Continuous wave terahertz systems exploiting 1.5 µm telecom technologies

B. Sartorius*, M. Schlak, D. Stanze, H. Roehle, H. Künzel, D. Schmidt, H.-G. Bach, R. Kunkel, and M. Schell

Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institut,
Einsteinufer 37, 10587 Berlin, Germany
**bernd.sartorius@hhi.fraunhofer.de*

Abstract: A fiber-assembled CW THz System operating at 1.5 µm is presented. High speed telecom photodiodes integrated with planar THz antennas serve as THz emitters with power up to 10 µW. Photoconductive antennas based on LT InGaAs/InAlAs multi-layer structures allow coherent detection. The system operates in a wide frequency range of 0.1 −1.6 THz.

OCIS codes: (300.6495) Spectroscopy, terahertz; (120.4290) Nondestructive testing.

References and links

1. M. Tonouchi, "„Cutting-edge terahertz technology," Nat. Photonics **1**(2), 97–105 (2007).
2. A. J. Deninger, T. Göbel, D. Schönherr, T. Kinder, A. Roggenbuck, M. Köberle, F. Lison, T. Müller-Wirts, and P. Meissner, "Precisely tunable continuous-wave terahertz source with interferometric frequency control," Rev. Sci. Instrum. **79**(4), 044702 (2008).
3. www.emcore.com/fiber_optics
4. M. Martin, J. Mangeney, P. Crozat, Y. Chassagneux, R. Colombelli, N. Zerounian, L. Vivien, and K. Blary, "Gigahertz modulation of tunable terahertz radiation from photomixers driven at telecom wavelengths," Appl. Phys. Lett. **93**(13), 131112 (2008).
5. H. Ito, F. Nakajima, T. Furuta, and T. Ishibashi, "Continuous THz-wave generation using antenna-integrated uni-travelling-carrier photodiodes," Semicond. Sci. Technol. **20**(7), 191–198 (2005).
6. C. C. Renaud, M. Robertson, R. Firth, P. J. Cannard, R. Moore, and A. J. Seeds, "A high responsivity, broadband waveguide uni-travelling carrier photodiode," Proc. SPIE **6194**, 61940C (2006).
7. H-.G. Bach; A. Beling; G. G. Mekonnen; R. Kunkel; D. Schmidt; W. Ebert; A. Seeger; M. Stollberg; and W. Schlaak, "InP-Based Waveguide-Integrated Photodetector With 100-GHz Bandwidth," IEEE J. Sel. Top. Quantum Electron. **10**, 668–672 (2004).
8. B. Sartorius, H. Roehle, H. Künzel, J. Böttcher, M. Schlak, D. Stanze, H. Venghaus, and M. Schell, "All-fiber terahertz time-domain spectrometer operating at 1.5 microm telecom wavelengths," Opt. Express **16**(13), 9565–9570 (2008).
9. R. J. Foltynowicz and R. E. Allman, "Terahertz Time-Domain Spectroscopy of Atmospheric Water Vapor From 0.4 to 2.7 THz," Sandia Report, October 2005.

1. Introduction

Terahertz spectroscopy promises attractive applications in various fields such as security, medicine, science, and non-destructive material testing [1]. THz systems, however, are presently bulky, expensive, and often need cryogenic cooling, thus preventing broader practical application. Exploiting mature telecom technologies is one promising way towards achieving compact and low cost Terahertz systems. This paper focuses on continuous wave (CW) THz systems and their improvements by using telecom technologies.

The big advantage of CW THz generation vs. time domain (TD) THz generation is its simple optical source. Only two single mode CW lasers are needed, with at least one of them tunable. Especially at the telecom wavelength 1.5 µm, a large variety of compact, tunable and low cost semiconductor lasers is already available.

The challenge for CW systems, on the other hand, is to achieve sufficient THz power. Photoconductive antennas (PCAs) work well in pulsed systems with high peak power at a moderate repetition rate. However, they have up to now had severe limitations as photomixer emitters in CW operation. Using LT-GaAs photomixers, THz power of 0.2 µW at 100 GHz is

#111168 - $15.00 USD Received 12 May 2009; revised 3 Jul 2009; accepted 15 Jul 2009; published 10 Aug 2009

reported in [2]. Emcore developed ErAs:GaAs based photomixers, also for operation at 800 nm, and achieved 4 µW at 100 GHz [3].

Ion irradiated InGaAs has been developed and evaluated as a possible photomixer for use at the telecom wavelength of 1550 nm [4]. However, much less THz power compared to the 800 nm solution of [2,3] was reported (45 nW at 100 GHz), detectable only with cooled bolometers. Obviously, the exploitation of telecom technologies for CW THz systems requires improved THz emitters.

2. Development of 1.5 µm operated telecom based emitters

Fortunately, telecom technology offers alternative devices for THz generation: photodiodes with integrated antennas. While speed up of photoconductors is achieved by incorporating fast recombination centers - which at the same time reduce the efficiency of the photo effect - the speed of the diodes is limited by the transit time through the pin structure. In pioneering work, NTT in Japan developed the Uni-Traveling-Carrier (UTC) photodiode structure, where only the fast electrons - not the slow holes - limit the device speed [5]. They were able to demonstrate THz emission of about 2 µW at 1 THz. By optimizing the UTC concept and combining it with resonant antennas, other institutions have published THz emission powers of more than 100 µW at 400 GHz [6]. Photodiode-based emitters are obviously the superior devices for optoelectronic CW systems.

We use another approach for high speed photodiodes: waveguide integrated devices. Using standard surface illuminated pin photodiodes (Fig. 1a) and minimizing the thickness of the active layer leads to a higher speed - but on the other hand directly reduces the absorption and the efficiency. Waveguide integrated photodiodes (Fig. 1b), however behave like side illuminated devices, and high absorption even for thin active layers can be achieved. High speed and high efficiency can therefore be combined.

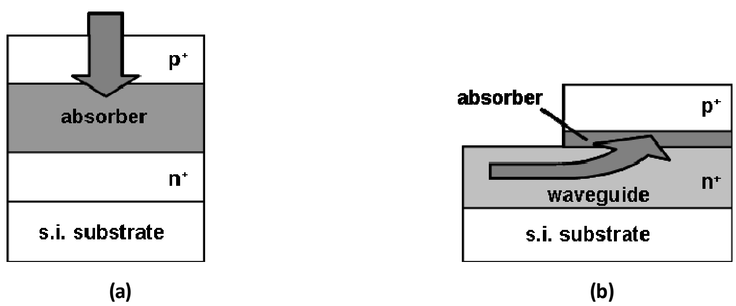

Fig. 1. Scheme of photodiode structures: (a) surface illuminated, (b) waveguide integrated

In the HHI waveguide integrated photodiodes have already been developed for telecom applications in the 1.5 µm wavelength range. These devices belong to the fastest worldwide, and they are suitable for additional antenna integration. The scheme of the HHI photodiode is shown in Fig. 2. The InGaAs/InGaAsP heterostructure is grown on semi-insulating InP substrates using MOVPE. The active layer has an effective thickness of about 0.3 µm. The waveguide includes a taper (Fig. 2a) for improved fiber-chip coupling. The processed photodiodes have a length of 20 µm and a width of 7 µm respectively, and are located above the waveguide. The control light is injected at the facet into the tapered structure and directed by the waveguide to the diode. There it is coupled into the active layer and absorbed. Further details on structure and processing are given in [7].

#111168 - $15.00 USD Received 12 May 2009; revised 3 Jul 2009; accepted 15 Jul 2009; published 10 Aug 2009

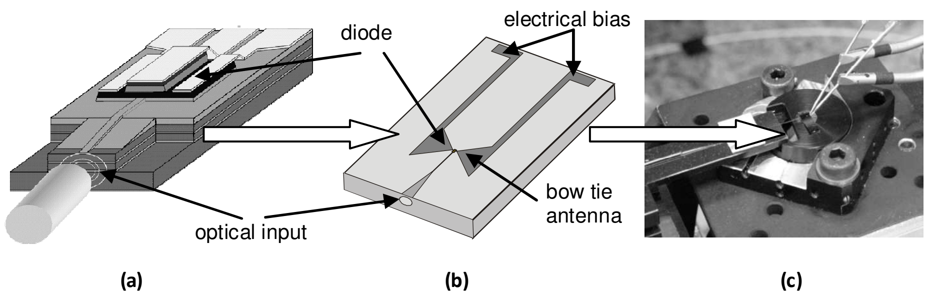

Fig. 2. Photodiode (win-PDA) THz emitter: (a) scheme, (b) antenna, (c) contacted chip on lens

On top of the photodiode, on an isolating nitride layer, bow tie antennas (size 160 µm, Fig. 2b), were integrated with electrical contacts to the diode. The bow tie antennas radiate in defined linear polarization, and the emission spectrum is broadband. We call this new device combining a waveguide integrated PhotoDiode with a THz Antenna "win-PDA".

The photodiode chips are cleaved, and the input facets are anti-reflection coated. As a first device test, the emission power of the win-PDA was measured using a manufacturer-calibrated Golay cell. At 200 GHz and for an optical input power of 30 mW, a THz output power of 10 µW was achieved. This is below the results for the best UTC devices but clearly better than the photoconductive antenna based photomixers. Thus the design and technology of the first wafer were successful, and the devices can be used as THz emitters.

3. Development of 1.5 µm operated coherent receivers

Photodiodes with integrated antennas (PDAs) have proved to be improved emitters. However, a completely photodiode based THz system is not feasible since these devices are not suitable for coherent detection. Illuminated photodiodes emit a current and voltage output signal even without a THz field applied via the antenna, and thus a mixing effect similar as in the photoconductive antennas cannot be achieved. On the receiver side PCAs are indispensible for coherent detection. The problem is that the commonly available LT GaAs PCAs work only for wavelengths in the 800 nm range, while PDA based emitters have so far only been developed for 1.5 µm operation. Therefore, all photodiode based emitters have been used with incoherent detection by means of Golay cells or bolometers. The full benefit of PDA emitters can only be exploited once coherent receivers for 1.5 µm operation become available.

In HHI the fundamental problem of LT (200°C) MBE grown InGaAs on InP, namely the high dark conductivity, has recently been solved. Two techniques were combined: First, conventional compensation of the electron concentration by balanced doping with Be acceptors. Second, in a novel attempt, very thin (12 nm) photoconductive layers were embedded between InAlAs layers with higher bandgap (transparent for 1.5 µm). The essential feature of the InAlAs exploited here is the existence of deep trapping centers. The residual electrons are captured by the InAlAs, resulting in a sheet resistivity up to 10^6 Ω/sq.

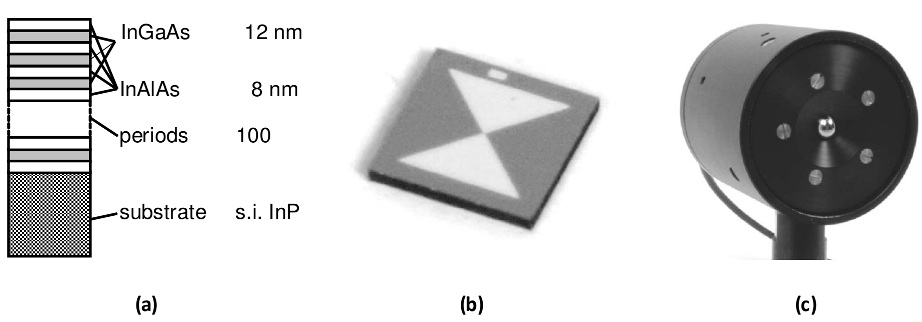

Fig. 3. Coherent photoconductive receiver: (a) heterostructure, (b) antenna chip, (c) fiber coupled module

#111168 - $15.00 USD Received 12 May 2009; revised 3 Jul 2009; accepted 15 Jul 2009; published 10 Aug 2009

For achieving sufficient absorption a sequence of 100 periods of this layer structure has been grown (Fig. 3a). The performance of this material for operation up to 3 THz has already been demonstrated in time domain spectrometers with strip line emitters and dipole receivers [8]. For our photomixer application, we use the same material with one exception - bow tie antennas are used, similar to the diode emitter. The 90° bow ties are 3 mm long on 4x4 mm chips and the gap is 10x10 µm (Fig. 3b). These antenna chips are packaged into modules (Fig. 3c). A standard single mode fiber is fixed to the module. The excitation light can be launched via an FC/APC connector into the fiber and to the antenna, and the Si lens for coupling out the THz radiation can be seen on the front of the module. An SMA connector is available for measuring the photocurrent.

4. Assembly of CW system with photodiode emitter and coherent receiver

The developed components are being used for the assembly of a revolutionary CW system combining photodiode based emitters with coherent photoconductive receivers. The scheme of the setup is shown in Fig. 4. The win-PDAs are not packaged in this early stage of development, so we constructed a platform with an inserted silicon lens. The win-PDA chips can be positioned on the flat side of the lens with the antenna in the center. The optical fiber is adjusted to the tapered waveguide using piezo controllers. Needles are used to contact the antenna and to bias the photodiode with −2 V (photograph in Fig. 2c). The THz emission radiated by the win-PDA is coupled out of the chip by the Si lens and guided via a first PE lens, a mirror and a second PE lens to the coherent receiver module. The optical control signals in the 1.5 µm range are presently generated by two external cavity lasers (ECL). To boost the power of the signal, fiber amplifiers (not shown) are used. The optical control signal is split by a 3 dB coupler and guided via fibers to the win-PDA emitter on the platform and to the PCA receiver module. The emitter control signal is optically chopped to enable lock-in detection and the receiver path contains a fiber delay line needed for the coherent detection. Thus this system is completely assembled using fiber technology and the key devices - emitter, receiver, lasers - are telecom related products for 1.5 µm operation.

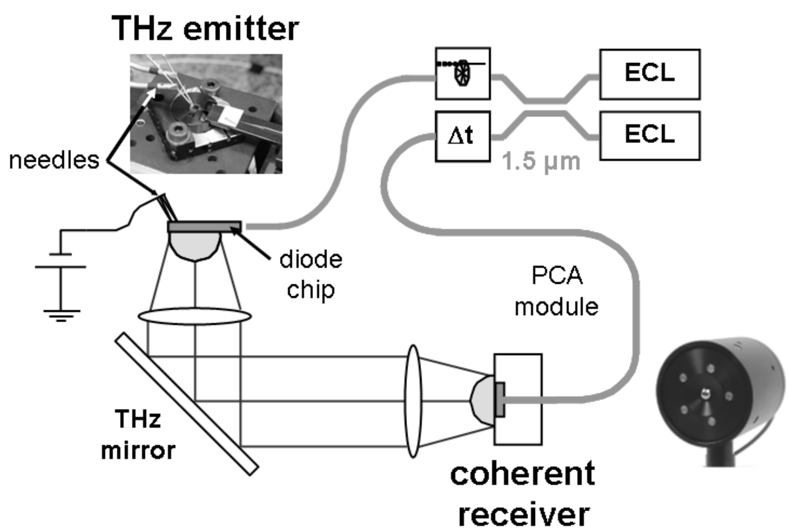

Fig. 4. Scheme of the CW THz setup

#111168 - $15.00 USD Received 12 May 2009; revised 3 Jul 2009; accepted 15 Jul 2009; published 10 Aug 2009

5. Performance of the assembled CW system

The bandwidth and performance of the setup were investigated by tuning the wavelength difference of the two ECLs and thus the beating frequency of the optical control signal. The optical power (measured in the fiber) was 30 mW at the emitter and 40 mW at the receiver. The photocurrent in the PC antenna (pre-amplified 10^8 V/A) was measured with the lock-in technique at 460 Hz modulation frequency. Integration and acquisition time were adapted to the signal amplitude: 30 ms / 100 ms at high amplitude (< 500 GHz), 300 ms / 1 s for low amplitude (> 1 THz), and 100 ms / 300 ms in the intermediate range. The tuning of the fiber delay line was computer controlled, and the amplitude of the receiver current versus time delay was measured. Figure 5a shows the according sine trace for several measurements within three hours. The traces match very well, indicating the excellent stability of the signal in amplitude and phase. Increasing the wavelength difference of the ECLs from 0.1 nm to 13 nm, adjusting the phase condition correctly, and recording the amplitude of the signal gives us the curve in Fig. 5b. The dips observed in the curve correspond almost exactly to the known absorption lines of water vapor in air. Our CW system operates up to 1.6 THz with a good signal to noise ratio, an excellent value for the first generation of our diode chips.

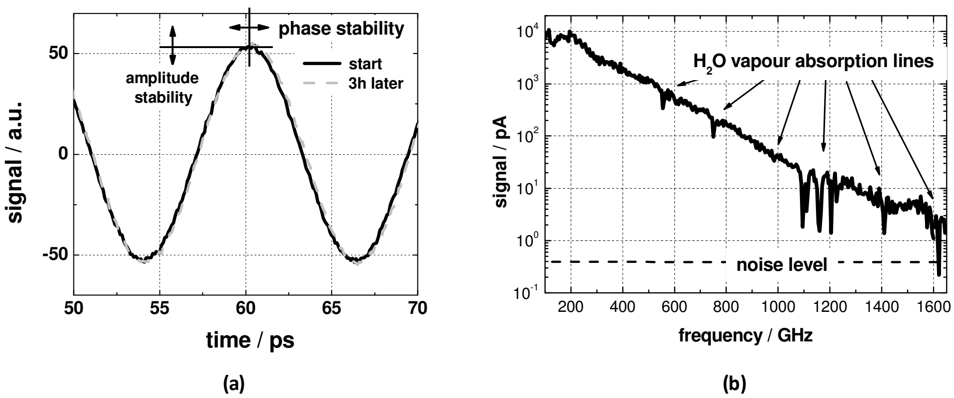

Fig. 5. THz signal: (a) measured vs. time delay, (b) measured vs. frequency (steps 5 GHz)

6. Application examples of the CW THz system

The first advantage of CW systems versus TD Systems is the higher spectral resolution. In theory the spectral resolution of a TD system is defined by the repetition rate of the pulse laser, which is around 100 MHz In practice the TDS resolution depends on the scanning range and amounts e.g. to 10 GHz for a scan range of 100 ps. In CW systems the line width of the lasers defines the resolution. For example our ECL's have a line width of less than 100 kHz. In our measurements, however, the smallest possible wavelength steps - 0.1 pm for these ECL's - limit the resolution to 12.5 MHz, still much better than the limit of TD systems. CW systems in addition allow focusing on the relevant frequency range. An example is given in Fig. 6. We analyzed the water vapor absorption lines between 1.1 and 1.25 THz in Fig. 6a. The total measuring time at a step width of 1 GHz is about one hour. The ECL wavelengths are currently set by computer control without additional monitoring, and the absolute frequency accuracy is given by the precision of the wavelength difference. We checked the absolute accuracy by adding literature values taken from [9]. All known lines could be detected, and the frequencies coincide well with the literature data. This verifies the excellent precision of the present system. Next (Fig. 6b.) we studied in more detail one selected absorption line at 556 GHz, using a step width of 250 MHz (measuring time three minutes). Similar highly resolved investigations as shown here are not possible by means of TD systems.

#111168 - $15.00 USD Received 12 May 2009; revised 3 Jul 2009; accepted 15 Jul 2009; published 10 Aug 2009

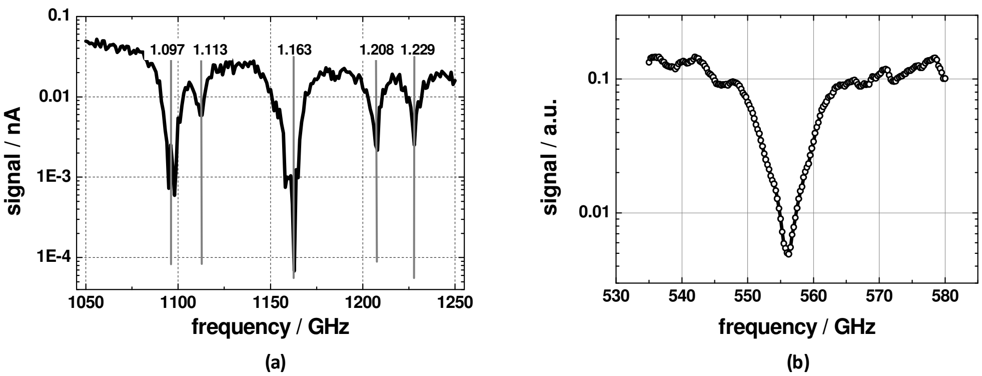

Fig. 6. Example for highly resolved spectroscopy: H_2O vapor absorption. (a) Step width 1 GHz, (b) 250 MHz

The second advantage of a CW system is the measurement speed if the significant information can be extracted by measurements at a fixed frequency. As an example we monitored the water vapor in air over a period of time by measuring the absorption at the significant frequency of 0.556 THz. The water vapor content was varied in the test tube by switching between streams of wet or dry nitrogen (Fig. 7a). The measured THz signal versus time is shown in Fig. 7b. The monitoring speed in this case is 100 ms, much faster than the gas exchange.

This proves the practical application of a gas monitoring technique that is even able to pierce tubes made of opaque plastic materials.

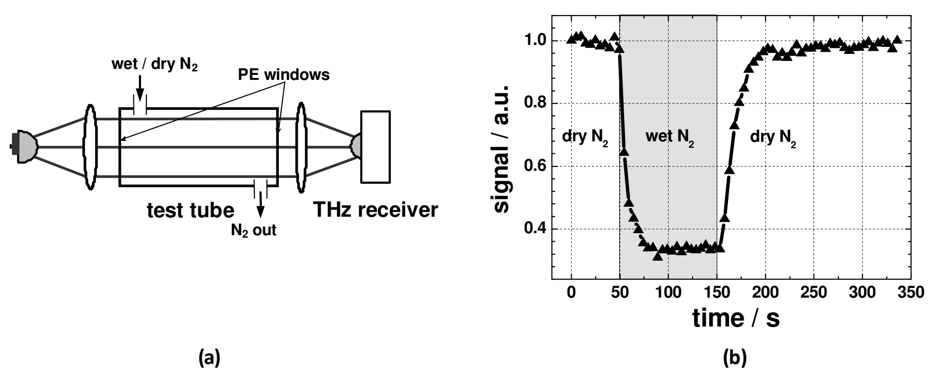

Fig. 7. Absorption versus time: (a) setup, (b) signal versus time

7. Summary and outlook

Size and costs of THz systems can be significantly reduced by replacing the pulsed lasers by continuous semiconductor lasers at the telecom wavelength 1.5 µm. The most critical components in a CW system are the emitters. Photoconductive antennas, while working excellently in TD systems, emit only low power in CW operation. High speed telecom photodiodes modified to integrate a THz antenna promise higher output power.

Combining these high THz output power photodiode antennas as emitters with sensitive coherent detection requires the operation of the both at the same wavelength. In this paper, we have presented the first CW system combining a photodiode antenna based emitter with a coherent photoconductive receiver. Both devices were fabricated at the HHI exploiting mature telecom InP technology. THz power up to 10 µW at 200 GHz was achieved with our first design iteration, and the operation of the system up to 1.6 THz was demonstrated. The

#111168 - $15.00 USD Received 12 May 2009; revised 3 Jul 2009; accepted 15 Jul 2009; published 10 Aug 2009

complete system was assembled using fiber technology. Our CW system will pave the way to flexible, robust and transportable systems at moderate cost - handheld in size and price.

#111168 - $15.00 USD Received 12 May 2009; revised 3 Jul 2009; accepted 15 Jul 2009; published 10 Aug 2009