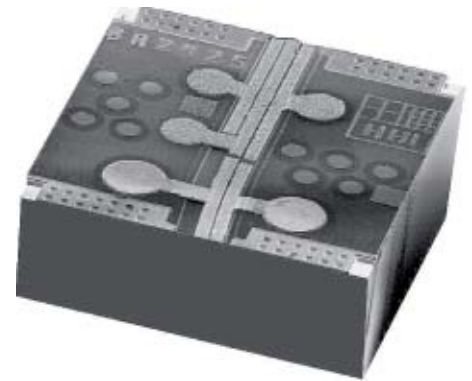


Fig. 4: Flip-chip adapted DFB-laser with electroplated contact pads and angled output facet at the end of the active taper (in this case the bumps have to be deposited on the complementary board level)

In addition, angled OEIC-waveguide facets are used to reduce parasitic back reflections from the planar-hybrid interfaces. Here, Fig. 4 shows a $1.55 \mu\text{m}$ buried heterostructure DFB laser diode consisting of a $300 \mu\text{m}$ $\lambda/4$ phase shifted DFB section and a separate $200 \mu\text{m}$ spot size converter region.

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FLEXIBLE PACKAGING SOLUTIONS

The Packaging Group of the FhI HHI offers flexible, tailored solutions for a various special needs in the field of chip assembly, to both internal and external customers. Examples are fibre coupling to superconducting optical detectors, mounting of optoelectronic devices for free-space applications, and a compact packaging of high-speed photodiodes.

Die Aufbau- und Verbindungsgruppe des FhI HHI bietet, sowohl für interne wie externe Kunden, flexible und maßgeschneiderte Lösungen an für verschiedenste spezielle Bedürfnisse auf dem Gebiet der Chip-Montage. Beispiele hierfür sind die Faserankopplung an supra-leitende Lichtdetektoren, Aufbau von optoelektronischen Bauelementen für die Freiraum-Übertragung und eine sehr kompakte Gehäuseform für schnelle Photodioden.

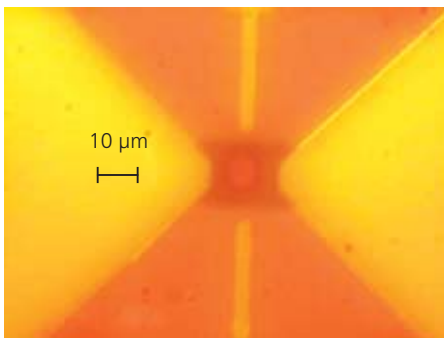


Fig. 1: The light of a HeNe laser helps to adjust a glass fibre to a superconducting single-photon detector

Single-photon detectors based on superconducting material had to be connected to butt-ended single-mode fibres. As these devices exhibit no output signal at room temperature the adjustment was accomplished by feeding the light of a HeNe laser into the fibre and observing the light spot on the detector surface under a microscope (cf. Fig. 1). An epoxy adhesive was used to fix the fibre.



Fig. 2: TO-5 housings with laser and photodiode, connected by their 'legs' to the rear side of SMA connectors

Semiconductor lasers and photodiodes for sensor applications and free-space transmission were mounted in TO-5 housings. In cases where only a low or moderate RF performance was required the TO-5 sockets were directly attached to the rear side of SMA connectors (see Fig. 2). Due to the rather long connecting wires the bandwidth of this assembly is limited to about 850 MHz.



Fig. 3: Photodiode on TO-5 socket; connected by a 50 Ω microstrip line to an SMA adaptor

For TO-5 mounted lasers and photodiodes to be operated at higher frequencies, i.e. up to 2 GHz, a special housing was developed. The TO-5 socket was fixed on an alumina substrate with a 50 Ω microstrip line on the rear side which provided the electrical connection to an SMA adaptor, see Fig. 3. This unit with a diameter of 25 mm fits into many different optical mounting systems.



Fig. 4: Photodiode directly mounted on a V-type connector (here shown in a measurement set-up with a fibre)

For fast photodetectors a very compact type of assembly was developed. A top-illuminated InGaAs pin diode (fabricated at FhI HHI) was directly mounted on a V-type connector, as depicted in Fig. 4. The arrangement inherently leads to short electrical interconnections, which reduces parasitics and thus enhances the high-frequency performance. Transmission experiments revealed that this kind of assembly, in conjunction with a small-sized photodiode (14 μm diameter), is suitable for the detection of data rates of up to 40 Gbit/s, as demonstrated in Fig. 5.

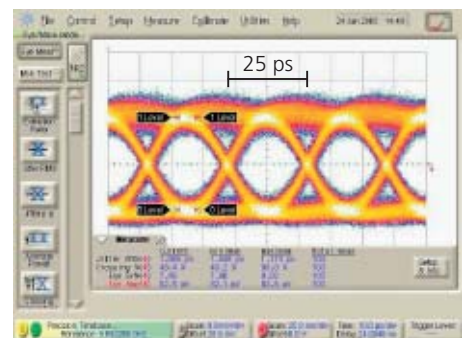


Fig. 5: Eye diagram of 40 Gbit/s data stream (NRZ) received by a photodiode mounted on a V-type connector.

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MICRO OPTICAL ELEMENTS

Optical components with feature sizes down to the micro- and nano-metre range are key components for systems and devices, where small dimensions, compactness and light weight are demanded.

Optische Komponenten mit Strukturgrößen bis hinab in den Nanometerbereich sind Schlüsselkomponenten für Geräte und Systeme, in denen kleine Abmessungen, Kompaktheit und geringes Gewicht erforderlich sind.

Refractive and diffractive micro- and nano-scale (MAN) optical components are playing an important role in a wide range of applications. They are successfully exploited in fields such as optical communications, metrology, optical sensor systems and medicine.

Based on novel micro- & nano-technologies (high resolution Ebeam writing combined with well adapted dry etching techniques) we have developed and fabricated a broad variety of microoptical components for research as well as commercial applications.

The MAN-elements with feature sizes down to 80–50 nm, were mainly realized in quartz glass (SiO₂) or silicon, for wavelengths ranging from the DUV

over the visible to the IR region; they may have binary, multi-level or continuous surface profiles. The palette of components includes binary and blazed gratings, refractive microlenses, Fresnel zone lenses, lens arrays, high frequency gratings, diffractive optical elements, photonic crystal- and waveguide components (Fig. 1).

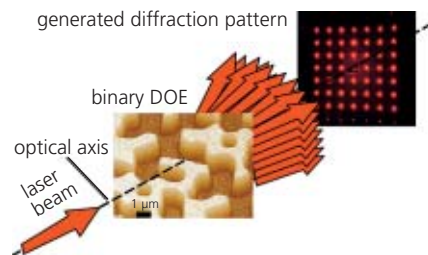


Fig. 2: Transformation of an incoming laser beam into an arbitrary, predefined – e.g. 7 by 7 dot-pattern by the use of a DOE

They fulfill optical functions/tasks like beam coupling, focussing, collimating, deflecting, beam steering, shaping, or beam splitting. They are used as filters (eg. AWGs) or for pattern generation.

Diffractive optical elements (DOE), -in general a complex pattern of micro- or nano-scale structures- which can modulate and transform light in a predetermined way, can be designed to handle a number of simultaneous tasks. With those, so called computer generated holograms (CGH) or CG-DOEs, optical functions can be realized, not achievable with conventional

optics. Examples for beam splitting CG-DOEs are shown in Fig. 2 to Fig. 4.



Fig. 3: A 7×7 beam splitter (see also Fig. 2) diffracts the different "colours" of white light (Halogen lamp) in various angles (negative dispersion typical for DOEs)

A CGH which generates a circle of dots (plus central dot) (Fig. 4) for example has been fabricated for application in a non-contact IR thermometer, in which it is employed to indicate the IR-measuring spot on the target at all distances. To keep the production costs as low as possible, the DOE served as master for replication in polymer material.

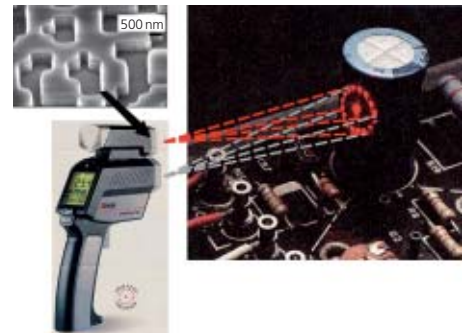


Fig. 4: Beam splitting DOE for indicating the (invisible) measuring spot of an IR-thermometer (courtesy of Raytek)

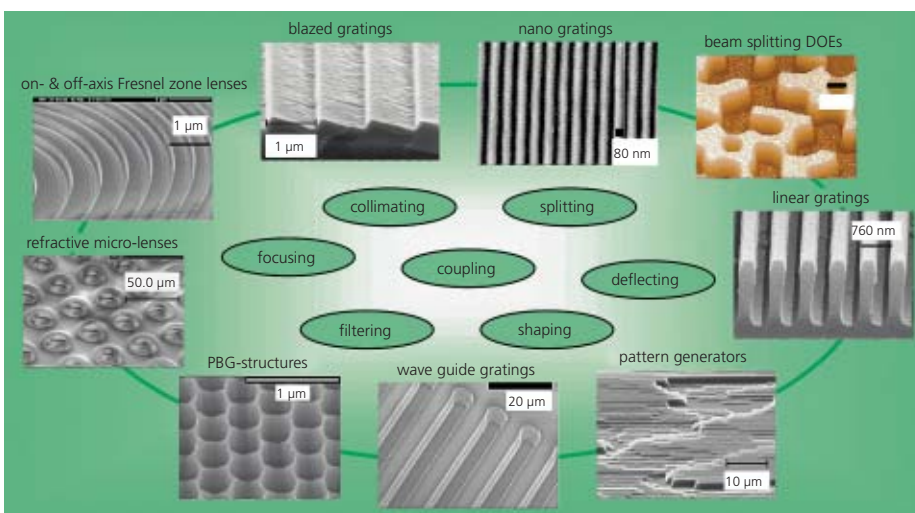


Fig. 1: Examples of micro- and nano-scale components realized in quartz glass and silicon

Our advanced fabrication capabilities, combined with our experience in micro- and nano-fabrication technologies, enable us to produce MAN-optical elements of high optical quality and performance. Replication technologies offer the possibility of low cost mass production of MAN elements, which is of great importance for the industry.

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Interactive Media – Human Factors

"Being digital" is significantly changing our role in the information age. We are rapidly moving from being 'classical' consumers of media content towards interacting users.

Interactivity becomes the key concept of future media.

Broadband networks and novel devices for end users provide access to a sheer endless source of multimedia content – at work, at home and on the move. Formally placing the letter "e" in front of the old terms, traditional services are being transformed into eGovernment, eCommerce, and eLearning offering a complete new level of qualities and possibilities. In addition, the rapidly growing sector of interactive software delivers new solutions for the individual user. Software packages for creating and managing databases containing text, digital music, photos and videos are now part of almost every new PC.

For the pacesetters of the digital future it is essential to recognise **new potentials** at an early stage and to utilise them in the best possible way. Providing tools and methods that empower users to smoothly interact with the emerging media technologies is a continuous challenge.

Compared with other innovations, interactive media take an exceptional position. We are confronted with extremely inhomogeneous groups of users – ranging from professional power users to novices; the devices and applications are extremely variable; the rate of innovation is high while standardisation is rather limited.

In close collaboration with partners from science and industry, we are creating solutions for interactive multimedia systems of the future. Our challenge is the design of next generation man-machine-interfaces, services and applications providing attractive and user-friendly access to multimedia information.

One of our core competences lies in the creation of novel **3D displays and multimodal sensing devices** allowing intuitive, smooth, and rich interaction between users and technology.

In this context we have implemented a set of at-a-distance, non-intrusive interfaces to sense people and to recognise non-verbal inputs through eye movements and hand gestures. Our remote stereo **Video Head Tracker** detects the 3D position of the eyes at a rate of 120 Hz. Interactive applications including 3D visualisations with motion parallax as well as optical systems can be adapted to the user's current vantage point without noticeable delay.





Our patented **Video Gaze Tracker** is particularly user friendly, since it works without individual calibration. Hence, in interactive applications it is possible to evaluate the user's current point of interest and to anticipate the user's wishes. Moreover, users may directly select interactive objects on the screen by simply looking at them.

With our multiple-baseline stereo **Hand Gesture Tracker** we achieve precise measurements in large interaction spaces by cascading sets of inexpensive chip cameras. In Mixed Reality applications users can touch and grab virtual objects floating in front of the 3D screen like they are used to do with real objects.

Our **sensing people interfaces** can be tailored according to all relevant parameters including range, precision, speed, operating conditions and costs. Beyond that, special procedures extract and describe personal features and data in digital video. Such sensing people functionalities are fundamental to a range of intelligent-camera applications used in surveillance, biometric-based personal identification and verification, as well as off-line description of video contents. These technologies are further developed and marketed by our new spin-off company, the VISaPIX GmbH, founded in 2004.

We develop **3D technologies** enabling users to watch stereoscopic video and 3D computer graphics without special stereo glasses. Our displays outperform competing technologies since they perfectly separate the stereo channels and provide extremely clear, high-resolution pictures (2×1600×1200 RGB pixels on 30 inch screen).

At the same time the patented optical system solves the accommodation conflict when users interact with virtual objects. This system enables perfect seamless mixture of virtuality and reality in **Mixed Reality** applications. Our special 3D flat-screen displays show interactive content in photo-realistic quality for desktop and kiosk applications (1600×1200 RGB pixels on 21.3 inch LCD screen).

In combination with the Video Hand Tracker, users can press virtual keys floating in front of the display ("touch-less touch screen"). Portable Mixed Reality displays with integrated video based tracking are under development.

eGovernment services have been developed in cooperation with the Senate of Berlin. Our mobile terminal takes government service to the citizens – when and where they are needed – in shopping centres, in hospitals, and in homes for the elderly. Sensitive personal data are transferred via secured wireless interfaces. A queue management system generates online available information about how many

people are waiting at a particular site, and it sends SMS messages to waiting citizens when they are next in the queue.

In order to handle the increasing amount of multimedia data we develop automatic tools for video **analysis and annotation**. Novel search, filter and visualization methods for multimedia data allow users to intuitively browse and search in large video archives. The multimedia descriptors used are conformable with the MPEG-7 standard. A fast algorithm detects shot boundaries in video footage, such as hard cuts, dissolves, fades and wipes. Hence, extended video material is automatically sub-divided into basic temporal units and each extracted shot is represented by a key frame in the video asset management system. In the international TRECVID 2004 contest our system has outperformed competitors in the hard cut detection category and was the second fastest in the entire contest.

With European partners we are developing a novel multi standard video capture and post production system. For image acquisition, a very high frame rate and resolution camera, exceeding current standards, is used. The high-volume data stream is analyzed on-the-fly, in order to derive standard video data and metadata describing the extra information available during the capturing process. This system shall meet the particular demands of cinematographers and TV producers as well.

Products in information technology should be adapted to the needs and abilities of their future users. Because successful marketing depends on user-friendly products, it is important to consider human factors in developing new products. Even at the earliest stages of conception and design, user-centred design helps create products that are user-friendly and marketable. Our **Human Factors Test Center** (HFTC) offers tests and consultation for all phases of the development of information technology services, systems, and devices. Our main goal is the fine-tuning of technology to the needs of the user, in order to provide easy to use and satisfactory products.

Our services include the analysis of user requirements, experts' assessment for the usability of products and prototypes, usability tests, design studies, and consultation in strategic decisions concerning future product lines.

In addition, the HFTC supports developers in designing websites which meet with the special requirements of handicapped users (Web Accessibility).



Interaktive Medien – Human Factors

Die Digitalisierung der Medien verändert mit Macht unsere Rolle als Nutzer: Wir werden von schlichten Konsumenten eines weitgehend vorgefertigten Medienangebots mehr und mehr zu aktiven Anwendern. Die **Interaktivität** entwickelt sich zum alles bestimmenden Merkmal künftiger Medien.

Breitbandige Netze und neuartige Endgeräte verschaffen uns Zugang zu den schier unerschöpflich sprudelnden multimedialen Informationsquellen des Internet – am Arbeitsplatz, am heimischen PC und unterwegs. Traditionelle Dienste bekommen durch das vorangestellte kleine „e“ (wie in eCommerce, eLearning, eGovernment) völlig neue Qualitäten und Möglichkeiten. Hinzu kommt die nicht minder rasant wachsende Vielfalt interaktiver Softwareanwendungen. Programme zur Erstellung eigener Datenbanken mit selbst gestalteten Texten, digitaler Musik, Urlaubsbildern und Videos gehören inzwischen zur Bonussoftware bei jedem PC-Kauf.

Für die Schrittmacher der digitalen Zukunft gilt es, **Potentiale** frühzeitig zu erkennen und in der bestmögliche Weise nutzbar zu machen. Als besondere Herausforderung stellen sich dabei die Bereiche heraus, die das reibungslose Zusammenspiel von Mensch und Technik unmittelbar betreffen.

Im Vergleich zu allen anderen technischen Neuerungen nehmen die interaktiven Medien eine Sonderstellung ein, hat man es doch hier mit einer ausgesprochen inhomogenen Nutzergruppe zu tun, die sowohl professionelle Poweruser als auch absolute Laien umfasst; die Geräte und Anwendungen sind äußerst vielfältig; die Innovationsrate ist sehr hoch – gleichzeitig gibt es noch recht wenige Standards, auf die man aufbauen kann.

In enger Zusammenarbeit mit Partnern aus der Industrie und Wissenschaft entwickeln wir Lösungen für die multimediale Interaktion und Kommunikation der Zukunft. Unser Ziel ist die Schaffung von Endgeräten, Systemen und Anwendungen, die einen attraktiven und nutzerfreundlichen Zugriff auf multimediale Daten und interaktive Dienste ermöglichen.

Eine unserer Kernkompetenzen liegt auf dem Gebiet neuartiger **3D-Displays und multimodaler Interaktionssysteme**, die ein intuitives, reibungsloses Zusammenspiel von Mensch und Technik ermöglichen.

In diesem Zusammenhang entwickeln wir eine umfassende Palette von Technologien zur berührungslosen Erfassung von nicht-verbalen Eingaben des Anwenders, z.B. durch Blickbewegungen und Handgesten. Unser **Video Head Tracker**

ortet die Augen des Menschen (3D-Koordinaten) mit einer Messrate von 120 Hz. Damit lassen sich sowohl interaktive Anwendungen als auch optische Systeme verzögerungsfrei und präzise an den aktuellen Blickwinkel des Betrachters anpassen.

Unser patentiertes Verfahren zur **Messung der Blickrichtung** erfordert keine individuelle Kalibrierung und ist daher besonders nutzerfreundlich. In interaktiven Anwendungen kann damit auf den aktuellen Interessenschwerpunkt des Betrachters geschlossen werden. Interaktive Objekte können durch einfaches Anblicken ausgewählt werden.

Mit unserem **Stereo Hand Tracker** erreichen wir durch Kaskadierung einfacher Chipkameras eine hohe Messgenauigkeit in einem großen Erfassungsbereich. In Mixed-Reality-Anwendungen können damit virtuelle Objekte, die dank stereoskopischer Verfahren scheinbar vor dem Display schweben, wie Realobjekte mit der bloßen Hand „berührt“ werden.

Unsere Tracking-Technologien können hinsichtlich aller relevanten Parameter wie Erfassungsbereich, Präzision, Geschwindigkeit, Einsatzbedingungen und Kosten maßgeschneidert werden. Darüber hinaus ermöglichen spezielle Verfahren eine automatisierte Beschreibung von Personendaten in digitalen Bild- und Audioquellen hinsichtlich des Aufenthaltsorts, der Aktivität und Identität und sonstiger personenbezogener Informationen. **Sensing-People**-Funktionalitäten mit intelligenten Kameras bilden so unter anderem die Grundlage künftiger sicherheitstechnischer Systeme. Diese Technologien werden von unserer neuen Ausgründung, der VISaPIX GmbH, weiter entwickelt und vermarktet.

Wir entwickeln 3D-Technologien, die das Betrachten von stereoskopischen Videobildern und 3D-Computergrafiken ohne spezielle Stereobrille ermöglichen. Unsere Displays zeichnen sich durch eine brillante und besonders augenverträgliche Stereowiedergabe aus. Beispielweise ermöglicht unser Verfahren eine perfekte Trennung der Stereokanäle bei extrem hoher Bildauflösung (2 × 1600 × 1200 RGB-Bildpunkte auf einem 30 Zoll Bildschirm).

Das patentierte optische System löst zugleich den Akkommodationskonflikt bei der Interaktion mit virtuellen Objekten und bietet so eine perfekte, nahtlose Mischung von Virtualität und Realität in **Mixed-Reality-Anwendungen**. Spezielle 3D-Flachbildschirme können als Arbeitsplatzdisplay oder 3D-Kiosk gestaltet und interaktive Inhalte in fotorealistischer 3D-Qualität dargestellt werden (1600 × 1200 RGB-Bildpunkte auf einem 21,3 Zoll Bildschirm).



In Verbindung mit unserem Hand Tracker kann der Anwender virtuelle Auswahltafeln betätigen, die vor dem Display schweben („touch-less touch screen“). Portable Mixed-Reality-Displays mit integriertem videobasierten Tracking sind in der Entwicklung.

Unter Beteiligung der Berliner Senatsverwaltung für Inneres entwickeln wir ein Endgerät, mit dem mobile Bürgerberater **eGovernment-Dienstleistungen** in Einkaufszentren, in Krankenhäusern und Altenheimen erbringen können. Dabei werden auch sensible personenbezogene Daten über entsprechend gesicherte Luftschnittstellen transportiert, bargeldlose Zahlungen abgewickelt und Dokumente erstellt. Ein integriertes Warteschlangen-Managementsystem zeigt über das Internet die momentane Zahl der Kunden an den verschiedenen Standorten an. Eine SMS benachrichtigt die Wartenden, sobald sie an der Reihe sind.

Um die zunehmende mediale Datenflut zu bewältigen, entwickeln wir ein **Video-Retrieval-System** der nächsten Generation. Neuartige Such-, Filter- und Visualisierungsverfahren ermöglichen eine wesentlich einfachere Sichtung und Nutzung von großen Video-Datenbanken, ohne dass dabei auf manuell erstellte Annotationen zurückgegriffen werden muss. Die Beschreibungen der Bild- und Tondaten sind konform zum MPEG-7 Standard. Ein schneller Algorithmus erkennt Szenenübergänge wie z.B. harte Schnitte und verschiedene Arten von Überblendungen in Videofilmen. Auf diese Weise wird umfangreiches Videomaterial automatisch in Szenen zerlegt. Jede einzelne Szene wird durch ein repräsentatives Bild in der Datenbank des Video-Verwaltungssystems dargestellt. Im internationalen TRECVID 2004 Wettbewerb war unser System das Beste in der Kategorie der harten Schnitte und das Zweitschnellste im gesamten Wettbewerb.

Gemeinsam mit europäischen Partnern entwickeln wir ein neuartiges Multi-Standard-System für die Videoaufnahme und Nachbearbeitung. Bei der Aufnahme wird eine spezielle Kamera mit sehr hoher Auflösung und Bildrate verwendet. Der extreme Datenstrom wird in Echtzeit analysiert, um Stand-Videosequenzen und Metadaten daraus abzuleiten. Die in den Metadaten abgelegten Zusatzinformationen können bei der Nachbearbeitung genutzt werden. Das System soll sowohl den speziellen Anforderungen des (digitalen) Kinos als auch des konventionellen Fernsehens gerecht werden.

Produkte der Informationstechnik lassen sich umso besser vermarkten, je mehr sie auf die Bedürfnisse und Fähigkeiten ihrer zukünftigen Nutzer zugeschnitten sind und je mehr die menschlichen Aspekte (human factors) berücksichtigt werden. Bereits bei der Konzipierung neuer Produkte erhöht ein nutzerzentriertes Vorgehen die Chance der späteren

erfolgreichen Vermarktung. Unser **Human Factors Test Center** (HFTC) bietet als einen besonderen Service Tests und Beratung in allen Phasen der Entwicklung von Diensten, Systemen und Endgeräten der Informationstechnik.

Unser Leistungsangebot umfasst die Analyse von Nutzeranforderungen, die Evaluierung von Produkten und Prototypen durch Human Factors Experten, sowie Usability Tests mit Versuchspersonen, Designstudien und die Beratung bei strategischen Entscheidungen über Produktlinien.

Darüber hinaus unterstützt das HFTC Anbieter von Webangeboten bei der Erstellung barrierefreier Websites, die auch den erhöhten Anforderungen von Behinderten gerecht werden.



Interactive Media – Human Factors

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Mobile office for citizen services. All devices needed fit in a box. An integrated queue management system sends SMS messages to waiting citizens when they are next in the queue.



Interactive workplace allowing users to “drag” computer-generated or scanned 3D objects from the two flanking LCD displays and “drop” them into the central 3D display for direct manipulation. The video-based device for hand-gesture recognition is embedded in the desktop. The high-resolution 3D display ($2 \times 1600 \times 1200$ RGB pixel) creates a floating 3D image hovering over the desk.



The Free2C Kiosk combines a high-resolution autostereoscopic 3D display with a gesture recognition device integrated into the desktop. This elegant information terminal is perfectly suited for applications in high-tech showrooms, convention halls, airports, and shopping malls.



The FingerMouse uses the camera on the rear side of a mobile phone. The position of the finger tip is translated into a cursor position on the screen. For clicking the user may press a suitable button with the thumb.



Our awarded shot boundary detection algorithm analyses video footage and creates a sequence of key frames representing the video content. The user can browse the storyboard, watch single shots and navigate the video.



NOVEL INFORMATION TERMINALS COMBINING OUTSTANDING 3D IMAGE QUALITY WITH EASE OF USE

The new Free2C 3D display is the most advanced development in autostereoscopic (glasses-free) 3D technologies available on the market. The special head-tracking lenticular-screen display principle allows free head movements in three dimensions at unprecedented image quality. The display provides a native resolution of 1600 x 1200 RGB pixels; it is available in two versions, for desktop and information-kiosk applications, respectively.

Das neue Free2C 3D Display definiert einen Meilenstein in der Entwicklung autostereoskopischer Displays (3D ohne Stereobrille). Mit einer Auflösung von 1600 x 1200 RGB Bildpunkten zählt es nicht nur zu den höchstauflösenden 3D-Displays; mit Free2C gelang es darüber hinaus, dem Betrachter einen freien Bewegungsspielraum in drei Dimensionen zu ermöglichen. Die neue 3D-Technologie ist in zwei Displayvarianten, als Desktop-Monitor und als Infoterminal, verfügbar.

3D displays provide different perspective views to the left and right eye. Like in natural vision, the differences in perspective are immediately used by the visual system to create a vivid, compelling and efficient sensation of depth in natural and computer generated scenes.

Usually, special user-worn devices like stereo glasses or head-mounted miniature displays are required to optically channel the left and right-eye views to the appropriate eye. The Free2C display allows free 3D viewing with the naked eyes since the optical elements for selective addressing of the two eyes are integrated in the display device. Hence, this display is much more comfortable to the viewer than conventional stereo techniques.

The display employs a special micro-optical plate mounted in front of the imaging screen. Small lenticular lenses, each of them covering two pixel columns, guide the light beams to the left and right eye of the viewer, respectively. The left and right views are displayed on alternate pixel columns. Hence, the viewer's left eye will see pixels of the left view only and the right eye will see the right view.

A dual-axes voice-coil tracking system adjusts the lens plate in real-time without noticeable delay when the viewer moves. The lens plate is shifted at a precision of about 10 µm allowing lateral as well as frontal head movements while watching the stereo images. The integrated high-speed video tracker senses the viewer's eye positions at 120 Hz measurement rate.



Fig. 1: CATIA CAD software running on the Free2C display

Typical Applications

- Medical applications (endoscopy and minimally invasive surgery)
- Design and engineering (CAD, virtual prototyping)
- Architecture (simulation and visualization of planned buildings)
- Education and simulation (driving/flight simulator, training of complex medical operations)
- Exploration of hazardous or inaccessible environments (archeology, oceanography, contaminated environments)
- Entertainment (3DTV, PC games)
- Information kiosks in trade shows, museums, show rooms, etc.

Major Display Characteristics

- No special viewing aids required
- Free viewing position within a tracking range of 60 degrees
- Extremely low crosstalk (< 2 %)
- High spatial resolution (1200 x 1600 RGB pixel)
- Excellent brightness and color
- Compatible with 3D application software like CATIA



Fig. 2: The Free2C Kiosk combines innovative 3D display and gesture recognition technologies with elegant terminal design

Kiosk systems must stand out by offering simple intuitive handling and eye-catching design. The Free2C Kiosk shown in Figure 2 presents any kind of interactive content on a large 21.3" 3D display in photorealistic 3D quality.

A computer-vision system which recognizes hand gestures is integrated into the desktop. Displayed 3D objects floating in front of the screen can be rotated by simple gestures; virtual buttons can be pressed by pointing at them (virtual 3D touch screen). The Free2C Kiosk is an eye-catching attraction for any museum, convention hall, airport, trade show, shopping mall, and store.

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ADVANCED VIDEO TRACKERS FOR INTERACTIVE MEDIA

Interaction with digital media should be as easy, convenient and intuitive as possible. We have developed a family of non-intrusive tracking devices allowing users to interact in a very natural way. The devices sense and recognise hand gestures (pointing, pushing and grabbing), the user's head movements, and the point of gaze. Another technology recognises objects and estimates the relative viewing position and angle. These technologies can be combined to create multi-modal interfaces.

Die Interaktion mit digitalen Medien sollte einfach, angenehm und intuitiv sein. Wir haben eine Familie von berührungsfreien Trackinggeräten entwickelt, die sehr natürliche Formen der Interaktion ermöglichen. Die Geräte erfassen Handgesten (Zeigen, Drücken und Greifen), Kopfbewegungen und den Blickpunkt. Eine weitere Technologie erkennt Objekte und schätzt die relative Betrachtungsposition und den Blickwinkel. Diese Technologien lassen sich zu multimodalen Schnittstellen kombinieren.

A major objective in advanced interface design is to supplement or even to replace traditional input devices such as keyboards and mice by more natural interaction systems. This includes the use of speech input as well as machine-vision techniques capable of sensing people and interpreting their gestures.

For example, hand gestures can be useful for selecting interactive objects on a display by pointing to them (deictic indications) or touching them with a finger, for moving irrelevant objects aside, and for indicating the direction of simulated ego-motion in interactive scene walkthroughs (view-point and trajectory, viewing angle).

Head movements are a natural means to inspect an object from different perspectives or to find out the spatial relations of multiple objects in a three-dimensional scene. In normal communications, the gaze direction signals special interest in the object or person being looked at (the focus of attention).

Our non-intrusive and marker-less machine-vision devices sense, track and interpret such gestures. The software is designed for a variety of cameras ranging from low-cost to high-end, allowing users to find a best compromise between performance and price. The devices communicate via established protocols (e.g. Polhemus protocol on serial line) and via specially designed DCOM interfaces.

The **head tracking** module accepts simple USB or fire-wire cameras. For applications where tracking latencies and speed are an issue, a special 120 Hz high speed camera is available. The high-end stereo version allows precision measurements (in the millimetre range) in three-dimensions.

The **gaze tracking** module applies a special cornea reflex method. It senses the user's current gaze point (the intersection of the lines-of-sight of both eyes) at a rate of 50 Hz with a single stationary camera (Fig. 1). Due to the wide-angle optics, the user may move in a range of 30×30×30 cm.

Gaze tracking can be used to trigger context sensitive applications (e.g.

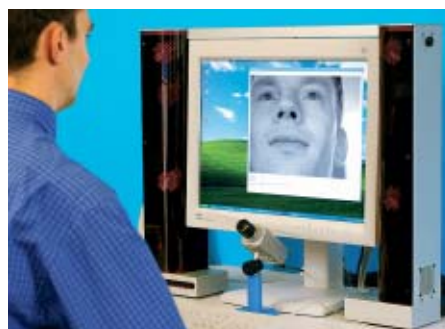


Fig. 1: Four switchable infrared spot-lights and a stationary high-resolution camera are used to measure the user's current point of fixation.

when looking repeatedly at certain screen elements) as well as in usability research, in order to study the visual reaction of test subjects. Knowing the user's gaze vector a speech recognition engine can infer the context and react more reliably.

Pointing with the fingertip is an easy and natural way to interact with objects shown on a (3D) display. Our **hand tracker** measures the 3D position of the user's fingertip at a rate of 50 Hz. Simple gestures intuitively used to start and stop an action, to move and to rotate an object (left and right, up and down) are recognized in real-time. Several trackers can be daisy-chained, in order to increase the tracking range.



Fig. 2: The object tracker camera on top of the monitor captures the real scene. The software is recognizing the position and orientation of a known object (in this example a loudspeaker) and correctly matching the edges and a virtual texture. All processing is done in real-time. The user can freely move the articulated monitor.

The video-based **object tracker** computes the position and orientation of known, geometrically defined objects. Markers on the object are not required. These data are used in mixed-reality applications to overlay 3D graphical objects and to annotate information about the scene on live video (Fig. 2). The object tracker can also be used as a flexible interacting device to manipulate virtual objects with real tools.

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THE OFFICE IN THE BOX – CITIZEN-FRIENDLY AND SECURE MOBILE GOVERNMENT SERVICES

In the future, it will be possible to meet mobile citizen consultants in shopping malls, on weekly markets, in hospitals or in residential homes for the elderly, in order to renew one's passport, to declare a new domicile, or to let modify one's wage tax card. For such kind of services we have developed various components, among other things, an "office of citizen services case" and an SMS queue management system.

In Zukunft wird es möglich sein, in Einkaufszentren, auf Wochenmärkten, in Krankenhäusern oder Seniorenheimen mobile Bürgerberater zu treffen, bei denen man seinen Personalausweis verlängern, seinen Wohnsitz ummelden oder Lohnsteuerkarten ändern lässt. Für solche Dienstleistungen wurden verschiedene Komponenten entwickelt, u.a. ein „Bürgeramts-Koffer“ und ein SMS Warteschlangen-Managementsystem.



Fig. 1: A mobile office of citizen services

Many communities are currently trying to improve the relationship between administrations and citizens. One step in that direction is to organize offices of citizen services – which are mainly located in town halls – as one-stop offices in which citizens can be advised and can use services offered by a wide range of public administrations.

As a second step, some administrations have started to offer access to some

citizen services over the Internet, e.g. for downloading forms or for filling in electronic forms.

However, these innovations do not adequately cater for citizens who are, for various reasons, not able or not willing to use those kinds of services. As an example, the use of the Internet requires suitable equipment and a certain experience in using software such as Web browsers etc. In addition, citizens often need qualified advice by an expert.

In view of this, we are researching novel possibilities based on the use of mobile/wireless network and terminal technologies. In particular, we have developed – together with a software company and two administrative districts of the city of Berlin – a wireless system offering the same services that are available in a stationary office. This system supports the entire work flow, from consultancy through application and payment to the final delivery of (hard) documents to the citizen (Fig. 1). The system allows to transfer sensitive personal data via a wireless interface (GPRS, WLAN, and UMTS). Hence, special emphasis has been put on a secure connection (VPN based on IPsec).

Mobile offices of citizen services will be present in residential homes for the elderly, in hospitals, in shopping malls, at weekly markets, in recreational centres, etc. Apart from being citizen-friendly, those mobile (or "nomadic") offices are more efficient, as they do not require such high rental fees and maintenance costs as stationary offices do. Moreover, they offer a new quality of public service by "taking the office/service to the citizen".

After establishing and testing a secure wireless connection, field/pilot trials took place at 11 test sites in Berlin. For these trials, we have developed an "office for citizen services case" which contains all components required (notebook computer, printer, network



Fig. 2: A "mobile office for citizen services case"

interface, etc.) in an ergonomically sound arrangement (Fig. 2).

During the one year pilot trials more than 3000 citizens used the mobile service. The collected data (questionnaires and interviews) show that citizens regard the service as being useful and highly citizen-friendly.

The system is now applicable as an all-purpose system for wireless citizen services. We expect this system to be particularly useful in sparsely populated regions and/or locations with no stationary telecommunications network (e.g. in developing countries).

Mobile citizen services are on the verge of becoming a regular service in Berlin. In 2005, an SMS queue management system will be introduced, informing about the time of waiting at a particular site. If requested, citizens will get an SMS text message when they are next in the queue.

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METADATA ASSISTED POST PRODUCTION THROUGH HIGH RESOLUTION AND HIGH FRAME RATE IMAGE ACQUISITION

The lack of a generic format for the digital acquisition of moving images that is suitable for many target applications could be overcome, if capturing took place with a high frame rate and high resolution. However, the resulting amount of data per unit time could not be handled by existing storage and transmission technology. The METACAMERA project attempts to solve this problem by processing this high-volume data stream in real time to derive from it a standard frame rate sequence together with metadata which describe the extra information that was available in the camera during the capture process. Those metadata can be used in postproduction to assist f.i. in the creation of time line effects.

Gegenwärtig fehlt ein allgemeingültiges Format zur digitalen Aufnahme von Bewegtbildern, welches sich für viele Zielanwendungen eignet. Es wäre möglich, diesen Mangel durch Aufnahmen mit hoher Bildrate und hoher Auflösung zu beseitigen. Allerdings könnte die Datenmenge, welche dabei pro Zeiteinheit entstünde, von existierender Speicher- und Übertragungstechnik nicht bewältigt werden. Das METACAMERA-Projekt versucht, das Problem zu lösen, indem es diesen umfangreichen Datenstrom in Echtzeit verarbeitet, um daraus neben einer Bildfolge in einer Standardfrequenz noch Metadaten abzuleiten. Diese Metadaten beschreiben die Zusatzinformationen, welche beim Aufnahmeprozess in der Kamera verfügbar waren. Sie können in der Postproduktion z.B. dafür genutzt werden, Änderungen im Zeitablauf des Films zu erzeugen.

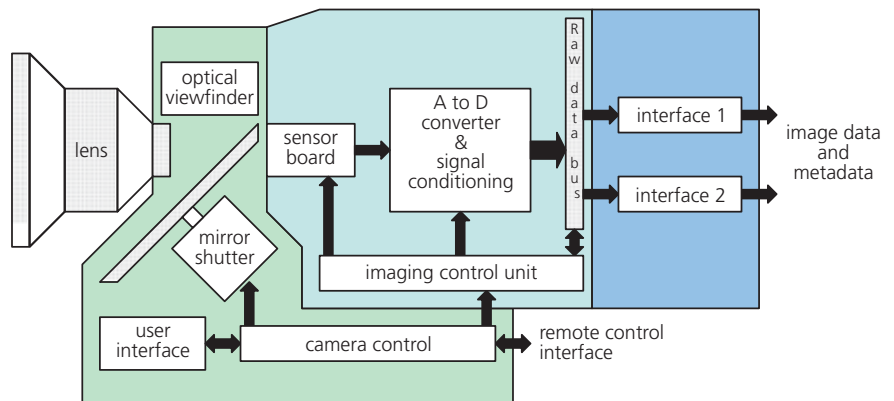


Fig.: Schematic drawing of the METACAMERA image acquisition device. Real time processing happens in the interface module shown in blue.

Even though format conversion has had a long history and is now fairly mature, certain compromises cannot be avoided as long as differences between the target systems in resolution, frame rate, colour gamut, interlacing, or aspect ratio prevail. Traditionally moving image acquisition devices have been tuned to the intended use of their output. Thus cinema cameras produce the best results when the acquired footage is presented in a cinema setting, whereas broadcast camera output is optimally viewed on a video monitor.

Digitization of the cameras has not changed this fact and, what is more, current digital cinema cameras yet even deprive cinematographers of the creative possibilities of film's high exposure latitude, of limiting the depth of focus, and of the slow motion effects that are possible by speeding up the film camera while shooting.

A European Commission sponsored international consortium is currently addressing these problems in the METACAMERA project. The project work is based on the assumption of a high resolution and high frame rate digital camera with a single CMOS sensor that is as large as a 35 mm film frame and carries a color filter array. The large sensor permits the use of film style lenses that can be narrowly focused on a desired object. From such a camera (cf. Fig.) two simultaneous data streams will be derived, one of which is in a viewable high quality

image format like HD 24p, while the other one preserves enough extra information as metadata to support the generation of time line effects (e.g. speed ramps) or standards conversion through the computation of intermediary frames. The metadata can also be used to enhance the color resolution for postproduction.

To achieve this the METACAMERA consortium is investigating a number of image processing issues like the generation of super resolution color components, temporal image interpolation, and near lossless compression.

The exact type of camera output data, the storage and transfer devices, and the data and control interfaces employed will depend on the user requirements on set, in post production and during later viewing.

Requirements capture is currently undertaken by the HHI with the help of an expert panel recruited from the moving image production industry. In later project phases tests will be conducted to validate that the user requirements concerning usability and perceived image quality are met by the METACAMERA system.

The project has been running since June 2004 and will be completed by the end of April 2007.

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FAST AUTOMATIC SHOT DETECTION FOR DIGITAL VIDEO ANALYSIS

Shots are basic temporal units of video. We have developed a fully automatic and fast shot detection system that can be used for video archiving and retrieval applications. The system can detect hard cuts as well as gradual transitions like dissolves, fades and wipes. In the international TRECVID 2004 shot detection contest it proved to be one of the fastest systems and showed excellent detection performance.

Die grundlegenden Einheiten eines Videos sind Shots. Wir haben ein voll automatisches schnelles Schnitt-Erkennungssystem entwickelt, das Shotgrenzen findet und für Anwendungen bei der Archivierung und Suche von Videos verwendet werden kann. Das System erkennt sowohl harte Schnitte als auch weiche Shotübergänge wie Überblendungen, Ein-/Ausblendungen und Wipes. Beim internationalen TRECVID 2004 Shot Detection Wettbewerb war es eines der schnellsten Systeme und überzeugte mit exzellenten Erkennungsraten.

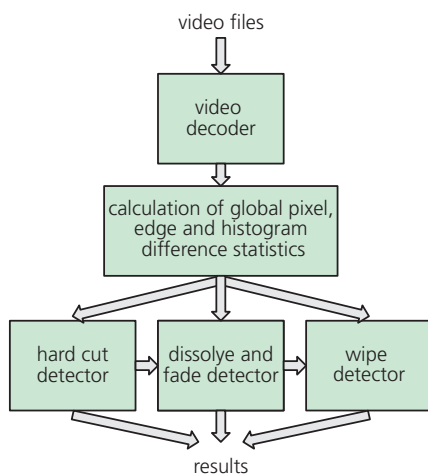


Fig. 1: Overview of the shot detection system

Huge amounts of video data are produced around the world each day. Without proper tools, efficient management of these ever growing amounts of video is out of reach.



Fig. 2: Example frames for a hard cut, dissolve, fade and wipe (top to bottom)

A robust fast and automatic video shot detection is a basic technology needed in this field.

A schematic overview of the system is shown in Fig. 1. After video decoding statistics are calculated for global pixel, edge and histogram differences. Then separate detectors for hard cuts, dissolves/fades and wipes are used. Results are merged afterwards into a list of detected shot boundaries.

For hard cut detection, differences between adjacent frames in the video are analysed. Techniques like adaptive thresholding and flash light detection are used to be sensitive enough to detect transitions between visually similar shots but at the same time to keep the false alarm rate low.



Fig. 3: Difference images between adjacent frames during a hard cut (left) and a wipe (right) used in the shot detection algorithm

For dissolve, fade and wipe detection several different temporal statistical properties have to be exploited since

for gradual transitions it is more difficult to distinguish between slow gradual changes caused by shot transitions, on one hand, and noise, motion or illumination changes on the other hand.

For dissolve and fade detection we use the fact that a loss in contrast can be observed reaching its maximum in the middle of the transition. During a wipe transition a spatial boundary can be observed moving through the image.

To compare our shot detection system with other competing systems, we participated in the international TREC Video Evaluation Track contest in the shot boundary determination task. 17 international major companies, research institutions and universities participated. Our systems produced the best results of all teams in the hard cut detection category. It took a shared third place in the overall detection performance while being the second fastest system in the contest.

This work is supported by the Federal Ministry of Economics and Labour of the Federal Republic of Germany (BMWA) under grant 01 MD 203.

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MPEG-7 BASED ARCHIVING AND RETRIEVAL OF DIGITAL VIDEO

We are developing new video analysis and archiving methods, capable of considerably simplifying the handling of, and retrieval from, large video databases for both professional users and home users of digital video. The core technology used for these approaches is based on descriptions of audio and video data derived from the MPEG-7 standard, which is strictly applied. Further features include intuitive video-summarization, rapid searching for similar video shots, and a camera detection and interpretation method.

Wir entwickeln neuartige Videoanalyse und -archivierungsmethoden, die professionellen Nutzern – aber auch Nutzern von digitalem Video im Heimbereich – die effiziente Sichtung und Nutzung von großen Video-Datenbanken wesentlich vereinfachen. Als grundlegende Basis des Vorhabens werden an den MPEG-7 Standard angelehnte Beschreibungen von Ton- und Bilddaten genutzt, um Videoarchivierung möglichst standard-konform zu gestalten. Weitere Merkmale sind eine intuitive Videozusammenfassung, eine schnelle Suche nach ähnlichen Videoshots und ein Verfahren zur automatischen Erfassung von Kamerabewegungen.

In recent years, the size of digital video archives has grown enormously. In particular, news agencies, TV broadcasters, and advertising agencies maintain large digital archives of movies and video footage. Furthermore, in the course of using digital technology, home users also amass tremendous amounts of video data. With the size of archives growing, the problem of actually locating certain sequences becomes more and more challenging. The intuitive, efficient, and straightforward ability to

sift through and manage large quantities of video data will be crucial for the success of most video asset management systems, both in the professional and home user application domains.



Fig. 1: Screenshot of the video management system

A new video asset management system is under development, which is capable of considerably simplifying the handling of and retrieval from large video databases, and is suitable for both professional users and home users.

Automatic analysis procedures decompose the video sequence into its components, the shots. To accomplish this, a very fast shot boundary detection method was developed that works directly on the MPEG-2 encoded data stream. The shot boundary detection method was submitted to the TRECVID 2004 contest, which promotes progress in content-based retrieval from digital video via open, metrics-based evaluation. We achieved the best results in Hard-Cut-Detection among 17 teams. In the overall results, we tied with another team for third place.

Each shot is represented by a keyframe. The frames are shown in a storyboard. Each shot is described by its audio characteristics, as well as by its color, texture, and motion features. The syntax of the descriptors is defined in the MPEG-7 standard. These descriptors provide the low-level information for intuitive searches.

Videos, single shots, or video segments can be displayed using a video-player (Fig. 1, top right). The storyboard presents the keyframe of each single shot.

The contents of the shots can be browsed in fast motion using a slider. The displayed timeline shows the chronology of shots and their properties.

A new feature of this system is the possibility to search for similar shots using example images. Many video segments, e.g., the weather forecast or the beginning of a newscast, are characterized by typical contents. These contents can be stored as references and learned by the system. With the help of similarity searches, previously "learned" video segments can be located and played back within a split second.

A further technology was developed that automatically detects camera motion from video sequences. The computation is based on the motion vectors of the MPEG-coded video streams, which has the advantage of being very fast. The plots of six different forms of camera motion (tilt, pan, zoom, rotate, track, and boom) are shown in diagrams (Fig. 2, top left). Sections with relevant camera motions are displayed in the lower half.

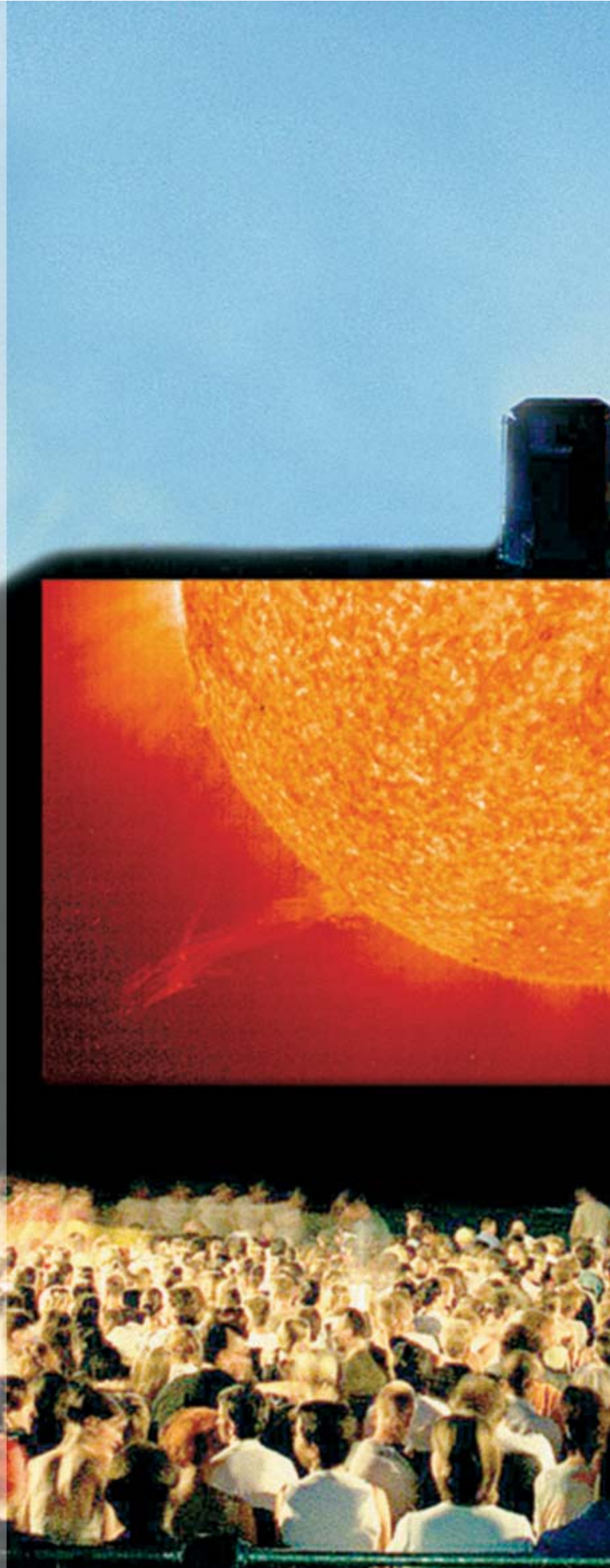


Fig. 2: Screenshot of the camera detection and interpretation system

The system is being developed in a joint project in cooperation with the Technische Universität Berlin and Canto GmbH.

This work is supported by the Federal Ministry of Economics and Labour of the Federal Republic of Germany (BMWA) under grant 01 MD 203.

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Multimedia services available for everybody at any time and in any place

Information Technology (IT) is the driving force behind the Information Society of the 3rd millennium. IT is penetrating into almost all business areas and into the private sector. Digital technologies help people in their businesses and private affairs, and digital technologies are more and more used to entertain people.

Multimedia is one of the key elements in Information Technology, because video, images, speech, sound and ancillary data are needed for an increasing number of services in the office, at home and in public areas.

The vision of *Multimedia services available for everybody at any time and any place* is the driving force behind the R&D developments of the Image Processing Department. It has built up key competencies and an internationally recognized reputation in the following areas:

- Image and video coding
- 3D image and video processing
- Image and video analysis, computer vision
- Image and video synthesis, computer graphics
- Multimedia transmission (IP, mobile, DVB)
- Hardware design and implementation of multimedia systems (video, audio, graphics)
- ASIC and IP design
- Image and video enhancement

One of the main activities in 2004 was the consolidation of the video coding standard H.264/AVC and the establishing of this standard in committees like DVB, 3GPP, DVD-Forum, BluRay Disk Forum und ATSC. Dr. Thomas Wiegand of HHI, who is co-chair of the Joint Video Team (JVT), a common activity of ISO/MPEG (Moving Pictures Experts Group) and ITU-T/VCEG (Video Coding Experts Group) developing H.264/AVC, acted as the editor of the "Visual Parts" of the specifications ETSI TR 102 005 und ETSI TS 101 154, which describe the DVB extensions (DVB-AVC) in relation to H.264/AVC.

Besides the standardisation activities, HHI developed its own software and hardware implementations of H.264/AVC. A key point is the usage of this standard for MBMS, DVB-H, DXB, i.e. for video services to mobile devices on the basis of UMTS, DVB-T and DAB respectively.



IMAGE PROCESSING

A third activity in this area concerns the development of the scalable video coding standard MPEG-SVC. Within the test carried out by MPEG, the proposal submitted by HHI outperformed by far all competing proposals. As a result, the scheme proposed by HHI, which is based on an extension of H.264/AVC, has been selected by MPEG as the basis for the future MPEG-SVC standard.

With these activities combined, HHI can offer to its customers a wide portfolio in compression technologies ranging from software implementations over hardware architectures to complete transmission systems and a number of applications such as wireless and wired video streaming or video surveillance.

Computer graphics and image processing technologies have reached a state that allows the development of novel multimedia applications and services. The new challenge in the field of television, electronic cinema and multimedia is called *immersive telepresence*, by which users should feel that they are immersed in the scene. Large displays with high resolution similar to cinema, IMAX or CAVE projections in VR applications are required. In this context, the current activities of the Image Processing Department are concentrated on four major applications: 3D videoconferencing, Digital Cinema, ultra-high resolution projection systems and 3D-TV.

Two other important topics are conversion from one video format to another (e.g. TV to HDTV) and image enhancement techniques (e.g. noise reduction). In the field of format conversion, HHI has established benchmark-setting know-how and expertise in numerous research activities. The developed motion-compensating video conversion algorithm (HiCON) provides a high quality conversion among different image sequence formats. It performs de-interlacing whilst preserving full spatial resolution. Image rate conversion is accomplished with good motion portrayal as it is required in high-quality image applications like digital cinema or optimised flicker-free and judder-free operation of high-end displays. HHI develops software implementations and architectures for ASICs and FPGAs on the basis of the HiCON technology. Besides the software solution HiCON³², which is sold as a product, an FPGA based hardware system will be built until mid 2005, which is suitable for the high-end consumer HDTV market and for professional HDTV and D-Cinema applications.

3D modelling of objects, persons or head and shoulders is now a mature technology allowing the development of new services. Thanks to 3-dimensional computer models, video clips can be transmitted to mobile phones or pocket PCs even over low speed network connections. A mobile phone or PDA display may show the face of the person on the other end of the line – smiling, laughing or frowning in

response to the last spoken words. Based on this technology an SMS-to-Video service has been developed and brought to market maturity.

Another technology deals with streaming von 3D panoramas. An MPEG-4 based system has been developed, which allows an interactive navigation through static panoramas, in which moving 3D objects (e.g. persons) can be found. Picture material has been captured at different locations in Berlin (Hotel Adlon/Pariser Platz, Hotel Estrel, airport Schönefeld, Ethnological Museum etc.) and processed for this system.

A new business field has been opened in the area of maskless lithography. In cooperation with the department ON of HHI, the FHG institutes ISIT and IOF as well as with a number of industrial companies a maskless lithography system will be developed, to which the Image Processing Department contributes a high speed transmission link and a multiplex unit for the mask data.



Multimedia-Dienste für jeden an jedem Ort und zu jeder Zeit

Die Informationstechnologie (IT) ist die treibende Kraft hinter der Informationsgesellschaft, IT zieht in fast alle Gesellschaftsbereiche, die geschäftlichen und in die privaten ein. Digitale Technologien unterstützen uns im Beruf und zuhause und tragen immer mehr zu unserer Unterhaltung bei.

Multimedia ist eine der Schlüsselkomponenten in der Informationstechnologie, da Bilder, Video, Sprache, Ton und andere Zusatzdaten für eine steigende Zahl von Diensten im Büro, im Haushalt und in öffentlichen Bereichen verwendet werden.

Die Vision *Multimedia-Dienste für jeden an jedem Ort und zu jeder Zeit* ist auch die treibende Kraft hinter den F&E-Aktivitäten der Abteilung Bildsignalverarbeitung. Diese hat Kernkompetenzen und international anerkannte Reputation in den folgenden Bereichen aufgebaut bzw. erlangt:

- Bild- und Videocodierung
- 3D-Bild- und Videoverarbeitung
- Bild- und Videoanalyse, Computer Vision
- Bild- und Videosynthese, Computer-Grafik
- Multimedia-Übertragung (IP, mobil, DVB)
- Hardware-Entwurf und Implementierung von Multimedia-Systemen (Video, Audio, Grafik)
- IP-Design für ASICs, FPGAs und „embedded“ Prozessoren
- Bild- und Videoverbesserung

Eine der Hauptaktivitäten in 2004 war die Konsolidierung des neuen Videocodierstandards H.264/AVC und die Etablierung dieses Standards in Gremien wie DVB, 3GPP, DVD-Forum, BluRay Disk Forum und ATSC. Dr. Thomas Wiegand, der Co-Chair des Joint Video Teams (JVT) ist, einer gemeinsamen Aktivität von ISO/MPEG (Moving Pictures Experts Group) und ITU-T/VCEG (Video Coding Experts Group), die H.264/AVC entwickelte, war Editor der „Visual Parts“ der Spezifikationen ETSI TR 102 005 und ETSI TS 101 154, die die DVB-Erweiterungen (DVB-AVC) in Bezug auf H.264/AVC beschreiben.

Neben den Standardierungsaktivitäten hat das HHI weiterhin eigene Software- und Hardware-Lösungen für H.264/AVC entwickelt. Ein Schwerpunkt dabei war und ist die Anwendung dieses Verfahrens für MBMS, DVB-H und DMB, d.h. für Videodienste auf mobilen Endgeräten auf Basis von UMTS, DVB-T und DAB.

Eine dritte Aktivität in diesem Bereich betrifft die Entwicklung des skalierbaren Videoverfahrens MPEG-SVC. Hier hat sich das HHI in mehreren von MPEG durchgeführ-

ten Tests mit großem Abstand gegen die gesamte internationale Konkurrenz durchgesetzt und die vom HHI vorgeschlagene H.264/AVC-Erweiterung wurde als Basis des neuen SVC-Standards ausgewählt.

Mit diesen Aktivitäten kann das HHI seinen Kunden ein breites Portfolio an Codierungstechnologien bieten. Diese reichen von Software-Implementierungen über Hardware-Architekturen bis hin zu kompletten Übertragungssystemen und einer Anzahl von Anwendungen wie dem drahtlosen und drahtgebundenen Video-Streaming oder wie der Videoüberwachung.

Computer-Grafik und Bildverarbeitungstechnologien haben einen Stand erreicht, der die Entwicklung neuartiger Multimedia-Anwendungen und Dienste ermöglicht. Die neue Herausforderung in den Bereichen Fernsehen, elektronisches Kino und Multimedia heißt *immersive Telepräsenz*. Immersiv bedeutet in diesem Zusammenhang, dass der Nutzer das Gefühl hat, sich in der Szene zu befinden. Große Displays mit sehr hoher Auflösung, ähnlich wie im Kino, im IMAX oder bei CAVE-Projektionen in VR-Anwendungen werden hierfür benötigt. In diesem Kontext gibt es in der Abteilung Bildsignalverarbeitung vier Hauptaktivitäten: 3D-Videokonferenz, digitales Kino, ultra-hochauflösende Projektionssysteme und 3D-TV.

Zwei andere wichtige Forschungsfelder sind die Formatkonversion (z.B. TV nach HDTV) und die Bildverbesserung (z.B. Rauschreduktion). Im Bereich der Formatkonversion hat sich das HHI in zahlreichen Forschungsprojekten ein führendes Know-how erarbeitet. Der entwickelte bewegungskompensierende Videokonversions-Algorithmus (HiCON) bietet eine hochqualitative Wandlung zwischen verschiedenen Bildsequenzformaten. De-Interlacing kann ohne Verlust an örtlicher Auflösung durchgeführt werden, eine Bildratenwandlung wird mit guter Bewegungswiedergabe durchgeführt, wie sie für hochqualitative Anwendungen wie digitales Kino oder flicker- und ruckelfreie Bilddarstellung auf High-end-Displays benötigt wird. Im HHI werden Softwareimplementierungen und Architekturen für ASICs und FPGAs auf der Basis der HiCON-Techniken entwickelt. Neben der reinen Software-Lösung (HiCON³²), die als Produkt vermarktet wird, entsteht bis Mitte 2005 eine FPGA-Lösung, die für den Einsatz im High-End-Consumer-Markt für HDTV sowie in professionellen HDTV- und Kinoanwendungen geeignet ist.

Die 3D-Modellierung von Umgebungen, Objekten, Personen oder Kopf- und Schulteransichten ist eine Technologie, die mittlerweile ihren Kinderschuhen entwachsen ist und nun die Entwicklung völlig neuer Dienste ermöglicht. So können z. B. dank 3-dimensionaler Computer-Modelle Videoclips mit extrem geringen Datenraten auf Handys und Pocket-PCs übertragen werden. Das Display eines Mobiltelefons oder



IMAGE PROCESSING

PDA's kann das Gesicht der Person am anderen Ende der Leitung in Abhängigkeit von der übertragenden Sprache lächeln, lachen oder die Stirn runzeln lassen. So wurde ein auf dieser Technologie basierender „SMS-2-Video“ Dienst zur Marktreife weiterentwickelt.

Ein anderes Beispiel betrifft das Streaming von 3D-Panoramen. Hierfür wurde ein auf MPEG-4 basierendes System entwickelt, mit dem es möglich ist, durch statische Panoramen, in denen sich bewegliche 3D-Objekte (z.B. Personen) befinden, interaktiv zu navigieren. Dazu wurde entsprechendes Bildmaterial an verschiedenen Plätzen in Berlin (Hotel Adlon/Pariser Platz, Hotel Estrel, Flughafen Schönefeld, Ethnologisches Museum usw.) aufgenommen und für das System aufbereitet.

Ein neues Geschäftsfeld hat sich im Bereich der maskenlosen Lithographie ergeben. Hier wird in Zusammenarbeit mit der Abteilung ON des HHI, den FHG-Instituten ISIT und IOF sowie einer Reihe von Industriefirmen ein maskenloses Lithographiesystem entwickelt, zu dem die Abteilung BS eine Hochgeschwindigkeitsübertragungsstrecke sowie eine Multiplexeinheit für Maskendaten beisteuert.



Image Processing

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Multi projection systems for Digital Cinema



Video codecs and streaming solutions for mobile communication



Video services and video based information systems in the vehicle



im.point: Immersive video conference system



MPEG-4 PANORAMAS

We present a system for interactive navigation through high-resolution cylindrical panoramas. The system is based on MPEG-4 and describes the virtual world by the scene description language BIFS. This allows the easy integration of dynamic video objects, 3-D computer models, interactive scene elements, or spatial audio in order to create realistic environments. The scene data can be stored locally or streamed from a server dependent on the navigation information of the client.

Wir präsentieren ein System für die interaktive Navigation durch hoch-aufgelöste zylindrische Panoramen. Das System basiert auf MPEG-4 und definiert die virtuelle Welt mittels der Szenenbeschreibung BIFS. Dies ermöglicht die einfache Integration von dynamischen Videoobjekten, 3-D Computermodellen, interaktiven Szenenelementen oder räumlichen Klang für eine realistische Darstellung der Umgebung. Die Szenendaten sind von der Navigation des Anwenders abhängig lokal oder als Stream von einem Server abrufbar.

Cylindrical panoramas for the creation of synthetic views from real scenes have a long tradition. Already in 1792, the painter Robert Barker built a panorama with a radius of 20 meters. Animated panoramas were presented around hundred years later in 1897 by Brimoin-Sanson. 10 synchronized projectors created the illusion of being present in foreign countries or distant places. Today, people are still attracted by gigantic panoramas like Asisi's 36 meters high Mount Everest panorama.

Fig. 1: Panorama image of the entrance hall at the Hotel Adlon in Berlin with approx. 38 MPixel



Fig. 2: Multiple panoramas from the Ethnological Museum in Berlin. Interactive scene elements allow the user to jump between the rooms. Dynamic objects are added to vitalize the scene.

In image-based rendering, cylindrical panoramas have received particular interest in current applications due to their simple acquisition setup. Only a couple of pictures need to be captured on a tripod or freely by hand. The images are stitched together forming one panoramic image as shown in Fig. 1. From the 360° scene information, new views can be rendered which enables the user to turn the viewing direction and interactively decide the point of interest. One well known example for such a system is QuicktimeVR.

At the FhG-HHI, we have developed a system for streaming and rendering of high-resolution panoramic views that is based on MPEG-4. The use of MPEG-4 technology provides many new features compared to conventional 360° panoramas. Video objects, dynamic 3-D computer models, or spatial audio as illustrated in Fig. 2 can be embedded in order to vitalize the scene. Pressing interactive buttons gives additional information about objects or modifies the current location. The MPEG-4 system also ensures that only visible data is transmitted avoiding long downloads of the entire scene. Thus, large high

quality environments can be created that enable the user to immerse into the virtual world.

The acquisition of large panoramas is quite simple in principle, in practice, the situation is often much more complex. For example, people, objects, or clouds in the scene may move while capturing the single images. As a result, the pictures do not fit to each other properly and ghost images appear. Moreover, capturing 360° of a scene may impose high demands on the dynamic range of the camera. Especially in indoor scenes, extreme changes in intensity may occur between windows and the interior. We have therefore investigated algorithms for the removal of moving people and objects in order to simplify the stitching. Multiple views are captured at different time instants and the covered regions are warped from the same areas in other views. Capturing the scene with different shutter times enables an spatial adaptive adjustment of the dynamic range and to create panoramas also for scenes with extreme brightness changes.

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FREE VIEWPOINT VIDEO

A real world scene is captured simultaneously with multiple cameras to generate a 3D reconstruction of dynamic objects. Free Viewpoint Video enables to render these so-called 3D Video Objects from arbitrary viewpoints by generating virtual intermediate views, as it is known from computer graphics.

Für die 3D Rekonstruktion dynamischer Objekte wird eine reale Szene mit mehreren Kameras simultan erfasst. Free Viewpoint Video ermöglicht es, ein so genanntes 3D Video Object aus beliebigen Blickwinkeln zu betrachten, indem virtuelle Zwischenansichten gerendert werden, wie es bisher aus der Computergrafik bekannt ist.

Interactivity is an important key feature of audio-visual media applications. Regarding to Free Viewpoint Video interactivity is the ability to look around within a scene by freely choosing a viewpoint. The first representations that provided such functionality were based on textured 3D mesh models, well known from computer graphics, games and virtual reality. But most of the scenes are either purely computer generated or contain static 2D views of real world objects. Due to recent achievements in image acquisition, mesh processing, and computer graphics we present a system for Free Viewpoint Video including 3D reconstruction of dynamic real world objects and scenes, flexible data representation and interactive rendering.

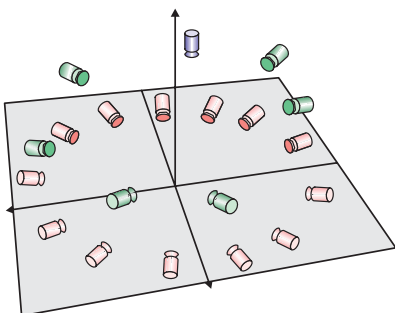


Fig. 1: Camera setup for scene acquisition

The scene is captured by a synchronized multi-camera setup as shown in Fig. 1. First, the camera geometry is estimated in relation to a 3D world coordinate system (extrinsic and intrinsic camera parameters). Then segmentation is performed for each view to separate the objects from the background, resulting in silhouette images.

An object's 3D volume is reconstructed from the silhouette images using a voxel-based shape-from-silhouette algorithm. Each voxel is back-projected into the silhouette images, taking the camera geometry into account. By deciding whether a voxel is part of the object's volume or not, a voxel model is generated for each time instance. In order to speed up processing, we use a hierarchical octree-structure for voxel reconstruction.

Because today's graphic hardware is highly optimized for rendering of 3D meshes, the resulting voxel models are converted into a classical 3D mesh, using the marching cubes algorithm (Fig. 2 left), and refined in two steps. First is to smooth the meshes via special 3D low-pass filters (Fig. 2 middle) as their surface is quite coarse. Because these meshes consist of too many triangles for efficient storage and real-time rendering the next step is to reduce the number of triangles by applying the edge collapsing technique to them (Fig. 2 right).

The extracted 3D model is then textured and colored for interactive rendering by a weighted combination of the original views available from the cameras. For that we developed a view-dependent multi texturing algorithm that approximates natural appearance when navigating through



Fig. 2: Refinement of 3D mesh models



Fig. 3: Virtual camera flight, rendered views at 3 times instances from 3 virtual viewpoints

the scene from any position as far as possible.

Interoperable exchange of such data between different systems requires standardized and efficient formats. Our solution is fully compatible to MPEG-4. The 3D geometry is coded using SNHC tools. The corresponding video textures are coded using H.264/AVC. Our algorithms for view-dependent texture mapping have been adopted as an extension of MPEG-4 AFX.

Such a reconstructed 3D video object can be rendered for any viewpoint and direction. Fig. 3 illustrates the functionality provided by our system. It shows the rendered snapshots of a virtual camera flight around a 3D video object while it is moving, 3 different time instances from 3 different virtual viewpoints. This also allows easy production of special effects such as stop-motion effects known from recent movies (e.g. Matrix).

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REAL-TIME VIDEO CAPTURE FOR ILLUMINATION RECONSTRUCTION IN AUGMENTED REALITY APPLICATIONS

We present an interactive real-time augmented reality system with realistic illumination of integrated virtual objects. A light-sphere is used to capture the lighting environment of the place the virtual object is to be rendered to. Therefore we developed an algorithm which does the lighting calculation for the object in real-time including soft diffuse shading and color-bleeding effects from the real world onto the virtual object.

Wir präsentieren ein System zur interaktiven Integration und realistischen Beleuchtung von virtuellen Objekten in realen Szenen. Die Umgebung wird dabei durch eine verspiegelte Kugel aufgenommen, die sich an der realen Stelle befindet, an der das virtuelle Objekt gezeichnet werden soll. Dazu wurde ein Algorithmus entwickelt, der die notwendigen Lichtberechnungen in Echtzeit durchführt und das Objekt mit sanften Schatten und indirekter Ausleuchtung in die Realität integriert.

In augmented reality applications, simple patterns (markers) are often used to calculate the position and perspective of a certain part of the real environment with respect to the camera. The marker used in our case is visible as a black square in Fig. 2. With this information one can project arbitrary virtual objects onto the real scene that fit in size and orientation over the marker. This technique only provides the user with the position and perspective warping of the virtual object but does not deliver any information about lighting conditions in the environment, that the object is to be placed into.

We now mounted a mirror sphere onto the marker and placed them in a scene

that is captured by a video camera. Dynamic illumination (as the marker or camera is interactively moved) is estimated from the video signal and used for realistic real-time integration of virtual objects into the video. The user can interact by moving the marker or camera and with that, the integrated virtual object in the augmented reality video. The computed illumination is adapted for every frame the camera captures. To achieve interactive real-time performance, we have developed a graphics-hardware accelerated approach.

In a preprocessing step we compute the virtual objects' self-occlusion and the form factors with respect to an environment map for each vertex. This information is stored in a low-resolution cube map for each vertex. These form factor cube maps for all the vertices are unfolded and assembled in a single large texture. The illumination information estimated from the video is resampled and low pass filtered into a low-resolution cube map. The form factor cube maps and the illumination cube map are multiplied on a per vertex basis. The results are summed up to compute the diffuse illumination for each vertex.



Fig. 1: Stanford Bunny which is directly illuminated by a desk lamp

Our approach works well for small virtual objects moving around in real environments. The real environment operates as a large area light source, which casts soft shadows on our dif-

fusely lit virtual objects. The prototype is implemented almost completely on the GPU, which allows real-time frame rates for virtual objects with ten thousands of vertices.



Fig. 2: Interactive color-bleeding effects casted from the real world onto the virtual object. The images have been taken from a live-camera demo running at 40 frames-per-second.

The current implementation uses just a single camera to capture the image of the mirror sphere and to insert the virtual object into the real scene. In the future we are planning to use a higher resolution camera with a zoom lens to capture the image on the mirror sphere and a separate camera or a video or optical see through HMD to allow users to walk freely around in an augmented environment with consistently illuminated virtual objects. This approach is not limited to augmented reality scenarios but could also be applied for lighting objects in complex virtual scenes with preprocessed lighting.

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DYNAMIC 3D MESH COMPRESSION

Dynamic 3D meshes, which describe the movement and deformation of an object over time, can be represented by a sequence of time-consistent polygonal meshes. These sequences contain a large amount of spatial and temporal statistical dependencies, which can be efficiently exploited in a dynamic 3D mesh compression framework. Through the combination of sophisticated technologies the new Differential 3D Mesh Coder (D3DMC) outperforms existing algorithms for the compression of dynamic 3D meshes.

Dynamische 3D-Drahtgittermodelle, welche die Bewegung und Deformation eines Objekts über die Zeit beschreiben, können durch eine Sequenz zeitkonsistenter Polygonnetze repräsentiert werden. Diese Sequenzen enthalten in großem Maße örtliche und zeitliche statistische Abhängigkeiten, welche effizient in einem Framework zur Kompression dynamischer 3D-Drahtgittermodelle ausgenutzt werden können. Durch die Kombination leistungsfähiger Technologien übertrifft der neue Differential 3D Mesh Coder (D3DMC) existierende Algorithmen zur Kompression dynamischer 3D-Drahtgittermodelle.

With the animation of synthetic or natural 3D objects over time, there is also the demand for efficient compression for transmission and processing purposes. Animated sequences of 3D objects stem from a number of different applications, starting with pure virtual Computer Graphics objects that deform over time. One of the newer application fields includes mixed-reality object reconstruction, where natural images are captured to reconstruct 3D objects with natural appearance for virtual environments.

The new Differential 3D Mesh Coder



Fig. 3: Comparison of static and dynamic mesh coding at 5 different time instances: Reconstruction error using static 3DMC at 915 kBit/s (top) and dynamic D3DMC at 364 kBit/s (bottom)

(D3DMC) implements an efficient algorithm for compression of such dynamic 3D meshes. It is suitable for sequences of time-consistent 3D meshes that use a common connectivity, where only the 3D position of the vertices changes over time. Such a sequence of meshes contains a large degree of temporal statistical dependencies that can be exploited for predictive compression.

D3DMC implements a classical closed DPCM loop and is embedded in a MPEG-4 framework. Figure 1 shows the block diagram of the encoder.

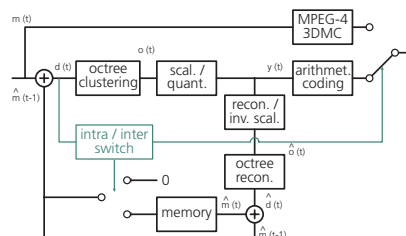


Fig. 1: Block diagram of the D3DMC encoder

MPEG-4 3D Mesh Coding (3DMC) is used for intraframe coding. The vertex positions of the intercoded frames are predicted at the encoder from the previously decoded mesh, which is available at the decoder too. The difference vectors are further clustered in an octree approach. Only a representative or substitute for a cluster of difference vectors is further processed, which is a significant reduction of the data rate. The representatives are scaled and quantized. This residual signal is finally entropy coded using Context-Based Adaptive Binary Arithmetic Coding (CABAC), the arithmetic coder used in the recent video coding standard H.264/AVC, which is highly optimized

for such kind of data. To close the prediction loop the mesh is then reconstructed at the encoder for prediction of the following mesh. To be able to react on scene changes (e.g. new objects entering the scene with a different connectivity) the prediction is limited to a certain group of meshes (GOM).

We compared the efficiency of D3DMC in terms of bitrate and quality with the static 3DMC used in MPEG-4. The appropriate rate distortion curves for the coding results measure the bitrate in kBit/s against geometry distortion between reconstructed and original mesh. For the distortion measure of wireframes, the Hausdorff distance was introduced to measure the maximum Euclidean distance between two wireframes. To analyze the overall reconstruction quality of the sequence, the average root mean squared error (AVGRMSE) was used. As expected the gain for D3DMC increases with the GOM size as can be seen in Fig. 2.

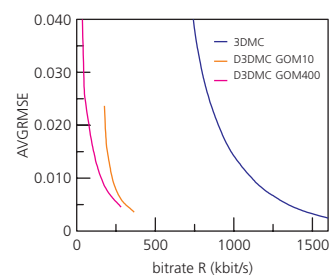


Fig. 2: AVGRMSE over bitrate for 3DMC and D3DMC, Chicken Crossing sequence

The results indicate a significant improvement of compression efficiency compared to static mesh coding (see Fig. 3). For some cases we report the same quality at 10 – 20% of the bitrate.

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IMMERSIVE MULTI-PROJECTION FOR ARBITRARY SCREEN SURFACES

Multiple projection systems represent a main key component for the successful introduction of immersive media. Even the next generation of digital high-end projectors will not be able to meet all requirements of immersive video applications such as dome projections, very wide projection walls or 360° cylinder projections. Against this background we have developed a PCI board that supports a wide range of immersive multi-projection applications with highest video quality using a modular and flexible PC-based architecture.

Überlappende Mehrfachprojektionen bilden eine Schlüsselkomponente für die erfolgreiche Markteinführung immersiver Systeme. Selbst die nächste Generation hochwertiger digitaler Projektoren wird nicht in der Lage sein, die Qualitätsanforderungen immersiver Videoanwendungen wie Projektionen in Domes, auf sehr breite Leinwände oder 360° Zylinderprojektionen mit nur einem Projektor zu erfüllen. Vor diesem Hintergrund wurde eine PCI-Karte entwickelt, die aufgrund ihrer Modularität und Flexibilität ein weites Feld immersiver Mehrfachprojektionen abdeckt.

The objective of immersive multi-projection is to stitch a given number of video frames to one image of ultra-high resolution that can be presented either at a large planar screen (projection wall) or at screens with a curved surface (360° panoramas or spherical domes). To avoid visible artefacts, sophisticated alpha blending and black level adjustments have to provide seamless transitions between the single video frames. Furthermore, all video frames have to be well-synchronised, in order to achieve an appropriate motion portrayal. Finally, efficient video compression techniques are required to

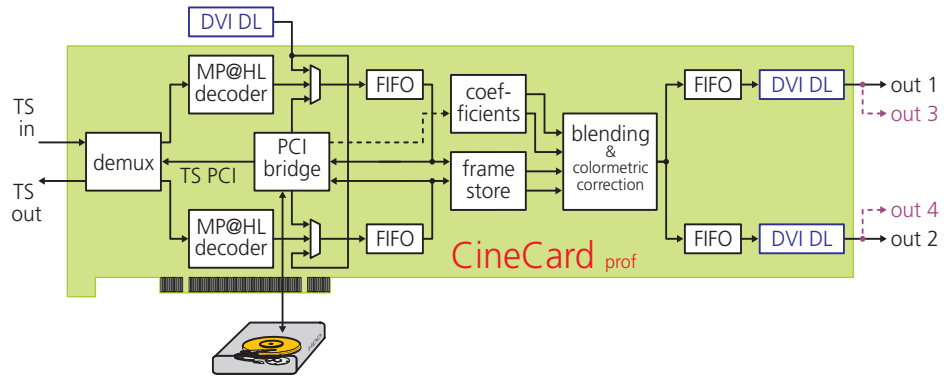


Fig. 1: Hardware architecture of PCI board for immersive multi-projection (CineCard prof)

handle the extremely large amount of video data.

For this purpose we have developed a modular and PC-based concept for an immersive multi-projection systems. The core of this system is a PCI board that can serve either four XGA or two HDTV (SXGA) projectors at once. This so-called CineCard contains dedicated hardware for real-time processing of required colormetric corrections such as alpha blending and black level adjustment. Inputs streams are allowed to be compressed or uncompressed. Uncompressed videos are grabbed from a Dual-Link DVI connector (either two HDTV streams with 24 bit/pixel or one stream with HDTV resolution but 48 bits/pixel), whereas compressed videos are taken from a MPEG-2 transport stream (either loaded from local disk via PCI bus or streamed from a LVDS SPI input). The transport stream is

de-multiplexed and the resulting MPEG-2 elementary streams are decompressed using two onboard MPEG-2 MP@HL decoders.

Projector arrays of arbitrary size and configuration can be achieved by cascading an appropriate number of CineCards. In this case precise synchronisation of the multiple video streams is achieved by a patented recovery of synch data from the MPEG-2 transport layer. Horizontal and vertical blending functions as well as pixel-selective colormetric processing allow to extend the projector array in each direction and to serve screens of almost any kind of curved surface. An additional warping board as well as an automatic camera-based calibration tool are under development for this purpose.

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Fig. 2: 360° panorama projection with 8 XGA projectors served by two CineCard PCI boards hosted by one PC (total resolution is app. 8000 × 720 pixels)



Fig. 3: Projection onto the curved surface of 72° panorama using two SXGA projectors with a total resolution of 2464 × 1024 pixels (shown at IBC 2004 in Amsterdam)



SCALABLE EXTENSION OF H.264/AVC

The FhG-HHI developed a new method for scalable video coding (SVC) as an extension of the latest and most advanced video coding standard H.264/AVC. Due to its superior coding efficiency in comparison to other scalable coding schemes, the FhG-HHI approach was chosen by ISO/MPEG as the basis for the new SVC standard.

Die FhG-HHI hat ein neues Verfahren zur skalierbaren Videocodierung (SVC) als Erweiterung des neuesten und effizientesten Videocodierstandards H.264/AVC entwickelt. Aufgrund seiner im Vergleich zu anderen skalierbaren Verfahren überlegenen Codiereffizienz, wurde der Ansatz des FhG-HHI von ISO/MPEG als Basis für den neuen SVC Standard ausgewählt.

Scalability at the bit-stream level represents a desirable feature of a video codec, especially for applications that require the transmission of video streams with a variety of spatio-temporal resolutions and bit-rates. With the intention to develop a new scalable video coding standard, the ISO/IEC Moving Picture Experts Group (MPEG) issued a Call for Proposals for efficient scalable video coding technology in October 2003. 14 submitted technical proposals were evaluated in March 2004, one of which was a scalable H.264/AVC extension contributed by

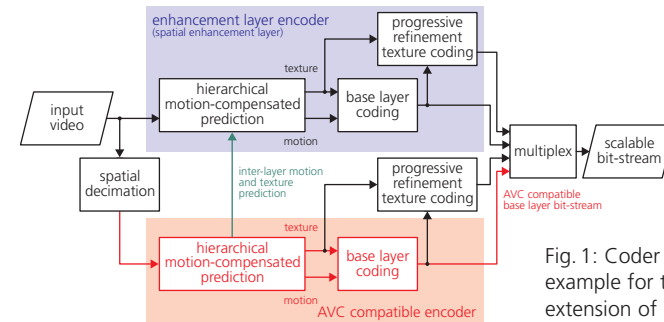


Fig. 1: Coder structure example for the scalable extension of H.264/AVC

the FhG-HHI. During the next two MPEG meeting periods, the FhG-HHI improved their approach in terms of both coding efficiency and supported functionality. Due to its superior coding efficiency in comparison to all other submitted proposals, which was verified in extensive subjective tests for different scalability scenarios, MPEG has chosen the scalable extension of H.264/AVC as a starting point of its Scalable Video Coding (SVC) project in October 2004. In January 2005, MPEG and the Video Coding Experts Group (VCEG) of the ITU-T agreed to jointly finalize the SVC project as an Amendment of their H.264/AVC standard, and the scalable coding scheme developed by the FhG-HHI was selected as the first Working Draft.

The basic coding scheme for achieving a wide range of spatial, temporal, and quality scalability can be classified as layered video codec. The coding structure depends on the scalability space that is required by the application. In Fig. 1, a block diagram for a typical scenario with 2 spatial layers is de-

picted. In each layer, an independent hierarchical motion-compensated prediction structure with layer-specific motion parameters is employed. This hierarchical structure provides a temporal scalable representation of a sequence of input pictures that is also suitable for efficiently incorporating spatial and quality scalability. The redundancy between different layers is exploited by different inter-layer prediction concepts that include prediction mechanisms for motion parameters as well as for texture data. For the decoding of any layer only a single motion-compensation loop is required. The base layer stream is compatible with H.264/AVC. Fine granular quality scalability is supported by a progressive refinement texture coding. Bit-streams for a reduced spatial and/or temporal resolution can be simply obtained by discarding network packets from a global bit-stream that are not needed for decoding the spatio-temporal target resolution. Packets that correspond to progressive refinement slices can also be arbitrarily truncated in order to further reduce the bit-rate and the associated reconstruction quality.

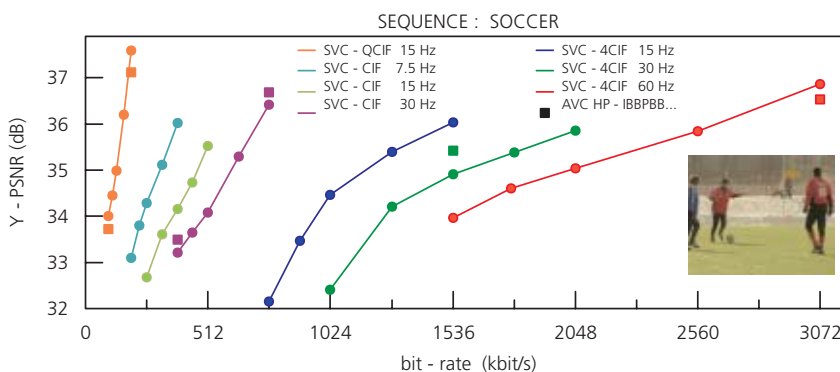


Fig. 2: Example for the coding efficiency of the scalable extension of H.264/AVC. All rate-distortion points have been extracted from a single global bit-stream of 3072 kbit/s. As reference, various single layer coding results with standard H.264/AVC High Profile and the classical "IBBPBBP..." temporal coding structure have been included in the diagram.

In the diagram of Fig. 2, the coding efficiency of the scalable H.264/AVC extension is compared to single layer coding with H.264/AVC High Profile and a classical "IBBPBBP..." temporal coding structure. All rate-distortion points for the scalable coder are extracted from a single global bit-stream of 3072 kbit/s that represents a spatial resolution of 704 × 576 samples (4CIF) and a frame rate of 60 Hz.

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HIGH-SPEED DATA STORAGE FOR OPTICAL INTERCONNECTS

Optical links are emerging as the preferred media when data rates beyond the "gigabit per second"-mark are concerned. A major challenge related to the use of high-speed optical links is the creation of an effective and robust electrical system for storing and preparing the transmission data to fully take advantage of the offered bandwidths. An FPGA-based system is introduced here.

Optische Übertragungsstrecken stellen bei Datenraten von mehreren „Gigabit pro Sekunde“ zunehmend die erste Wahl dar. Eine große Herausforderung ist die Entwicklung eines leistungsfähigen und robusten elektrischen Systems für die Datenspeicherung und -vorbereitung, um vollen Nutzen aus der angebotenen Bandbreite zu ziehen. Ein FPGA-basiertes System wird hier vorgestellt.

Optical links gain in importance in many different applications. Thus it is also a major topic in the field of the Projection Maskless Lithography technology (cf. page 16). The optical data transfer system described in the article mentioned above comprises a self-designed real time data buffer besides off-the-shelf optical equipment.

The high-speed data buffer is used to store a subset of the input data and generate a continuous data stream for the optical transmission. It is realized as a printed circuit board (PCB) featuring a Xilinx Virtex-II Pro FPGA as the central unit. The FPGA offers four integrated IBM PowerPC embedded processors and up to 20 multi-gigabit serial transceivers called RocketIOs. The PowerPC core is used to perform controlling functionality while the RocketIOs help to solve high-performance architectural challenges related to the multi-gigabit transmission.

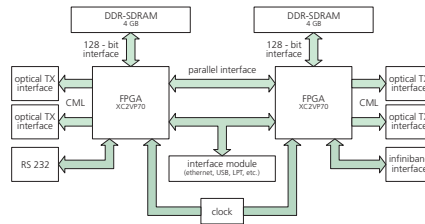


Fig. 1: Architecture of the data buffer

Fig. 1 shows the architecture of the high-speed buffer. A 128-bit wide memory interface allows for data traffic at up to 51Gbps. Two design components play a decisive role in providing the desired throughput: An application-optimized DDR-SDRAM controller accounting for a high-speed address generation and the parallel high-speed I/O ports, both being directly related to the need of a proper clocking solution using the FPGA's Digital Clock Manager (DCM).

All functional blocks are implemented in the Virtex-II Pro device. The controller provides the necessary address and control signals for driving standard DDR-SDRAM modules. The pipelined structure of the controller allows for concurrent operations, thereby providing high effective bandwidth by hiding row precharge and activation time. The backend interface of the DDR SDRAM controller is formed by a synchronous FIFO structure (providing configuration and command registers).

For the high-speed I/Os the RocketIO cores are used, providing serial links at up to 3.125 Gbps each. Ensuring synchronized parallel operation of the serial links with minimal skew is a major concern. By preparing the data for the optical transmission another requirement is added. To avoid charging or discharging the transmission line the transmitted signal must be DC-balanced, meaning the number of transmitted ones and zeros must be equal over time. For this purpose a proprietary 6B/8B coding scheme was implemented in the buffer, guaranteeing DC balance and moreover providing error detection of one-bit errors in the data stream.

At data rates in the GHz-range time skew among multiple channels can easily corrupt data. Synchronization is done by interlacing commas into the data stream. Once a comma is detected, a state machine checks for additional commas that are defined wordlengths apart. As soon as those commas are found, the link is considered aligned and the incoming data is checked against bit errors.

Besides various standard interfaces, the buffer is planned to provide an Infiniband interface. The Infiniband Architecture (IBA) defines a high-speed packet-based switched fabric system, operating in serial and parallel mode (channel bonding). Through the Infiniband interface the buffer can be connected to a RAID system, offering a data rate of 2.5 Gbps per channel. The transfer protocol is structured equivalent to the ISO/OSI model, Physical and Link Layer being already completed.



Fig. 2: Data buffer printed circuit board

The design of a first prototype capable of handling a data amount of 512 MB with a transfer rate of 16 Gbit/s is finished (see Fig. 2). A revision providing a throughput of 36 Gbps and 8 GB memory is momentarily under development, following approved concepts of the first version.

The application not only poses a challenge on the part of the VHDL implementation designed for highgrade pipelining and complying with the rigid timing constraints but it also requires deep skills for printed circuits routing. Impedance adaptation of lines was needed to guarantee signals integrity and control of high density boxes technologies.

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FPGA SOLUTION FOR A HD VIDEO FORMAT CONVERTER

Presenting video from different sources like PAL, NTSC, ATV (Advanced Television) or HDTV (High Definition Tele-vision) on a high resolution digital display requires a video format converter with good quality and high flexibility. This calls for a high performance platform. FPGAs (Field Programmable Gate Arrays) evolved from niche products for glue logic on PCBs to universal and complex (millions of gate equivalents) hardware platforms. This is the ideal base for rapid prototyping and low volumes of a HD (high definition) video format converter.

Die stärkere Nutzung von Displays neuester Technologie für die Wiedergabe unterschiedlicher Video-standards erfordert Videoformat-konverter mit hoher Qualität und großer Flexibilität. Bei hohen Datenraten und komplexen Algorithmen ist hierfür eine hohe Rechenleistung erforderlich. FPGAs (programmierbare Logikbausteine) haben sich in den letzten Jahren von Nischenprodukten für die sogenannte „glue logic“ auf Leiterplatten zu universell einsetzbaren Bausteinen höchster Komplexität (mehrere Millionen Gatteräquivalente) entwickelt. Sie stellen somit eine ideale Basis für die Implementierung eines Videoformatkonverters zur Prototypenentwicklung dar.

Within the last years, FPGAs have evolved from small logic devices (like the Xilinx XC4000) to devices enabling system on a chip solution (e.g. Virtex-II Pro™ XC2VP50). They contain lots of logic gates, processors (like PowerPC or MicroBlaze™), and fast IO interfaces. The most important feature is there reprogrammable logic. This makes these electronic devices an ideal base for a rapid prototyping platform.

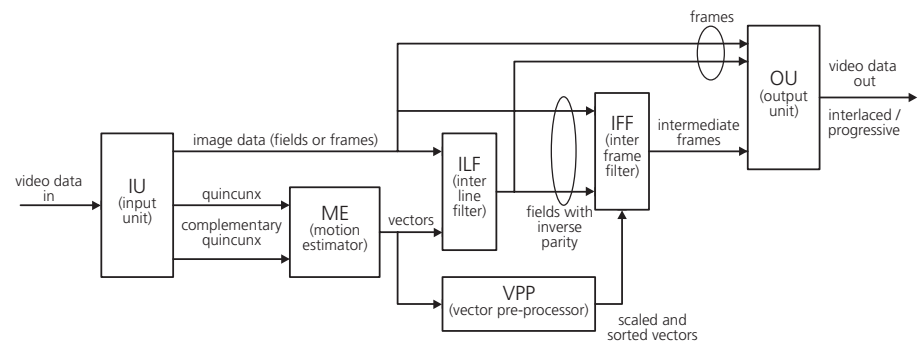


Fig. 1: Functional architecture of video format converter

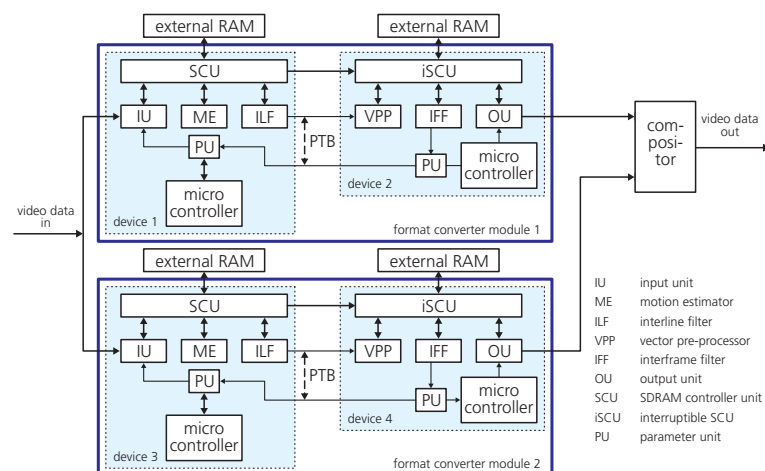


Fig. 2: Decomposition of video format converter on two FPGAs

Figure 1 shows the basic architecture for the HD format converter. For incoming video data motion vectors are calculated. If incoming images are fields, the opposite field can be generated by using these motion vectors directly. The produced frames can be used to generate intermediate frames, if frame rate conversion is required. Therefore vectors produced by motion estimator have to be scaled and shifted by the vector pre-processor. The frames can be scaled and displayed by output unit fieldwise or framewise.

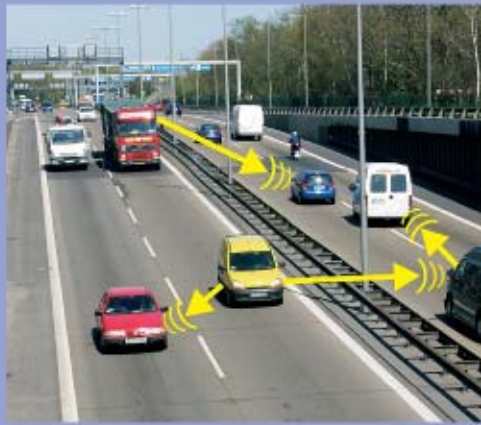
Figure 2 shows the architecture for a video format converter implementation on four FPGAs. Because some data has to be used on multiple occasions at different times, data delay paths have to be introduced. The on-chip data storage devices are insufficient for complete images. Therefore an external synchronous memory (like SDRAM or DDR-SDRAM) has to be used. The SCU (SDRAM controller unit) handles all

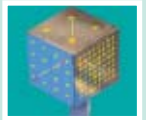
access from and to the external RAM. A micro-controller is necessary for configuring and controlling all units. The parameter units (PU) are interconnecting the micro-controller and all units via the parameter transfer bus (PTB).

Large scale images like HD formats exceeds the existing processing power and bandwidth, so that they cannot be handled by a single module. A reduction of the required processing power and bandwidth can be achieved by splitting incoming video data in half and merge the processed video streams at the output into a resulting one.

First estimations show, that only one very large (and also very expensive) FPGA is suitable to contain one module of the video format converter. Splitting the module onto two smaller FPGAs is a more economic and flexible solution.

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Broadband Mobile Systems

Mobility finds its way into all fields of society – last but not least into communications. Today already more people worldwide use mobile phones than traditional fixed network phones and the leading mobile network operators anticipate two billion cellular subscribers worldwide by the end of 2005.

The department of broadband mobile communication systems develops solutions within the entire range from theory about channel measurements, design of detection algorithms, system simulations up to implementation of algorithms in the demonstrator with the following emphasis:

1. Cellular systems
 - MIMO-OFDM Systems
 - Gbit Systems (60 GHz und MIMO)
 - Adaptive Modulation and Coding
 - Cross-layer Design
 - Smart MAC
2. Real time demonstrators
 - MIMO and Multi user aspects @ 5 GHz
 - Gbit/s MIMO @ 5 GHz
 - Gbit/s transmission techniques @ 60 GHz
3. Sensor networks
4. Ad-hoc networks

To keep pace with the increasing demand for data transmission, further developments of 3G as High Speed Downlink Packet Access (HSDPA) and High Speed Uplink Packet Access (HSUPA) were included into standardization. These systems present an enormous challenge for our research activities, since the resources have to be allocated according to the Quality-of-Service (QoS) demands of the users under the respective channel quality. For these techniques the full control of cross-layer optimization is necessary which is due to the time variance of the channel quality and the mobility of the users a very complex problem, that has to be solved under real-time conditions.

Another promising research strand for UMTS long term evolution is the application of multi-carrier systems such as OFDM in combination with MIMO technology. In collaboration with our industry partner ALCATEL new air interfaces based on cross layer design methods are currently being developed and investigated. Research focus is the design of control channels in upward and backward direction so as to benefit from multi-carrier and multi-antenna gain even under tight system limitations. New concepts have already been deployed and show significant performance gain compared to standard WCDMA HSDPA air interfaces.



A change of paradigms in mobile communications opens the possible changeover to cooperative systems. The research focus is on cooperative communication strategies for distributed antennas (a subtask within the BMBF funded project 3GET – 3rd Generation Evolving Technologies). By allowing cooperation between multiple distributed antennas, one can take advantage of the spatial structure of the wireless propagation medium. Significant gains in spectral efficiency are possible by exploiting spatial diversity and by reducing interference. This is especially important for users at the cell boundaries, which have a very low capacity due to the propagation loss. A promising way to overcome this problem is the use of distributed relays, which forward the information over multiple hops. This not only extends the coverage and reduces the requirement for costly infrastructure, but also leads to a significant reduction of interference between cells. Our department develops protocols and algorithms for adaptive relaying in combination with multi-antenna techniques and resource allocation.

Wireless ad hoc networks, a relatively new networking paradigm for mobile terminals, are characterized by the lack of a fixed infrastructure. This property distinguishes them from traditional mobile wireless networks and make them interesting for an increasingly wide range of applications such as disaster relief or car-to-car communications. Cars being able to communicate with other cars and with their environment could not only help to avoid crash situations and to save lives on our streets but could also significantly improve the comfort and efficiency of driving. On the other hand, due to the lack of central coordination facilities, ad-hoc networks pose significant new technical challenges in management of scarce wireless resources. We cover all aspects related to the design of the physical layer, medium access control layer and network layer for wireless ad-hoc networks and also investigate and exploit the coupling and interaction between these layers of the protocol stack to ensure the best possible network performance. These research activities also include different kinds of fixed and mobile wireless mesh networks.

A wireless sensor network is a collection of sensor nodes being able to capture different physical phenomena and/or act on the environment. Sensor nodes have wireless communication capability and sufficient intelligence for signal processing and networking of the data. Due to the self-organizing capabilities, wireless sensor networks can be deployed at almost any location, and hence they have an enormous potential for many applications. The energy constraint is a major design criterion for wireless sensor networks and, since the transmit power associated with data transmission dominates the power consumption in most cases of practical interest, there is a strong need for energy-efficient communication algorithms to make the idea of

ubiquitous sensor networks come true. Our research work includes distributed coding for correlated sources and the development of energy efficient communications algorithms and protocols.

In cellular mobile scenarios the number of users within reach of one base station can be quite high and will be time variant, in general. An efficient and channel quality aware resource allocation in the domains of time, frequency and space (for multiple antenna base stations) is a prerequisite for all future generation systems. This resource allocation which is commonly referred as multi-user scheduling can then be used to optimize the system/cell load or throughput with additionally considering quality of service parameters (e.g. delay, average rates, BER), such that the operator can run the system optimized towards a controllable cost function. The in general, complex optimization algorithms can be performed in real-time when the results from the underlying theoretical frame work are appropriately reduced in complexity.

In a joint effort, Siemens AG, Fraunhofer HHI and IAF GmbH have shown in November 2004 for the first time a mobile over-the-air transmission experiment with a gross data rate of 1039 Mbit/s. Therefore, the well-known OFDM technique, which is already used in multiple wireless standards as DVB-T, 802.11a/g (WiFi) and 802.16 (WiMax), was combined with a multiple antenna system, which is also known as MIMO (Multiple-Input Multiple-Output). The System has successfully been shown by the Siemens AG at the 3GSM World Congress 2005 in Cannes. At the CeBit 2005 link-adaptation and scheduling has been demonstrated for MIMO multi-user scenarios. This is also an example for the work currently being performed in cross layer optimization.



Breitband Mobilfunknetze

Mobilität hält Einzug in alle Bereiche der Gesellschaft – nicht zuletzt in die Kommunikation. Heute nutzen weltweit bereits mehr Menschen Mobiltelefone als traditionelle Festnetztelefone und die Netzbetreiber rechnen mit 2 Mrd. Nutzern weltweit bis Ende 2005.

Die Abteilung Breitband Mobilfunknetze erarbeitet Lösungen innerhalb der gesamten Spanne von Theorie über Kanalmesung, Entwurf von Detektionsalgorithmen, Systemsimulation bis hin zur Algorithmenimplementierung im Demonstrator mit folgenden Schwerpunkten:

1. Zellulare Systeme
 - MIMO-OFDM Systeme
 - Gbit Systeme (60 GHz und MIMO)
 - Adaptive Modulation und Kodierung
 - Cross-layer Design
 - Smart MAC
2. Echtzeitdemonstrator
 - MIMO und Mehrnutzeraspekte @ 5 GHz
 - Gbit/s MIMO @ 5 GHz
 - Gbit/s Übertragungstechniken @ 60 GHz
3. Sensor Netzwerke
4. Ad-hoc Netzwerke

Um der steigenden Nachfrage an Datenraten gerecht zu werden, befinden sich die Weiterentwicklung aus 3G wie z.B. High Speed Downlink Packet Access (HSDPA) und High Speed Uplink Packet Access (HSUPA) bereits in der Standardisierung. Diese Systeme stellen für die Forschung eine große Herausforderung dar, weil die Ressourcen in Abhängigkeit der Dienstgüteanforderungen der Teilnehmer zur jeweiligen Kanalqualität verteilt werden. Hierfür ist die Beherrschung der Cross-Layer-Optimierung unbedingt notwendig und stellt auf Grund der Zeitvarianz der Kanalqualität und auf Grund des Mobilitätsverhaltens der Teilnehmer ein sehr komplexes Problem dar, das unter Echtzeitbedingungen gelöst werden muss.

Ein weiteres vielversprechendes Forschungsgebiet für UMTS-Langzeitentwicklungen ist die Kombination von Vielträgersystemen (wie z.B. OFDM) mit MIMO-Techniken. In Zusammenarbeit mit unserem Industriepartner Alcatel werden zur Zeit neue Luftschnittstellen entwickelt und untersucht, die auf Cross-layer-Design basieren. Der Forschungsschwerpunkt liegt dabei auf dem Design vom Kontrollkanälen in Aufwärts- und Rückwärtsrichtung, um somit von der Steigerung bei Mehrträger- als auch Mehrantennensystemen auch unter strengen Systemeinschränkungen zu profitieren. Neue Konzepte sind bereits getestet worden und zeigen im Verhältnis zu Standard-WCDMA-HSDPA-Luftschnittstellen hervorragende Durchsatzwerte auf.

Ein Paradigmenwechsel in der Mobilkommunikation ermöglicht den Übergang zu kooperativen Systemen. Der Forschungsschwerpunkt liegt hier auf kooperativen Kommunikationsstrategien für verteilte Antennen (Unterauftrag im BMBF-Projekt 3GET – 3rd Generation Evolving Technologies). Indem man Kooperation zwischen mehreren verteilten Antennen zulässt, kann man Vorteil aus der räumlichen Struktur des drahtlosen Ausbreitungsmediums ziehen. Man kann beachtliche Ergebnisse in der spektralen Effizienz durch die Nutzung räumlicher Diversität und durch Reduktion von Interferenz erzielen. Dies ist vor allem für die Nutzer an den Zellgrenzen entscheidend, die bedingt durch den Ausbreitungsverlust eine sehr niedrige Kapazität haben. Ein vielversprechender Weg um dieses Problem zu bewältigen ist die Nutzung von verteilten Relais, die die Information über mehrere Hops weiterleiten. Dies erhöht nicht nur die Reichweite und reduziert die üblicherweise hohen Infrastrukturkosten, sondern führt zusätzlich zu einer außerordentlichen Reduzierung der Interferenzen zwischen den Zellen. Wir entwickeln Protokolle und Algorithmen für adaptive Relais-Systeme in Verbindung mit Mehr-Antennen-Techniken und Ressource Allokation.

Drahtlose Ad hoc Netzwerke, ein relativ neues Netzwerkparadigma für mobile Terminals, sind charakterisiert durch das Fehlen einer festen Infrastruktur. Diese Beschaffenheit unterscheidet sie von traditionellen mobilen drahtlosen Netzwerken und macht sie interessant für einen immer breiter werdenden Anwendungsbereich wie z.B. von Katastrophenschutz bis Fahrzeug-zu-Fahrzeug-Kommunikation. Autos, die die Fähigkeit haben mit anderen Autos und mit ihrer Umgebung zu kommunizieren, können nicht nur dazu beitragen Unfallsituationen zu vermeiden und Leben auf unseren Straßen zu retten, sondern können auch den Komfort und die Effizienz beim Fahren steigern. Andererseits stellen Ad hoc Netzwerke, gerade wegen der fehlenden zentralen Koordinierung, eine große technische Herausforderung an die Verwaltung der knappen drahtlosen Ressourcen dar. In unseren Arbeiten decken wir alle Aspekte ab, die sich auf das Design der physikalischen Schicht, der Medium-Access-Control-Schicht und der Netzwerkschicht beziehen und untersuchen die Kopplung und Interaktion zwischen diesen Schichten, um die bestmögliche Netzwerk-Performance zu gewährleisten. Diese Forschungsaktivitäten umfassen auch unterschiedliche Arten der festen und mobilen drahtlosen vermaschten Netze.

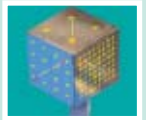
Ein drahtloses Sensornetzwerk ist eine Ansammlung von Sensorknoten, die in der Lage sind unterschiedliche physikalische Phänomene zu erfassen und/oder auf die Umgebung einzuwirken. Sensorknoten haben das Potential zur drahtlosen Kommunikation und ausreichend künstliche Intelligenz für die Signalverarbeitung und Vernetzung der gesammelten Daten. Wegen ihrer Fähigkeit zur Selbstorganisation, können



drahtlose Sensornetzwerke fast an jedem Ort eingesetzt werden und haben damit ein enormes Potential für zahlreiche Applikationen. Die Energieeinschränkung ist eines der zentralen Designkriterien für drahtlose Sensornetzwerke und da die bei der Datenübertragung benötigte Energie bei den meisten praktischen Anwendungen den Hauptteil des gesamten Energieverbrauchs ausmacht, besteht ein starkes Interesse an energie-effizienten Kommunikationsalgorithmen, um die Idee eines ubiquitären Sensornetzwerkes zu verwirklichen. Unsere Forschungsaktivitäten schließen Arbeiten zu verteilter Kodierung für korrelierte Quellen und die Entwicklung von energie-effizienten Kommunikationsalgorithmen und Protokollen ein.

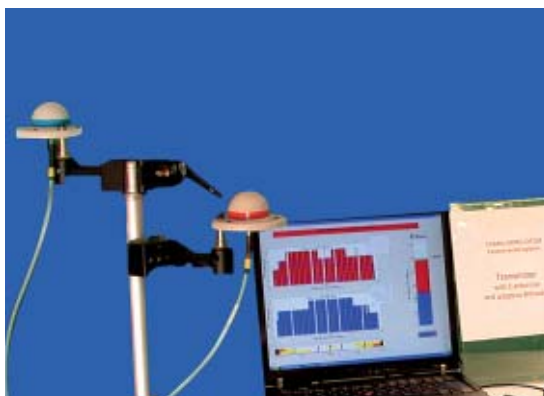
In Szenarien für zellulare und mobile Systeme kann die Zahl der sich in Reichweite der Basisstation befindenden Nutzer sehr hoch sein und ist in der Regel zeitvariant. Ein effiziente Ressourcenallokation, die die Kanalqualität hinsichtlich Zeit, Frequenz und Raum (für Mehrantennen-Basisstationen) berücksichtigt, ist eine grundlegende Voraussetzung für alle zukünftigen Systeme. Diese Ressourcenallokation, die gemeinhin auch als Mehrnutzer-Scheduling bekannt ist, kann genutzt werden, um die System- bzw. Zelllast oder den Durchsatz mit zusätzlichen Dienstgüteparametern (z. B. Verzögerung, Durchschnittsraten, BER) zu optimieren, so dass der Operator das System als optimierte, kontrollierbare Kostenfunktion fahren kann. Der in der Regel komplexe Optimierungsalgorithmus kann in Echtzeit ausgeführt werden, wenn der zu Grunde liegende theoretische Rahmen in seiner Komplexität entsprechend reduziert wird.

In einem gemeinsamen Projekt haben die Siemens AG, das Fraunhofer HHI und die IAF GmbH im November 2004 zum ersten Mal eine breitbandige mobile Funkübertragung mit einer Brutto-Datenrate von 1039 Mbit/s demonstriert. Dafür wurde die bekannte OFDM-Technik, welche schon in einigen drahtlosen Standards verwendet wird wie z. B. DVB-T, 802.11a/g (WiFi) und 802.16 (WiMax), mit Mehrantennentechniken kombiniert, die auch als MIMO (Multiple-Input Multiple-Output) bekannt sind. Das System wurde erfolgreich von der Siemens AG auf dem 3GSM World Congress 2005 in Cannes der breiten Öffentlichkeit vorgestellt. Auf der CeBit 2005 konnten außerdem Link-Adaption und Scheduling für MIMO Mehrnutzer-Szenarien demonstriert werden. Dies ist damit auch ein Beispiel für Arbeiten die zur Zeit im Bereich der Cross-layer Optimierung durchgeführt werden.



Broadband Mobile System

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MIMO-OFDM transmission with real-time adaptive bit-loading



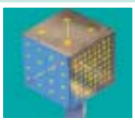
Ad-hoc car-to-car communication



Reconstructed MIMO-OFDM data symbols from 3 transmit antennas (64 QAM)



Multi-user scheduling in cellular networks



CAPACITY OF MIMO SYSTEMS UNDER MULTI-USER INTERFERENCE BASED ON WORST CASE NOISE BEHAVIOR

In future wireless communication systems, multiple transmit and receive antennas will be applied in order to improve performance and spectral efficiency. The capacity of a cellular multi-user MIMO system is limited by additive white Gaussian noise, intra-cell interference from other users within the cell, and inter-cell interference from users outside the considered cell. We analyze the impact of the spatial signature of the noise plus interference on the capacity of a MIMO system.

In zukünftigen Mobilkommunikationssystemen werden Mehrantennensysteme eingesetzt werden um die Leistungsfähigkeit und spektrale Effizienz zu steigern. Die Kapazität eines zellularen MIMO Systems mit mehreren Teilnehmern wird durch additives Rauschen und Interferenz innerhalb der Zelle und der Nachbarzellen gestört und begrenzt. Wir analysieren den Einfluss der räumlichen Signatur der Interferenz auf die erreichbare Kapazität eines MIMO Systems.

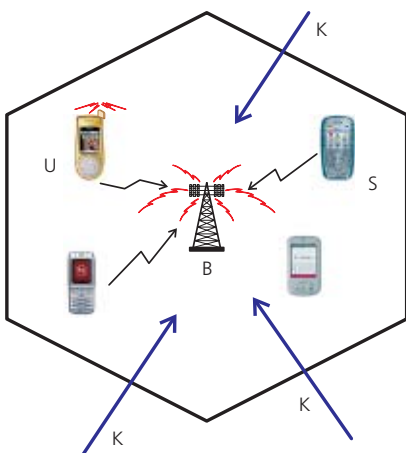


Fig. 1: Cellular multi-user MIMO uplink

Consider the typical flat-fading MIMO MAC model with multiple transmit and multiple receive antennas in cellular multi-user uplink transmission. In figure

(1), we show an uplink transmission from user (U) to the base (B). On the one hand, inter-cell interference comes from neighbour cells (K) and on the other hand user in the same cell create intra-cell interference (S).

We assume that the interference plus noise is complex Gaussian distributed with a certain spatial covariance matrix. This assumption is motivated by the law of large numbers for a large number of interferers. Furthermore, the zero-mean complex Gaussian distribution is the worst case noise distribution under a variance constraint.

Three noise and interference models are studied: 1) The trace of the noise covariance matrix is constraint. In this scenario, the sum noise power which arrives at the base station is kept fixed. This model corresponds to a scenario in which the *inter- and intra-cell interference dominates*. 2) The eigenvalues of the noise covariance matrix are fixed. This constraint leads to the *worst case noise directions*. 3) The diagonal of the noise covariance matrix is constraint to be less or equal to some constant. In this scenario, we *fix the noise power at each receive antenna* at the base station because of the equal noise power of the receivers. The color in the noise is created by the intra- and inter-cell interference. This scenario provides the worst case colored noise.

The problem is formulated as the solution of a two player game: the first player corresponds to the transmitter which maximizes the performance and the second player corresponds to the spatial noise plus interference that minimizes the performance. Therefore, we study minimax problems of the following type:

$$\inf_{\mathbf{Z}} \max_{\mathbf{Q}} \text{Tr} F \left[\mathbf{Z}^{-\frac{1}{2}} \mathbf{H} \mathbf{Q} \mathbf{H}^H \mathbf{Z}^{-\frac{1}{2}} \right].$$

$\mathbf{Z}$ is the spatial noise covariance matrix $\mathbf{H}$ the MIMO channel, and $\mathbf{Q}$ the transmit strategy. The solution to this mini-

max problem is in all three cases a saddle-point solution.

In case 1) the performance equals the performance of a MIMO link with white noise and an uninformed transmitter. Due to the worst case noise with trace constraint the channel information at the transmitter gets lost as shown in Fig. 2. P is the transmit power and σ_n^2 is the noise power.

$$\begin{aligned} \mathbf{x} \rightarrow \boxed{\mathbf{H}} \rightarrow \oplus \rightarrow \mathbf{y} &= \mathbf{x} \rightarrow \boxed{\mathbf{H}} \rightarrow \oplus \rightarrow \mathbf{y} \\ \sim \text{CN}(0, \mathbf{Q}) \quad \uparrow \quad \uparrow &\quad \sim \text{CN}(0, \frac{P}{K} \mathbf{I}) \quad \uparrow \quad \uparrow \\ &\quad \sim \text{CN}(0, \mathbf{Z}) \quad \quad \quad \sim \text{CN}(0, \frac{M\sigma_n^2}{K} \mathbf{I}) \end{aligned}$$

Fig 2: Worst Case Noise with trace constraint

In case 2) the worst case noise directions correspond to the right eigenvectors of the channel matrix. The resulting performance equals that of parallel fading channels depicted in Fig. 3.

$$\begin{aligned} \mathbf{x} \rightarrow \boxed{\mathbf{H}} \rightarrow \oplus \rightarrow \mathbf{y} &= \begin{matrix} \mathbf{x}_1 \rightarrow \boxed{\lambda_1(\mathbf{H})} \rightarrow \oplus \rightarrow \mathbf{y}_1 \\ \vdots \\ \mathbf{x}_K \rightarrow \boxed{\lambda_K(\mathbf{H})} \rightarrow \oplus \rightarrow \mathbf{y}_K \end{matrix} \\ \sim \text{CN}(0, \mathbf{Q}) \quad \uparrow \quad \uparrow &\quad \quad \quad \uparrow \quad \uparrow \\ &\quad \sim \text{CN}(0, \mathbf{Z}) \quad \quad \quad \lambda_i(\mathbf{Z}) \quad \lambda_K(\mathbf{Z}) \end{aligned}$$

Fig 3: Worst Case Noise Directions

In case 3) the performance under worst case noise color equals that of a system without transmitter cooperation, i.e. a multiuser single-antenna uplink. This is shown in Fig. 4.

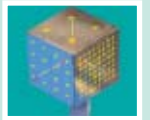
$$\begin{aligned} \mathbf{x} \rightarrow \boxed{\mathbf{H}} \rightarrow \oplus \rightarrow \mathbf{y} &= \begin{matrix} \mathbf{x}_1 \rightarrow \boxed{h_1} \rightarrow \oplus \rightarrow \mathbf{y} \\ \vdots \\ \mathbf{x}_n \rightarrow \boxed{h_n} \rightarrow \oplus \rightarrow \mathbf{y} \end{matrix} \\ \sim \text{CN}(0, \mathbf{Q}) \quad \uparrow \quad \uparrow &\quad \quad \quad \uparrow \quad \uparrow \\ &\quad \sim \text{CN}(0, \mathbf{Z}) \quad \quad \quad \sim \text{CN}(0, \mathbf{I}) \end{aligned}$$

Fig 4: Worst Case Colored Noise

The results are used to predict the multiuser MIMO performance and to quantify the advantage of spatial interference avoidance algorithms.

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1 E. Jorswieck and H. Boche, Performance Analysis of Capacity of MIMO Systems under Multiuser Interference Based on Worst-Case Noise Behaviour, EURASIP Journal on Wireless Communications and Networking 2004:2, 273–285.



REAL-TIME IMPLEMENTATION OF ADAPTIVE CHANNEL INVERSION

A real-time implementation of Adaptive Channel Inversion on a multi-antenna (MIMO) test-bed was demonstrated for the first time. The proven concept allows a multi-antenna base station to support several mobile terminals with one antenna each simultaneously in the same time slot and frequency band and therefore to improve the spectral efficiency of the system.

Erstmals wurde eine Implementierung von adaptiver Kanal inversion in Echtzeit auf einem Mehrantennen-Experimentalsystem realisiert. Das Verfahren ermöglicht es von der Basisstation aus mehrere Mobilterminalen mit jeweils nur einer Antenne gleichzeitig im selben Zeitschlitz und Frequenzband zu versorgen, und somit die spektrale Effizienz des Systems zu erhöhen.

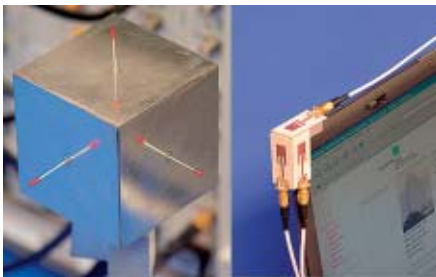


Fig. 1: Left: close-up of MIMO Triple antenna for 5.2 GHz used in the experiments, right: triple patch antenna suitable for device corners

By exploiting channel knowledge at the base station (BS) MIMO techniques can be applied even if the mobile terminals have only one antenna each. The remaining signal processing at the mobile terminal is kept at a minimum which allows for low cost solutions at the terminal side. The antennas from the BS together with the antennas from several mobile terminals (MTs) form a joint multiple-input multiple-output (MIMO) channel which can be jointly preprocessed at the BS and all transmission links to the MTs can be fully adapted to the actual channel state realization.

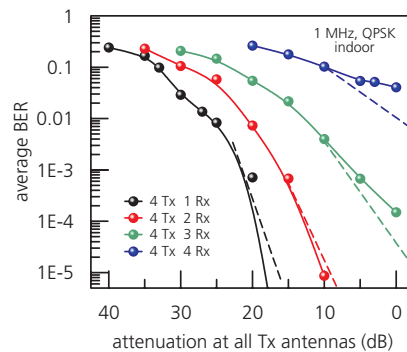


Fig. 2: Measured BER with 4 BS antennas and 1 to 4 users with transmit channel inversion

The transmission equation with a Linear Channel Inversion transmit filter reads

$$\hat{d} = y = Hx + n = H \cdot H^{-1}d + n = d + n$$

which is equivalent to parallel transmission links with additive white Gaussian noise (AWGN). The equally preconditioned parallel channels may require impractical high transmit power especially in ill conditioned channels. Therefore the limited transmit power will translate directly into SNR decrease at the receiver which results in an average bit error rate performance, which is very similar to that well known from linear receiver detection. The achievable transmit diversity gain expected from theory is depicted with dashed lines in Fig. 2 and is well matched by the measurements. The underlying statistical model assumed an i.i.d. Rayleigh channel between all antenna pairs which is not perfectly met in reality since a non-negligible line-of-sight component between some antenna pairs was apparent during the measurements creating a partial Rician component.

The exploitation of linear spatial precoding (Adaptive Channel Inversion) for spatial multiplexing and transmit diversity allowed control of the number of reliably supportable users. Furthermore, channel adaptive bitloading allows to control BER targets for all users individually by choosing the appropriate modulation levels on each link. The modulation is chosen on the basis of the calculated actual SINR at each receive antenna.

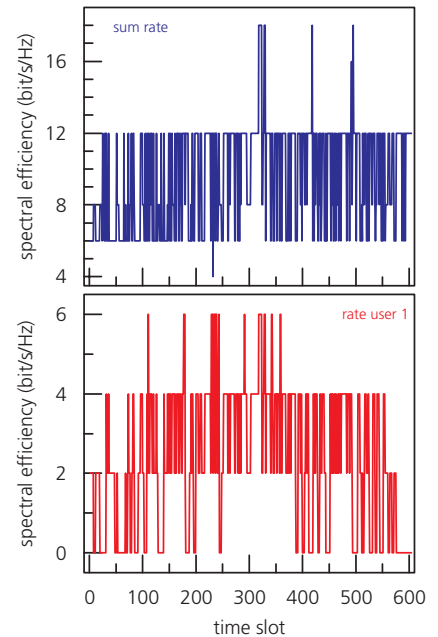


Fig. 3: Spectral efficiency with Adaptive Channel Inversion. Top: Sum Rate, bottom: user 1

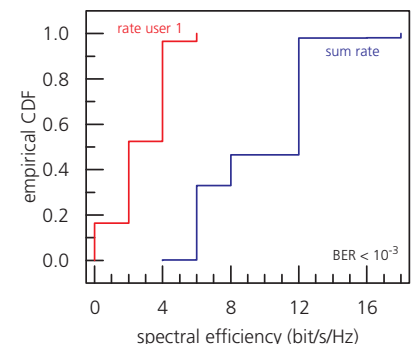


Fig. 4: Cdf of the spectral efficiency BER < 10⁻³

The measurement results in Fig. 3 show, that a stable sum rate throughput of several 10 Mbit/s can be realized within 5 MHz bandwidth for a MIMO base station with 4 transmit antennas which can support up to 4 mobile terminals, simultaneously. The bottom left figure shows that the achievable throughput for one particular user is varying between 0 and 8 bit/s/Hz when a certain target BER is to be met for each user and the sum throughput is aimed to be maximized. When the joint MIMO channel becomes rank deficient, the system sacrifices one or two users out of four and uses the four BS antennas in order to benefit from transmit diversity, which allows higher order modulations in general.

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EXPERIMENTS ON MULTI-USER SCHEDULING WITH A MULTI-ANTENNA BASE STATION

A real-time implementation of several multiuser scheduling schemes on a multi-antenna test-bed was demonstrated. It was shown that cross-layer optimized multi-user scheduling is applicable already on state-of-the-art hardware under real-time constraints and allows high cell throughput and a simultaneous support of quality of service requirements of the individual users.

Eine Implementierung verschiedener Mehrnutzer Scheduling-Strategien unter Echtzeitanforderungen wurde auf einem Mehrantennen Experimentalsystem realisiert. Es konnte gezeigt werden, daß bereits mit heutiger Hardware eine echtzeitfähige schicht-übergreifende Optimierung des Mehrnutzervielfachzugriffs möglich ist. Dies ermöglicht sowohl einen hohen Datendurchsatz pro Zelle als auch die Unterstützung von Quality of Service Anforderungen der einzelnen Nutzer.

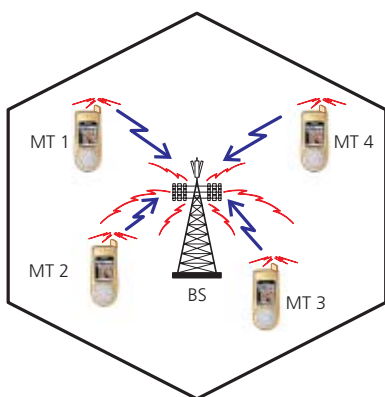


Fig. 1: Multi-user MAC – uplink from mobile terminals to a multi-antenna base station

The limited resource frequency has to be shared within the multiple access channel (MAC) describing the up-link from several mobile terminals (MTs) to a base station (BS) with multiple antennas. Therefore, efficient multi-user scheduling in time and space is a key issue for future radio systems.

A cross-layer based approach allows to exploit channel state information from the physical layer and queueing state information from the data link layer at the same time.

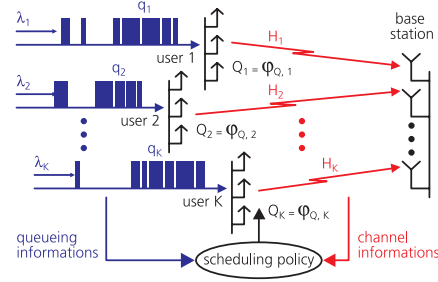


Fig. 2: The Routine to compute a cross-layer scheduling policy in the MIMO uplink

The optimization problem to find the desired scheduling policy can then be formulated as

$$Q_s = \arg \max_k \sum_k q_k(t) R_k(Q_s, H(t))$$

where $q_k(t)$ denotes the queue state of the k-th user at time instant t and $R_k(Q_s, H(t))$ denoting the achievable rate for the k-th user depending on the actual channel realisation and the chosen scheduling policy. Assuming successive interference cancellation the optimum detection order is determined by the ordered queueing states, such that for a given user set, the user with longest queue will be detected last.

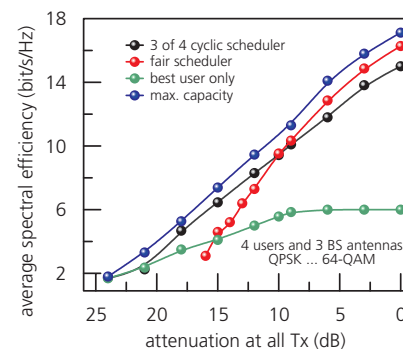


Fig. 3: Measured average sum rate with MU scheduling. BS has 3 Rx antennas, 4 users

Since an exhaustive search over all possible user sets is often not an option under real-time constraints, the problem complexity has to be reduced dramatically. We can exploit the fact that the BS can support up to MR users simultaneously where MR denotes the number of BS antennas. For the experi-

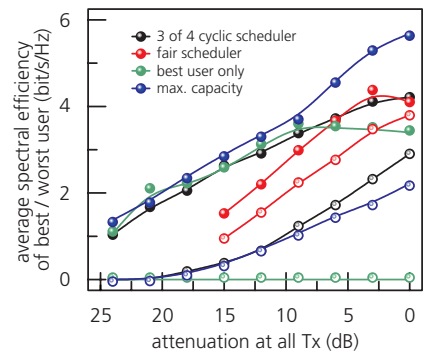
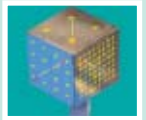


Fig. 4: Average individual user rates with different schedulers. filled symbols: best rate user, open symbols: lowest rate user

ments we chose a sub-optimum but very fast algorithm which could be implemented on a real-time MIMO test-bed. The "fair scheduler" in Fig. 3 and 4 always selected the user with the longest queue plus two additional users to achieve a maximum sum throughput with the first selected user. By this simple means we realized a scheduling policy which supports high cell throughput (Fig. 3) while reducing the queue length to a minimum which is reflected in the highest throughput for the worst user (see Fig. 4). Here, the achievable rates for the worst and the best user are very similar and the rate of the worst user could be guaranteed to all users as a QoS parameter. A scheduling policy only considering the overall throughput (blue) achieves a higher sum throughput but the average rate for the worst user in the cell is much lower as to be seen (open blue symbol) in Fig. 4. A scheduler which always supports 3 from 4 users in a cyclic fashion achieved a remarkable good performance in our experiments since the channel gains between the BS and the MTs were very similar. In real outdoor scenarios a significant performance degradation is expected since neither channel state information nor queueing state information is included in the selection process for the allocated user sets. The performance of the best user only scheduler shows that scheduling only one user is strictly sub-optimum at high SNR.

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HIGH-SPEED INDOOR TRANSMISSION EXPERIMENTS AT 60 GHz

Experimental results on high-speed transmissions at 60 GHz in an indoor environment are described. Two alternatives using a multi-carrier or a single carrier technique have been investigated. We demonstrated a wireless Gigabit-Ethernet connection between two PCs.

Bei Übertragungsexperimenten im 60 GHz-Bereich wurden zwei alternative Modulationsarten eingesetzt, die auf einem Mehrträger- oder einem Einträgerverfahren basieren. Zwei mit Gigabit-Ethernet-Schnittstellen ausgestattete Rechnersysteme wurden per 60 GHz-Funkstrecke miteinander verbunden.

Nowadays there is a growing demand for wireless high-speed short-range communication systems to be used in wireless personal area networks (WPANs). The 60 GHz range offers a wide frequency band and appropriate standardisation¹ is under way. Applications are in the fields of high speed wireless multimedia connectivity and interoperability, (WiMedia²).

The goal of our experiments is to investigate the performance of 60 GHz short range indoor radio links³ using single and multi-carrier techniques at data rates ranging from some Mbit/s up to 1.25 Gbit/s.

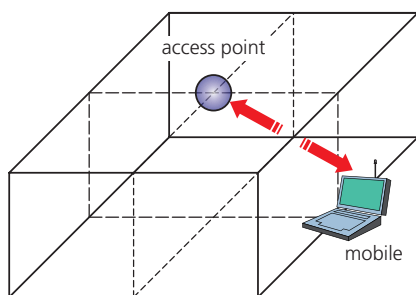


Fig. 1: Wireless indoor transmission link

The theoretical description of the system shown in fig. 1 is based on the power budget equation of the radio

link and the Ray-Tracing-method. An isotropic antenna at the mobile receiver (MT) and an omnidirectional antenna at the access point (AP) transmitter is assumed. The transmission between AP and MT is corrupted by multi-path propagation resulting in intersymbol interference (ISI) at high speed single carrier transmission. The power delay profile (PDP) describes the multi-path link, an example is shown in Fig. 2.

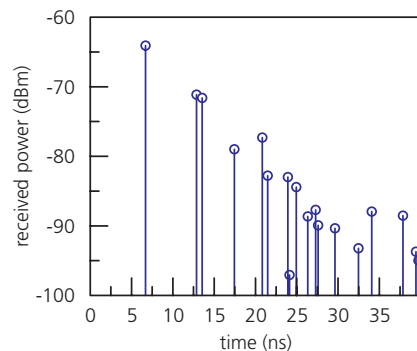


Fig. 2: Calculated power delay profile PDP for the scenario given in Fig. 1, room size: 7 m x 5 m x 3 m

We investigated two techniques which may be used to reduce ISI:

- a multi-carrier technique including signal processing and OFDM or
- a single carrier technique using a directive antenna at the MT.

OFDM-experiments: The spectrum of the 100 MHz OFDM testbed⁴ (Fig. 3) was built by 192 modulated subcarriers. AP and MT were equipped with omnidirectional antennas. The OFDM signal was converted to 60 GHz. After transmission the signal was down-converted and applied to the OFDM receiver for further processing. The system performance was determined by measuring the BER of PRBS data signals (Fig. 4).

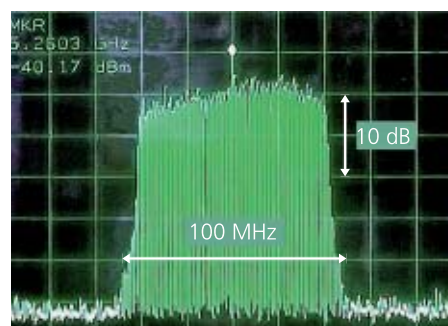


Fig. 3: OFDM spectrum after transmission via the 60 GHz link

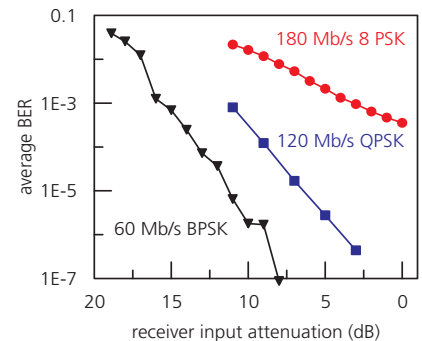


Fig. 4: Averaged BER vs. receiver input attenuation for uncoded signals applying different data rates and modulation formats

Single carrier experiments: The alternative technique avoids ISI by applying a 22 dBi antenna at the MT which is directed toward the AP. 1.25 Gb/s PRBS data signals on a single RF carrier have been transmitted in the DBPSK format. In case of a line of sight connection we measured BER < 10⁻⁹. Fig. 5 shows the measured and calculated RF-power at the receiver antenna input at various locations within the laboratory. This technique was used for a wireless Gigabit Ethernet connection of two PCs.

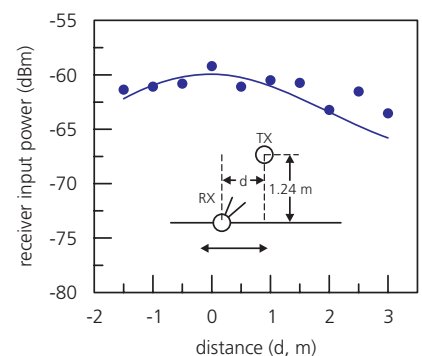


Fig. 5: Measured (dots) and calculated (line) signal power at the receiver input, inset: positions of receiver and transmitter

The project is part of the joint project "MaiNet" funded by the German research ministry BMBF under contract 01BP269.

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¹ IEEE 802.15.3 SG3c, <http://www.ieee802.org/15/pub/SG3c.html>

² <http://www.wimedia.org/>

³ G. Grosskopf et al.: Proc. 13th Internat. Plastic Optical Fibres Conf. 2004, Sept. 2004, Nürnberg (DE), pp. 27–34

⁴ Testbed provided by Siemens/IAF, Institut f. angewandte Funksysteme



OFDM HSDPA DOWNLINK AIR INTERFACE FOR UMTS

A promising concept for UMTS downlink transmission is the incorporation of multicarrier techniques such as Orthogonal Frequency Division Multiplexing (OFDM) in combination with multiple antenna techniques. In addition to WCDMA air interface the basestation can switch to OFDM downlink air interface, e.g. for very high data rates in hot spot areas. The development of this air interface in the context of High Speed Downlink Packet Access (HSDPA) UMTS evolution is the goal in this project.

Ein vielversprechendes Konzept für die UMTS Abwärtsstrecke stellt die Orthogonal Frequency Division Multiplexing (OFDM) Mehrträgerübertragung dar. Hierbei ist vorgesehen, dass zusätzlich zur WCDMA Abwärtsstrecke je nach Szenario eine OFDM Luftschnittstelle für sehr hohe Datenraten hinzugeschaltet wird. Die Entwicklung dieser Luftschnittstelle im Rahmen der High Speed Downlink Packet Access (HSDPA) UMTS Evolution ist das Ziel in diesem Projekt.

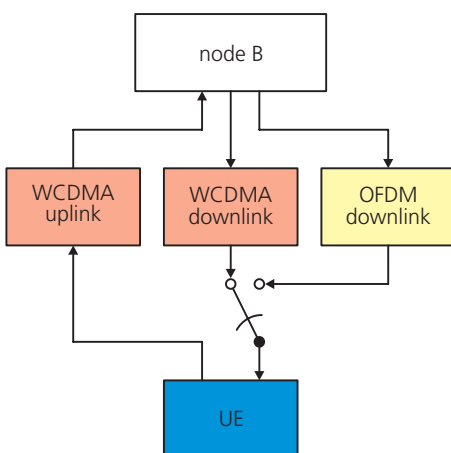


Fig. 1: Expected UMTS evolution

There are currently significant efforts to enhance the downlink capacity of UMTS within the 3rd Generation Partnership

Project (3GPP) UTRAN standardization body. Recent contributions show that alternatively using OFDM as the downlink air interface yields superior performance and higher implementation-efficiency compared to standard WCDMA and is therefore an attractive candidate for the UMTS cellular system. Furthermore, due to fine frequency resolution, OFDM offers flexible resource allocation schemes and the possibility of interference management in a multicell environment. It is therefore self-evident that OFDM will be examined in the context of High Speed Downlink Packet Access (HSDPA) (so-called OFDM HSDPA hereafter) where channel quality information is used at Node B in order to boost link capacity and support packet-based multimedia services by proper scheduling of available resources. First introduced in the 3GPP Rel. 5 standard, HSDPA aims at peak data rates of approximately 10 Mbit/s. Rel. 7 will include antenna array and MIMO techniques (shifted from Rel. 6) and is expected to achieve peak data rates of 20–30 Mbit/s. The main features of HSDPA are as follows:

- A combination of TDMA and CDMA is employed to enable fast scheduling in time (asserting time slots to User Equipments (UE)) and code domain (asserting a number of parallel channelization codes to UEs).
- Fast flexible link adaptation is achieved by adaptive modulation, variable FEC coding and power control.
- Hybrid-ARQ with incremental redundancy transmission.

Additionally, it is worth noting that since HSDPA does not support frequency-selective scheduling only frequency-nonselective channel quality information has to be reported back leading to a very low feedback rate. Obviously, the same channel information can be in principle used by OFDM HSDPA taking advantage of the higher spectral efficiency of OFDM air interface. More-

over, by exploiting frequency-selective channel information the OFDM downlink capacity can be theoretically further drastically increased. However, practically one faces the difficulty that frequency-selective scheduling affords a much higher feedback rate if the feedback scheme is not properly designed which can serve as a severe argument against the use of this system concept. Moreover, resource allocation is completely different to standard HSDPA and more elaborate due to huge number of degrees of freedom. Thus, in order to fully exploit the capability of OFDM HSDPA conceptual solutions for physical and MAC layer have to be devised which is the focus of this research. Some significant research results concerning feedback channel design and resource allocation have been previously obtained¹. The main result is that frequency selective scheduling can be implemented even by using standard low rate HSDPA channels.

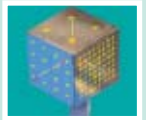
Beyond this development multiple antenna techniques are also investigated in the context of MIMO OFDM. Recent results indicate further impressive increase in spectral efficiency². Again proper scheduling policies have to be devised in order to fully exploit this capacity while simultaneously taking care of the implementation efficiency.

This research is supported by the German Ministry of Research and Education under grant 01BU350 and by industries.

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MEDIUM ACCESS CONTROL FOR WIRELESS DISTRIBUTED NETWORKS

Medium access control including power control and link scheduling is a central mechanism for resource allocation and interference management in wireless communications networks. Our focus is on power control to provide the best possible quality-of-service to the users. We have developed efficient and robust power control algorithms for distributed wireless networks.

Leistungskontrolle und Link Scheduling sind Elemente zur Steuerung des Medienzugriffs, eines für die Ressourcenverwaltung und das Interferenzmanagement in drahtlosen Kommunikationsnetzen bedeutenden Mechanismus. Wir konzentrieren uns auf die Leistungskontrolle, um den Nutzern die bestmögliche Dienstgüte zur Verfügung zu stellen. Dazu haben wir effiziente und robuste Algorithmen der Leistungskontrolle für verteilte drahtlose Netze entwickelt.

Future generations of wireless networks will have to support a wide range of services that have fundamentally different quality of service (QoS) requirements and traffic characteristics. The number of transmission links with high QoS requirements is expected to surpass the traditional voice connections. As a consequence, the problem of providing acceptable QoS to the users will become one of the central problems in wireless network design. This problem will be intensified by the physical limitation of the mobile radio propagation channel as well as the limitation on the bandwidth and the transmit power.

Medium access control including power control and link scheduling is a central mechanism for providing QoS to the users. When developing access control policies, it is a common practice to assume that there is a one-to-one rela-

tionship between signal-to-interference ratio (SIR) at the output of a linear receiver and the QoS performance in terms of bit-error-rate, data rate or service delay. This is especially true if SIR is used in connection with soft decoders. Early work on power control focused on the problem of maximizing the minimum SIR (SIR balancing problem). A closely related problem is to satisfy certain target SIR levels with a minimum total transmit power. In either case, optimal allocations of transmit powers are well-known and can be obtained by means of efficient iterative algorithms that allow a distributed implementation. Both approaches are user-centric in the sense that the users either require a fair allocation of resources (SIR balancing) or have some SIR requirements that need to be satisfied permanently.

However, the notion of being able to guarantee QoS to applications is simply unrealistic in certain scenarios. This is particularly true for ad-hoc wireless networks with mobile users, and a dynamic network topology. Furthermore, many data applications are delay-insensitive, and therefore can be regarded as elastic in the sense that certain QoS requirements do not need to be satisfied permanently. This relative delay tolerance of data applications can be exploited to achieve performance gains. In such cases, a common approach is to provide the best possible QoS to the users expressed in terms of a certain global QoS function. A widely studied example of such a function is a weighted sum of QoS values, and in particular a weighted sum of data rates. The weights may be adjusted to some system variables (e.g. to queue states) to ensure better fairness, lower delays and/or network stability. The weights can also be used to prioritize users.

The problem of optimizing a weighted sum of QoS values is strongly influenced by the geometry of the so-called feasible QoS region, which is defined as a set of all QoS values that can be

supported by a network with all users active concurrently. In particular, if the feasible QoS region is a convex set, a weighted sum of QoS values attains its optimum at the boundary of the feasible QoS region where the hyper-plane with the normal weight vector supports this set. However, in real systems, the QoS values are only indirectly accessible, for instance, by means of transmit powers, which leads to the power control problem.

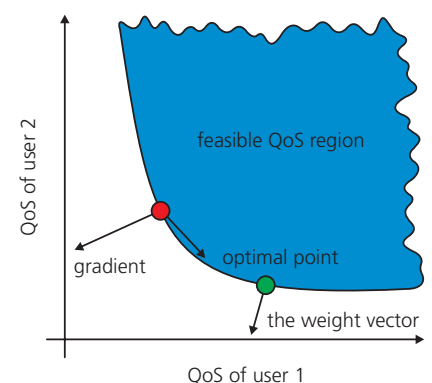
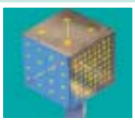


Fig. 1: The convexity property of the feasible QoS region

The convexity property of the feasible QoS region opens the door to a widely developed theory for characterizing optimal power control policies. In [1,2] we showed that the feasible QoS region is a convex set for a large class of QoS-SIR mappings. Based on these results, we have been developing centralized and distributed algorithms for power control in wireless networks. Our algorithms have been shown to converge to the optimum. They can be modified to be robust against noisy measurements and to have a geometric convergence to the optimum. These properties make the algorithms interesting for applications in wireless networks.

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INTERFERENCE PRE-COMPENSATION FOR POINT-TO-MULTIPOINT WIRELESS LINKS

We address the problem of joint precoding for multi-user point-to-multipoint systems, where the transmitter is equipped with multiple antennas and each of the independent receivers has a single antenna. We combine non-orthogonal MMSE beamforming with optimal power allocation and non-linear interference pre-subtraction. Residual interference is controlled at the transmitter prior to transmission. In addition, signal shaping is performed over a periodically extended constellation by numerically searching for the transmit vector with minimal Euclidean norm.

Das MCI entwickelt Verfahren zur gemeinsamen Vorkodierung für Punkt-zu-Mehrpunkt Mehrnutzersystemen, unter der Annahme, dass der Sender mehrere Antennen hat und die unabhängigen Empfänger mit Einzelantennen ausgestattet sind. Wir kombinieren nichtorthogonales MMSE Beamforming mit optimaler Leistungsverteilung, sowie nichtlinearer Interferenz-Vorkompensation. Verbleibende Störungen werden bereits am Sender kontrolliert, d.h., vor dem Versenden der Signale. Zusätzlich wird eine Signalformung über den periodisch fortgesetzten Signalraum durchgeführt. Es wird numerisch der Sendevektor mit der geringsten Euklid'schen Norm bestimmt.

Information theory predicts that if interference is known non-causally at the transmitter, then this knowledge can be exploited by the precoder to achieve the same capacity as if the interference would not exist. Moreover, such an ideal precoding comes at no extra cost in terms of transmit power. It has been shown that a combination of beamforming and such 'Dirty Paper'

precoding achieves the optimal sum capacity of the broadcast channel. However, it is not yet fully understood how these theoretical bounds can be achieved.

Reference¹ proposes a precoding technique for decentralized receivers, which combines Tomlinson-Harashima-Precoding (THP) and Zeroforcing filtering. The known causal interference terms are pre-subtracted and the transmit signals are transformed back to the original signal constellation region by modulo operations. The effect of the modulo operation is as follows. At each layer, a unique precoding symbol is added to the data symbol, so that the symbol after interference pre-compensation falls into the original constellation region. Applying the same modulo operation at the receiver, the original signal can be recovered perfectly. If the transmission is corrupted by noise, then bit errors occur.

However, the modulo operation causes power enhancement, known as precoding loss, due to the uniform distribution of the output signal from the modulo operation. It is not optimal in terms of the totally required transmit power. Thus, additional constellation shaping should be performed to improve the power efficiency. On the other hand, Zeroforcing filtering has larger power enhancement as compared with MMSE filtering.

In [2], we combine non-orthogonal MMSE beamforming with power efficient precoding, named Sphere Precoding (SP), which makes use of ideas from THP and constellation shaping. We derive the optimal MMSE pre-filters and transmission powers which minimize the total transmit power while maintaining individual Quality-of-Service targets.

The proposed algorithm exploits the triangular structure, which is imposed on the effective channel³. The partial interference is cancelled by SP. The

basic idea of SP is to replace the one-dimensional modulo operation by an equivalent vector modulo operation to improve the power efficiency. The optimal precoding vector is obtained by solving an integer least square problem with minimum Euclidean norm. We observe that the output signal is approximately Gaussian distributed for large constellation size.

The proposed strategy controls the individual output powers, which allows to handle multi-user interference. In particular, it enables the application of the optimal pre-filtering, which reduces residual interference subject to given SINR constraints at the receiver. Since the users are intertwined by interference, the problem consists of jointly optimizing the beamformers, the power allocation, the interference pre-subtraction, and the precoding vector. All these quantities are mutually interdependent. The shaping gain obtained by the sphere precoder is not used to minimize the total transmit power, but rather to enlarge the distances between the transmit data symbols, which leads to a better bit error performance.

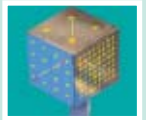
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1 GBIT/S DATA TRANSMISSION USING REAL-TIME MIMO-OFDM SIGNAL PROCESSING

Mobile data transmission with a gross data rate of 1 Gbit/s is demonstrated over the air using a dedicated real-time implementation of the MIMO-OFDM technique (provided by HHI). It is jointly integrated and tested in a fully functional radio link with SIEMENS and IAF GmbH. Results show that the spatial multiplexing becomes feasible for broadband mobile applications with realistic effort due to the combination with OFDM.

Erstmals wurden Daten über eine mobile Luftschnittstelle mit einer Brutto-Datenrate von mehr als 1 Gbit/s übertragen. Das HHI hat die Echtzeit-Implementierung des MIMO-OFDM Verfahrens entwickelt, und die Signalverarbeitung gemeinsam mit SIEMENS und der IAF GmbH in ein komplettes Mobilfunksystem integriert. Die Ergebnisse zeigen, dass Räummultiplex durch die Kombination mit OFDM auch für mobile Breitbandkanäle mit vertretbarem Aufwand realisierbar ist.

According to the ITU Recommendation M.1645, 'potential new radio interface(s) will need to support data rates of up to approximately 100 Mbit/s for high mobility such as mobile access and up to approximately 1 Gbit/s for low mobility such as nomadic/local wireless access'. These high data rates may be feasible within a realistic spectrum by combining multi-antenna and multi-user techniques.

In order to proof that 1 Gbit/s is feasible in real-time, we have built an experimental mobile communication system with 3 transmit and 5 receive antennas suitable for the transmission in the same room. The OFDM system uses 48 out of 64 sub-carriers in a total bandwidth of 100 MHz.

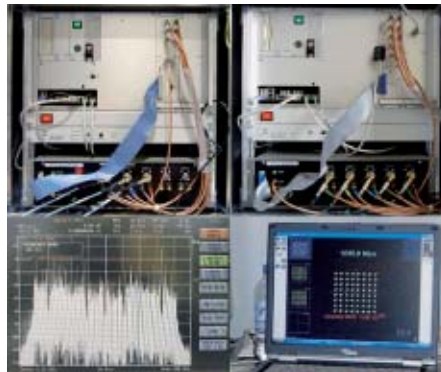


Fig. 1: Top: MIMO transmitter and receiver units. Bottom: Spectrum in 100 MHz span and reconstructed 64-QAM constellation of over-the-air received signals at 1 Gbit/s.

The bit transmission is organized in 3 parallel OFDM streams, each for one transmit antenna. The signals from different antennas are identified by inserting a dedicated sequence of pilot OFDM symbols (out of an orthogonal set) in each data stream based on which the channel between each transmit and each receive antenna is instantaneously estimated at the receiver using a bench of dedicated correlation circuits.

The spatially multiplexed data streams are received with 5 antennas. Based on the estimated channel coefficients, the transmitted data are instantaneously reconstructed with a linear MMSE filter.

The system is implemented in real-time on a hybrid DSP/FPGA platform. It is fully operational with 64-QAM modulation on each stream, using dedicated 5.2 GHz RF front-ends with ultra-low IQ imbalance.



Fig. 2: Antenna configurations in mobile measurements. Left: Transmit (top) and receive (bottom) antennas. Right: The transmitter is moved on a wheeled photo stand along a 4 m track in the office.

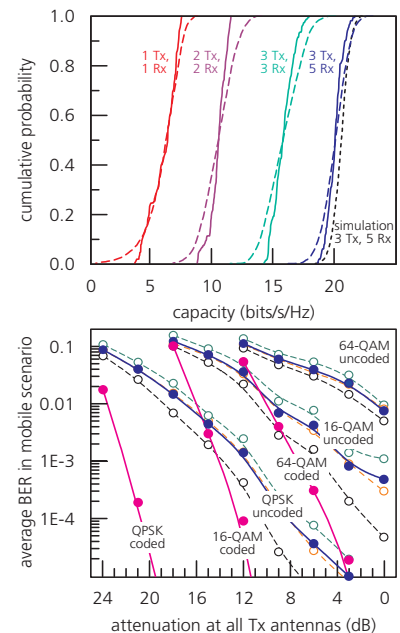


Fig. 3: Top: Measured cumulative distribution of the capacity for various antenna configurations (full lines: broad-band, dashed lines: narrow-band). Bottom: Measured average bit error rate in mobile scenario with and w/o coding for different modulation formats.

The transmitter and receiver units are shown in Fig. 1, as well as the spectrum and properly reconstructed 64-QAM constellations. Fig. 2 shows the mobile-transmit and fixed-receive antenna arrangement in the measurement scenario. Note that omni-directional and patch antennas are used at transmitter and receiver, respectively. The coded MIMO-OFDM scheme is robust against the multi-path effects resulting from that widely opened antenna apertures.

Fig. 3 shows measurement results. The built-in channel estimator is used to evaluate the statistical distribution of the capacity in the scenario. The results proof that broadband MIMO systems potentially provide high capacities more reliable than their narrow-band relatives, due to multi-path diversity. In the 64-QAM mode, substantial areas in the scenario were found, where the 1 Gbit/s link allows un-coded error rates well below 1 % and where no errors occurred after forward error correction with code rate $\frac{1}{2}$.

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FOOTNOTES

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- 51 Tel-Aviv University, IL
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- V. Jungnickel, A. Forck, Th. Haustein, St. Schiffermüller, C. v. Helmolt, W. Zirwas (Siemens AG), **Aufwandsarmes Verfahren zur Datenübertragung in frequenzselektiven Kanälen mit mehreren Sendern und Empfängern und Funkübertragungssystem** (Low-complexity method for data transmission in frequency-selective channels with multiple transmitters and receivers and radio transmission system), DE 10 2004 035 018.3
- T. Tekin, M. Schlak, H.-P. Nolting, **Elektro-optisches Modul mit integrierten Bauelementen** (Electro-optical module with integrated devices), DE 10 2004 040 891.2-51
- M. Kautzner, K. Müller, A. Smolic, Th. Wiegand, **Codierschema für einen ein zeitlich veränderliches Graphikmodell darstellenden Datenstrom** (Coding Scheme for a data stream representing a time varying graphics model), DE 10 2004 049 156.9
- D. Marpe, H. Schwarz, Th. Wiegand, **Scalable video coding using a multi-layer MCTF approach**, US 60/619,457
- S. Pastoor, R. de la Barré, **Verfahren zur autostereoskopischen Erzeugung von dreidimensionalen Bildinformationen aus gerasterten Subpixelauszügen und Anordnung zur Verfahrensdurchführung** (Method for generating autostereoscopic three-dimensional images from rastered sub-pixel components and device for carrying out said method), DE 10 2004 059 729.4
- D. Marpe, H. Schwarz, Th. Wiegand, **Video Encoder and Method for Encoding a Video Signal**, US 11/012,631
- D. Schmidt, R. Steingrüber, A. Seeger, **Elektronische Schaltungsanordnung mit Kontaktlöchern und Verfahren zur Herstellung** (Electric circuit layout with viaholes and their fabrication process), DE 10 2005 011 617.5

AWARDS

T. Haustein, A. Forck, H. Gaebler, C.v. Helmolt, V. Jungnickel, U. Krueger, **Best paper award** from the **PIMRC 2004** program committee (15th IEEE Internat. Symp. on Personal, Indoor and Mobile Radio Comm.) for the paper "Implementation of Adaptive Channel Inversion in a Real-Time MIMO System".

K. Hopf, **Deutscher Multimedia Award 2004** (nominated for Short List), Free2C 3D-Kiosk mit Handinteraktion, Berlin, June 2004.

I. Keller, ranked in 2nd place at **Business-Plan-Wettbewerb Berlin Brandenburg** f. Spin-off-concept "Visapix", February 2004

I. Keller, ranked in 1st place at **Business-Plan-Wettbewerb des BMWA "Multimedia"** f. Spin-off-concept "Visapix", September 2004

R. Ludwig, S. Ferber, C. Börner, C. Schubert, C. Schmidt, J. Berger, M. Kroh, E. Hilliger, V. Marembert, H.G. Weber, **Best paper award** from the **OECC 2004** (OptoElectronics and Communications Conf., Yokohama (JP)) for the paper "160 Gb/s DPSK transmission system with high long-term stability", July 2004

D. Marpe, H. Schwarz, Th. Wiegand, **Best Patent Award 2004** of the Association of the Friends of the HHI for the patent "Apparatus and methods for entropy-encoding or entropy-decoding using an initialization of context variables" applicated in 2003, Berlin, Dec. 2004.

D. Marpe, H. Schwarz, T. Wiegand, **Joseph von Fraunhofer Prize 2004** for outstanding scientific achievements in solving application-related problems, Dresden, October 2004.

D. Marpe, H. Schwarz, T. Wiegand, **Best paper award 2004** of the ITG (Information Technology Society) in the Association for Electrical, Electronic & Information Technologies (VDE) for the paper "Context-Based Adaptive Binary Arithmetic Coding in the H.264/AVC Video Compression Standard", published in IEEE Transactions on Circ. and Syst. for Video Technology, vol. 13 (2003), no. 7, pp. 620–636.

Y. Chang, **Award for the best Diploma Theses 2004** of the Elektrotechnischer Verein Berlin-Brandenburg for the Diploma Theses "Design and Analysis of the MIMO Rake Receiver", TU Berlin, Fakultät IV (Elektrotechnik und Informatik), Institut für Telekommunikationssysteme.

DOCTORATE THESES

C. Schmidt-Langhorst, **Optical Sampling of High Bit Rate Optical Data Signals**, TU Berlin, Fakultät II - Mathematik u. Naturwissenschaften, Prof. Dr. H.-J. Eichler, Prof. Dr. H.-G. Weber.

C. Schubert, **Interferometric Gates for All-Optical Signal Processing**, TU Berlin, Fakultät II – Mathematik und Naturwissenschaften, Prof. Dr. H.J. Eichler, Prof. Dr. H.G. Weber.

T. Tekin, **Monolithically Integrated Gain Shifted Mach-Zehnder Interferometer for All-Optical Demultiplexing**, TU Berlin, Fakultät IV – Elektrotechnik und Informatik, Prof. Dr. K. Petermann, Prof. Dr. H.-G. Weber.

S. Bischoff, **Konstruktion einer Suchmaschine für segmentierte Bilder, die speziell durch interpretierte Graphen beschrieben werden (Construction of an image retrieval system for segmented images, described by labelled graphs)**, TU Berlin, 2005, Fakultät IV – Elektrotechnik und Informatik, Prof. Dr. F. Wysotzki, Prof. Dr. T. Sikora.

E. Jorswieck, **Unified approach for optimisation of single-user and multi-user multiple-input multiple-output wireless systems**, TU Berlin, Fakultät IV – Elektrotechnik und Informatik, Prof. Dr. H. Boche (TUB), Prof. Dr. B. Ottersten (KTH).

DIPLOMA THESES

Y. Chang, **Design and Analysis of the MIMO Rake Receiver**, TU Berlin, Fakultät IV (Elektrotechnik und Informatik), Institut für Telekommunikationssysteme. Supervisor at HHI: V. Jungnickel. (Preis des Elektrotechnischen Vereins Berlin-Brandenburg 2004 für die beste Diplomarbeit).

H. Chen, **Untersuchung von MIMO-Systemen auf der Basis von Ein- und Mehrträger-Kodemultiplex**, TU Berlin, Fakultät IV (Elektrotechnik und Informatik), Institut für Telekommunikationssysteme. Supervisor at HHI: V. Jungnickel.

T. Eggert, **Vergleich von S-Band-Raman-Verstärkern und S-Band-EDFAs in 40 GBit/s WDM-Systemen**, FHTW Berlin. Supervisor at HHI: E. Schulze.

G. Istoc, **Aufbau und Untersuchung eines reziproken MIMO Systems**, TU Berlin, Fakultät IV (Elektrotechnik und Informatik), Institut für Telekommunikationssysteme. Supervisor at HHI: U. Krüger.

M. Kautzner, **Effiziente Codierung zeitlich veränderlicher 3D-Drahtgittermodelle zur Verwendung für Free Viewpoint Video Szenarien**, TU Ilmenau, Fakultät für Elektrotechnik und Informationstechnik. Supervisor at HHI: K. Müller.

A. Liedtke, **Untersuchung von WDM-Systemen mit bidirektionaler Übertragung und verteilter Raman-Verstärkung**, Fachhochschule Oldenburg, Wilhelmshaven. Supervisor at HHI: E. Schulze.

D. Maljevic, **Optimierung der Facettenbeschichtung von Halbleiterlasern und deren Charakterisierung**, Technische Fachhochschule Berlin (TFH), Fachbereich II Mathematik – Physik – Chemie. Supervisor at HHI: R. Molt.

A. Riechers, **3-D-Szenen- und Gesichtsmodellierung sowie Animation mit MPEG-4 BIFS**, TFH Berlin, Medieninformatik. Supervisor at HHI: P. Eisert.

J.-L. Rouvière, **Dynamic control of transient effects in Raman amplifiers**, EST Ecole Nationale Supérieure des Télécommunications, France. Supervisor at HHI: R. Freund.

S. Thiebes, **Synthese von Gesichtsbewegungen durch Analyse von Sprache**, HU Berlin, Institut für Informatik. Supervisor at HHI: P. Eisert.

A. Warnke, **Untersuchung des WDM-Übertragungsverhaltens Raman-verstärkter Faserstrecken mit unidirektionalen, bidirektionalen und zweistufigen Pumpanordnungen**, FHTW Berlin. Supervisor at HHI: E. Schulze.

A. Weidlich, **Experimenteller Vergleich von zwei Hilfesystemen für Microsoft Excel nach Usabilitykriterien**, FU Berlin, FB 12 (Erziehungswissenschaften und Psychologie). Supervisor at HHI: J. Faber.

Y. Zhang, **Optoelektronische Charakterisierung von wellenleiter-integrierten InGaAs-Photodioden im Frequenzbereich bis 110 GHz**, Technische Fachhochschule Berlin (TFH), FB VII. Supervisor at HHI: A. Beling.

L. Ziskel, **Hochauflösende 3D-Rekonstruktion von Objekten aus kalibrierten Einzelansichten**, TU Berlin, Fakultät IV – Elektrotechnik und Informatik. Supervisor at HHI: P. Eisert.

GRADUATE THESES

P. Allwardt, **Entwicklung und Validierung eines hierarchischen prädiktiven Schätzverfahrens zur Generierung von Mosaiken als Superresolution**, TU Berlin, Fakultät IV (Elektrotechnik und Informatik). Supervisor at HHI: A. Smolic.

P. Merkle, **Entwicklung eines Octree-Verfahrens zur 3D-Volumenrekonstruktion auf Voxelbasis**, TU Berlin, Fakultät IV (Elektrotechnik und Informatik). Supervisor at HHI: A. Smolic.

J. Shen, **Investigations on the Basis of an SNR-Scalable Extension of H.264/AVC**, TU Berlin, Fakultät IV (Elektrotechnik und Informatik), Institut für Telekommunikationssysteme. Supervisors at HHI: D. Marpe, H. Schwarz.

H. Chen, **Digitale Abwärtsmischung für ein breitbandiges MIMO-OFDM System**, TU Berlin, Fakultät IV (Elektrotechnik und Informatik), Institut für Telekommunikationssysteme. Supervisor at HHI: V. Jungnickel.

LECTURES

H.-G. Bach, **Grundlagen der optoelektronischen Halbleiterbauelemente**, TU Berlin

H. Boche, **Digitale Mobilkommunikation I+II**, TU Berlin

H. Boche, **Mehrnutzerinformationstheorie**, TU Berlin

P. Eisert, **Visualisierung, Codierung und Übertragung virtueller 3D Welten**, TU Berlin

L. Ihlenburg, **Signale, Netzwerke und Systeme**, TU Berlin

V. Jungnickel, **MIMO Übertragungssysteme I+II**, TU Berlin

V. Jungnickel, **Adaptive Übertragungsverfahren**, TU Berlin

V. Jungnickel, **Echtzeitverarbeitung**, TU Berlin

I. Keller, **Klassifikationsverfahren in der Nachrichtenverarbeitung**, TU Berlin

P. Ndjiki-Nya, **Audio- und Bildsignalverarbeitung**, TFH Berlin

M. Schubert, **Raum-Zeit-Signalverarbeitung für die Mobilkommunikation**, TU Berlin

O. Schreer, **Stereobildverarbeitung in der Videokommunikation**, TU Berlin

O. Schreer, **3D Bildsynthese in der Videokommunikation**, TU Berlin

A. Smolic, **Entwicklungstendenzen der Multimediatechnik**, TU Berlin

P. Stammnitz, **Einführung in Kanalcodierungsverfahren**, TU Berlin

S. Stanczak, **Mehrnutzerdetektion für drahtlose Kommunikationssysteme**, TU Berlin

H.-G. Weber, **Grundlagen und Anwendungen der linearen und nichtlinearen Faseroptik**, TU Berlin

T. Wiegand, **Digital Image Communication**, TU Berlin

G. Wunder, **Statistische Signalverarbeitung, Detection and Estimation Theory**, TU Berlin

WORKSHOPS ORGANISED

Sino-German Symposium on Optical Communication Networks, Beijing CN), March

Key components for the optical access network, HHI Berlin, June

BMBF Workshop Next Generation Networks, Statusseminar MultiTeraNet, HHI Berlin, July

2nd VISNET General Meeting, HHI Berlin, July

European Leica Beamwriter Users Meeting (ELBUM), Rotterdam, NL, September

3D-TV Workshop on Acquisition, Scene Representation and Coding, HHI Berlin, November

CONTRIBUTIONS TO EXHIBITIONS

CeBIT 2004, Hanover, February/March:

3D Kiosk-System

Mixed Reality PC Working Place

MPEG7 Video Retrieval

Mobile Services for Citizens – the Office in a Box

3D Imedia, 3D Scene-Reconstruction for interaktive Media

H.264/AVC – Adaptive End-To-End Internet Streaming Solution

Immersive Meeting Point (im.point)

MPEG-4 Facial Animation

NAB 2004, Las Vegas (USA), March:

H.264/AVC Broadcasting via DVB-T

Laser Optik Berlin 2004, March:

10 Gb/s transmission system using 1.55 μ m VCSEL and 10 km standard single mode fibre

FKTG 2004, Koblenz, May:

Cylindrical Multi Projection

Lange Nacht der Wissenschaften, Berlin, June:

3D Kiosk-System

Mixed Reality PC Working Place

3D-Szenen-Rekonstruktion für interaktive Medien

Das Handy als Bildtelefon

Interaktive Navigation durch reale Welten

3D-Display Innovationsforum im IOF, Jena, July:

Free2C 3D-Display with hand interaction

Tag der offenen Tür der Bundesregierung im BMBF, Berlin, August:

Mixed Reality PC Working Place

ECOC 2004, Stockholm, September:

Demonstration of 160 Gbit/s DPSK transmission over a 160 km fiber link (jointly with U²t and SHF)

IBC 2004, Amsterdam, September:

Cylindrical Multi Projection

DVB-Compatible 3D-TV System

H.264/AVC & Streaming Technologies for DVB-H

HiCon³² Video Converter

Interactive Panoramas for Virtual Tours

VISNET – Networked Audiovisual Media Technologies

VDE Kongress 2004, Berlin, October

3D Kiosk-System

Augmented Reality and Free Viewpoint Video

MPEG-4 Gesichtsanimation und interaktive 360° Panoramen

EVA 2004, Berlin, November:

3D Kiosk-System

COMMITTEE ACTIVITIES

Standardisation Committees

DIN
DVB Technical Module: Member
DVB-AVP: Member
DVB-H: Member
DVB-CMBS: Member
IPC-Standard (J-STD-040, "Optoelectronic Assembly and Packaging Technology, OPTO-ELECTRONICS ASSEMBLY SUBCOMMITTEE, 5–25"): Member
ISO/MPEG
ISO/MPEG AHG: Chair
ITU-T: SG 16, Associated Rapporteur
JVT: Co-Chair
3GPP TSG-SA4 31th meeting – Montreal (CA): H.264/AVC streaming with retransmission and rate adaptation, Tdoc S4-040287: member
3GPP TSG-SA4 33th meeting – Helsinki (FI): Adaptive Streaming Testbed using PSS Rel.6 Features: member
14th ISMA Forum Santa Clara – Demonstration of H.264/AVC streaming with retransmission and rate adaptation: member

Research Program Committees

IST (Inform. Society Technologies): Evaluator
3D Display Innovationsforum BMBF: Co-Chair

Conference and Workshop Program Committees

Broad Band Europe, Brügge (BE), 2004
ECOC Technical Program Committee: Member
12th European Conference on Integrated Optics (ECIO '05), 2005, Grenoble (FR): Program Committee Member
European Leica Beamwriter Users Meeting: Chairman
Human Factors in Telecommunications: Permanent Steering Committee
IEEE Wireless Communications and Networking Conference (WCNC): Program Committee
International Picture Coding Symposium: Steering and Program Committee Member
International Zürich Seminar: Program Committee
ITG Workshop on Smart Antennas: Program Committee
Münchner Kreis, Congress "Protected or Dependent? Living in a Digital Environment": Chairman and Head of Program Committee
OFC Technical Program Committee: Member
Packet Video Workshop: Program Committee
SPIE Conf. on Three-dimensional TV, Video and Display: Program Committee

Editorial Boards

Springer Verlag Berlin, Heidelberg, Series "Photonics": Co-Editor
Springer Verlag Berlin, Heidelberg, Series "Optical Fiber Communication": Co-Editor

Other Committees

Arbeitskreis Integrierte Optik (AkIO): Member
Competence Center for the Application of Nanostructures in Optoelectronics (NanOp): Member of Executive Board
FKTG, Urteil-Preis-Komitee: Curatorship
ITG, FA 3.1 Fernstechnik und elektronische Medien: Chairman
ITG, FG 3.1.2 Digitale Bildcodierung: Chairman
ITG, FA 5.1 Informations- und Systemtheorie: Member
ITG FG 5.2.5 Access- und Inhouse-Netze: Member
ITG, FA 5.3 Optische Nachrichtentechnik: Member
ITG, FG 5.3.1 Modellierung photonischer Komponenten und Systeme: Committee Member
ITG, FG 5.3.2 Photonische Aufbau- und Verbindungstechnik: Chairman
ITG, FG 5.3.3 Photonische Netze: Member
Münchner Kreis, Supranational Association for Communications Research: Research Committee
OPTEC BB, Berlin: Member

EXCHANGE PROGRAM

Scientists Visiting HHI

H. Chen, Southeastern University Nanjing, Nanjing (CN), financed by DAAD, for one year
F. Futami, Fujitsu Laboratories Ltd., Kawasaki (JP), financed by Fujitsu, for two weeks
J. Kim, Yonsei-University, Seoul (KR), financed by DAAD, for four months
C. Möller, NL Nanosemiconductor GmbH, Dortmund (DE), financed by NL Nanosemiconductor GmbH, for one month
K. Schulze, Universidad Politecnica de Valencia, Valencia (ES), financed by Universidad Valencia, for six months
B. Schumitsch, Stanford University, Stanford (USA), financed by Fulbright – Kommission, for seven months, and financed by Anderson, Tackmann & Co. PLC, for three months
M. Vu Doan, Institute of Material Science, NCST, Hanoi (VN), for one week
S. Watanabe, Fujitsu Laboratories Ltd., Kawasaki (JP), financed by Fujitsu, for two weeks

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