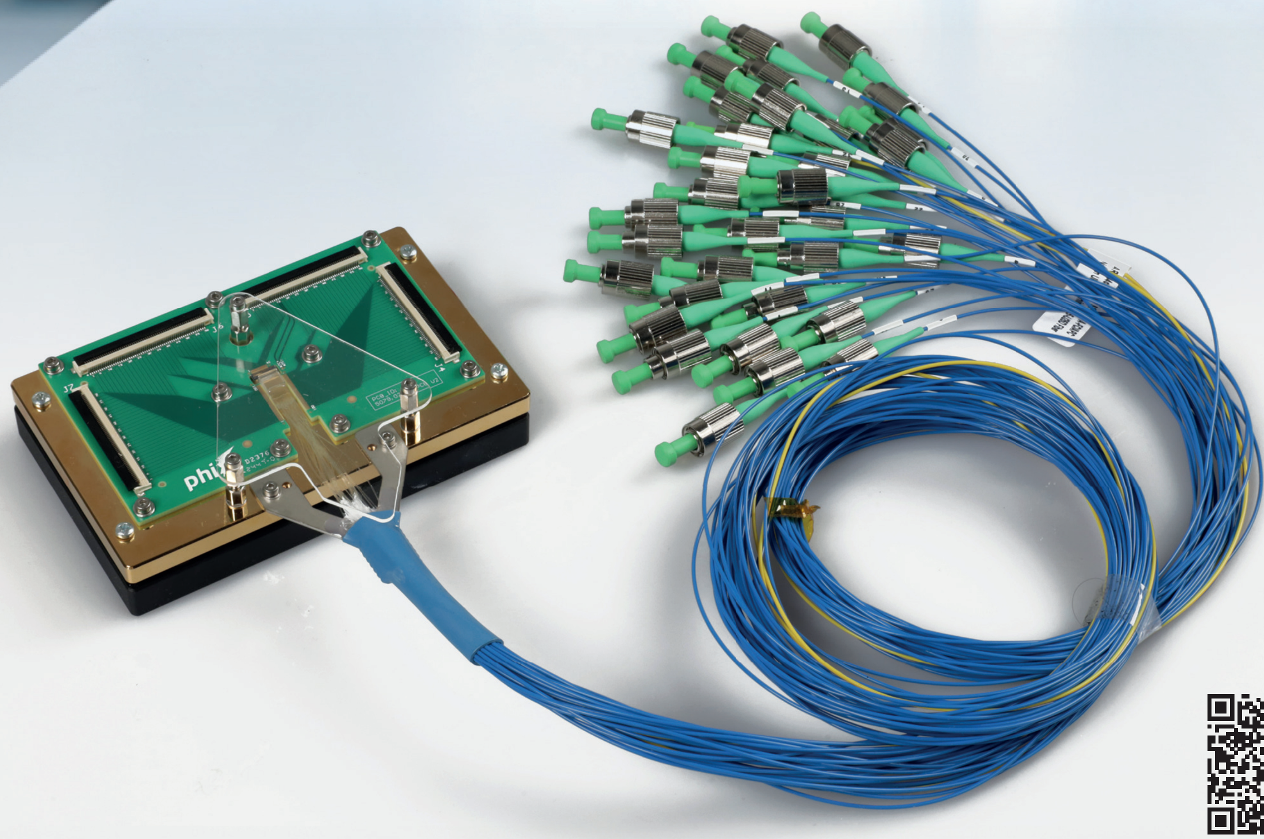
Fraunhofer HHI

APPLICATION NOTE

Photonic Neural Networks

Smarter Systems Through Light



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1 What are Photonic Neural Networks?

Photonic neural networks are neural networks that process information using light instead of electrical signals (see Figure 1). They mirror the familiar building blocks of digital neural networks, weighted connections, layers, feedback, and non-linear activation functions, but implement them with optical components. Interference, phase shifts, and modulation by light take over the role of numerical operations such as matrix multiplications, so that computation happens as the optical signal propagates through the network.

In contrast to conventional digital neural networks, which first convert optical signals into electrical form and then into digital samples, photonic neural networks can operate directly in the optical domain. They work with the full optical field, using both amplitude and phase, rather than just detected intensity values. As a result, they can preserve and exploit information that is often lost during photodetection and digitization, and can be particularly sensitive to subtle changes in an optical waveform.

At their core, photonic neural networks perform analog computing with light. Linear transformations are realized by passive optical circuits, while nonlinear optical elements provide the equivalent of activation functions, enabling genuinely nonlinear processing. With suitable training, such networks can approximate a wide variety of input–output relation of optical signals, from classification and regression tasks to complex signal transformations. This makes them attractive, for example, as optical pre processors placed in front of digital electronics, where they can generate features or partially compensate distortions before the signal is converted to the electrical domain. Photonic neural networks are therefore a promising building block wherever intelligent processing is desired directly in the optical layer.

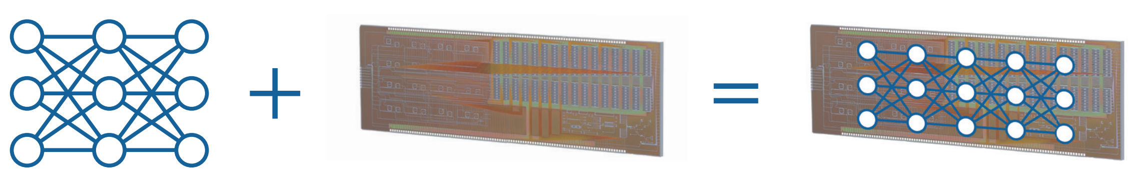


Figure 1: A Photonic Neural Network brings the power of (digital) neural networks into the optical domain.

2 The Platform for Photonic Neural Networks

At Fraunhofer HHI, photonic neural networks are realized on integrated photonic chips, bringing optical "intelligence" down to the size of a fingernail.

At Fraunhofer HHI we support multiple material platforms depending on the architecture (see Figure 2):

- Silicon nitride (SiN) is attractive for low-loss passive circuitry and broadband operation
- Lithium niobate offers fast and efficient modulation
- Indium phosphide (InP) allows the integration of active components such as lasers and amplifiers

Heterogeneous integration at Fraunhofer HHI makes it possible to combine these strengths on one platform, so that the photonic neural network can be tailored to specific performance and integration requirements.

The photonic neural network chip can be connected to your product, for instance via optical fibers. This allows straightforward coupling to existing fiber-based systems and test setups. Several input and output channels can be supported, enabling both single-input–single-output (SISO) and multiple-input–multiple-output (MIMO) configurations. In this way, the platform can address tasks ranging from the processing of a single optical signal to the parallel handling of multiple data streams. Eventually, our photonic neural networks are compatible with established optical infrastructure and packaging approaches.

Furthermore, photonic neural networks could also be implemented in free-space optics, for example in front of CMOS cameras.

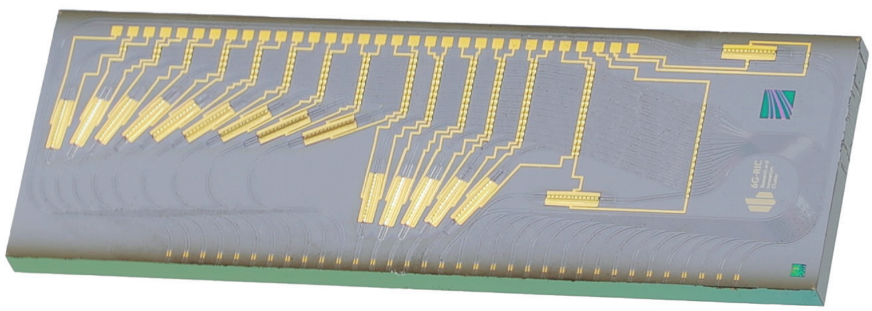


Figure 2: Example of an on-chip optical nonlinear activation function with 16 inputs and 16 outputs fabricated at Fraunhofer HHI.

3.1 Application 1 – Smart Monitoring

Problem

Modern reconfigurable optical networks rely on continuous insight into signal quality. Today, this typically requires complex measurement setups with coherent receivers and extensive digital signal processing. Such testbeds are costly, power hungry, and bulky, which limits where and how often true in-depth monitoring can be deployed in the field. Photonic neural networks offer a different route. By processing the signal directly in the optical domain, they operate at propagation speed and add virtually no latency.

Why Photonic Neural Networks

In the smart monitoring scenario, the photonic neural network acts as an optical pre-processor: it performs advanced analysis of the waveform and hands over a much slower, rich information signal to low-speed electronics (see Figure 3). In this way, tasks such as modulation format identification become possible without coherent detection and without running heavy digital signal processing. In addition, the parallel nature of integrated photonics opens the door to monitoring several wavelength channels at once.

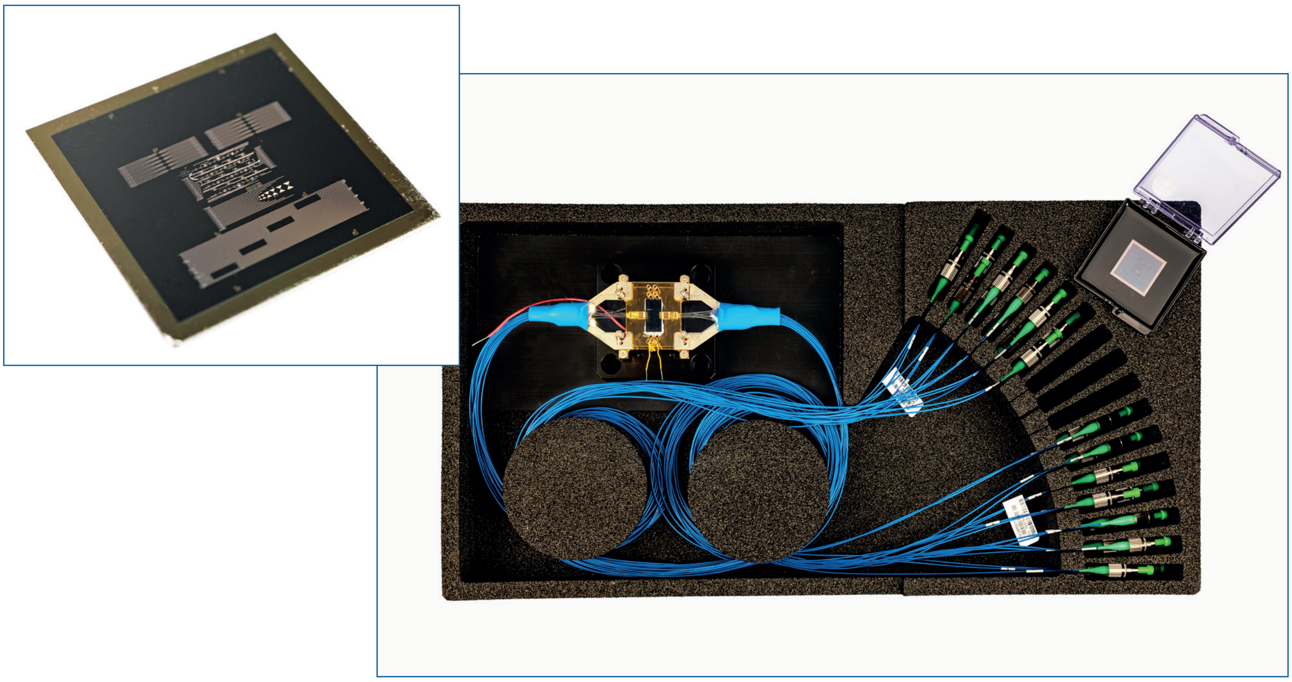


*Figure 3: (left) Image of the photonic reservoir chip.
(right) Packaged 4-port photonic reservoir acting as a compact, low-power feature generator for robust modulation format identification.*

Photonic Neural Networks

Smarter Systems Through Light

Photonic Neural Networks for Smart Monitoring

The team at HHI developed a photonic neural network which teamed up with a digital neural network. It was used to classify dual-polarized wavelength-division multiplexed (WDM) signals with symbol rates between 32 and 35 GBaud. Our photonic neural network successfully identified 4QAM and 16QAM modulation formats without the need for an expensive and bulky coherent receiver.

During a live demonstration lasting almost 7 hours, 400 individual identifications were performed. The modulation format identification accuracy remained at 100% throughout, with average classifier confidence levels of 85.3% for 4QAM and 76.9% for 16QAM (see Table 1).

These results indicate that photonic neural networks can serve as compact, low power building blocks for smart monitoring and sanity checking in reconfigurable optical networks.

	HHI Transmitter	
Duration	6.67 h	
No. Identifications	400	
Inference Interval	60 s	
Modulation Format	4QAM	16QAM
Mean Confidence Level	85.3 %	76.9%
Accuracy	100%	100%

Figure 4: The live demonstration ran for 6 hours and 40 minutes, during which we performed 400 individual identifications, each based on 40000 recorded samples. The classifier's output for each modulation format represents the confidence level of that format being present in the signal, which averaged 85.3% for 4QAM and 76.9% for 16QAM signals. The MFI accuracy remained at 100% throughout the whole length of the demonstration.

The Properties of the Photonic Neural Network

The core element of the hybrid architecture is a passive photonic reservoir implemented on a silicon-on-insulator (SOI) photonic integrated circuit shown in Figure 3. As the optical signal propagates through this reservoir, it is transformed into a high-dimensional set of optical features. These features are then detected with low-speed electronics and passed to a digital neural network that performs the final classification.

The reservoir itself requires no electrical power for operation; it is a purely passive circuit. In the demonstrated system, the photonic reservoir occupies an area of 7.0 mm × 3.7 mm, provides 16 inputs and 16 outputs, and therefore fits easily into standard integrated photonic platforms and packaging concepts.

Further Details

G. von Hünefeld et al., "Artificial Neural Network With Photonic Reservoir for Multiclass Modulation Format Identification," Journal of Lightwave Technology, vol. 43, no. 9, pp. 4175–4182, 2025, https://ieeexplore.ieee.org/document/10850751

3.2 Application 2 – Optical Signal Correction

Problem

In optical transmission links, linear distortions (e.g. dispersion) and nonlinear effects (e.g. Kerr effect) introduced by waveguides and components progressively degrade signal quality. Conventional correction is typically performed after detection using digital signal processing, which increases power consumption and system complexity and often requires coherent receivers.

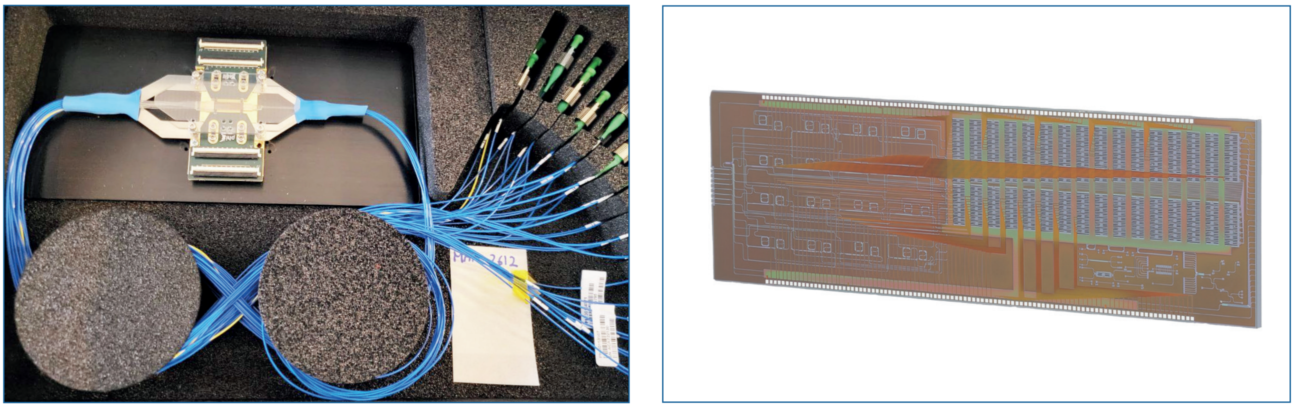
Why Photonic Neural Networks

Photonic neural networks enable signal correction directly in the optical domain, before detection. By leveraging the optical field information, photonic neural networks naturally process amplitude and phase information and can address linear and nonlinear distortions. This pre-detection correction capability allows the photonic neural network to function as an in-line optical signal corrector, compatible with WDM operation and suitable for deployment without a coherent receiver, while improving overall power efficiency.

Architecture and performance

The demonstrated optical signal correction relies on a photonic neural network that combines multiple neural network elements entirely in integrated photonics (see Figure 5). A four-port optical reservoir generates features from the time-dependent dynamics of the input signal. The reservoir output is processed by a programmable matrix multiplication. Both elements are implemented on the same silicon nitride chip. Nonlinear activation is provided by semiconductor optical amplifiers on an indium phosphide chip (see Figure 2 & 8).

Figure 5: (left) Packed photonic neural network layer, including 4×4 configuration corresponds to a photonic reservoir with 16 nodes, followed (on-chip) by a 16x16 optical matrix multiplication. (right) Microscopic image of the packaged chip.



In simulation, this architecture achieves more than a two-order-of-magnitude improvement in bit error rate for a 10 km transmission link affected by both linear and nonlinear distortions (see Figure 6).

Further Details

G. von Hünefeld et al., "Neuromorphic reservoir for nonlinear optical signal equalization," in Proc. SPIE, Physics and Simulation of Optoelectronic Devices XXXII, vol. 12880, paper 128800H, San Francisco, CA, USA, Mar. 11, 2024, https://doi.org/10.1117/12.3002627

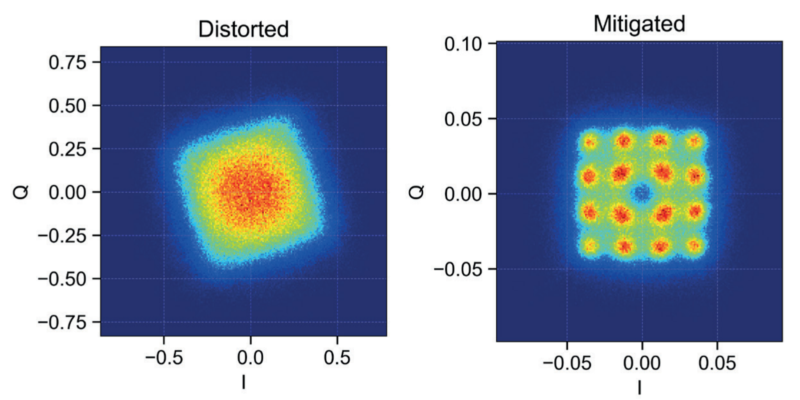


Figure 6: Simulation results show more than a two-order-of-magnitude improvement in BER for 10 km transmission links affected by both linear and nonlinear distortions.

4 Photonic Neural Networks Tailored to Your Application

Imagine your optical system not only transporting or measuring light but also interpreting it in real time. A photonic neural network can turn your optical front end into a trainable, task specific processor that works directly in the optical domain. Instead of treating light as something that must first be converted and digitized, it becomes the medium in which intelligent processing takes place.

A practical way to assess, whether your application is a good match, is to ask three questions:

- Is my information already in the optical domain? For example, in a fiber link, an optical sensor, a LiDAR front-end, or an imaging system.
- Do I want more information from this signal than I currently (can) extract? For example, using phase information without coherent detection. Here, the photonic neural network can act as a compact pre-processer before electronics. Eventually, improving sensitivity and enhancing robustness of classification & monitoring.
- Do I need to correct my signal from distortions? For example, distortions introduced by components, transmission channels, or reconfigurable network elements.

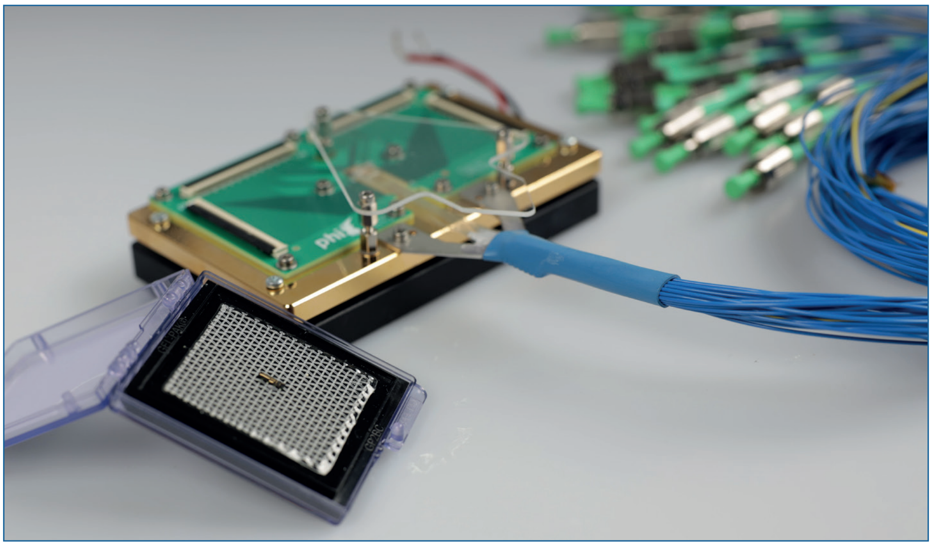


Figure 8: Packaged InP photonic chip offering 16 SOA-based activation functions

5 From idea to your Photonic Neural Network: HHI as your partner

Fraunhofer HHI can support you along the entire development path of a photonic neural network from the initial concept to a tailored evaluation kit. Figure 9 shows an example evaluation kit for your lab.

We do not stop at the algorithmic level. At HHI, the structure of the photonic neural network is developed, simulated, and designed to match your specific task, including the choice of material platform and architecture. Based on this design, we can fabricate the photonic integrated circuit in-house. This keeps the number of external interfaces low and helps maintain a coherent timeline from specification to first samples.

Around the photonic neural network chip, we design the required control environment. This may include electronics, control hardware, and suitable packaging, so that you receive a sample that can be integrated into your setup with low effort. Depending on the project, this can take the form of a chip-level solution or a more complete evaluation module that exposes clearly defined optical and electrical interfaces.

Software for controlling and training the photonic neural network is, of course, part of the package. We provide the tools needed to configure the device, to run experiments, and to train or adapt the underlying photonic neural network architecture to your data. In this way, you receive a coherent solution: a custom photonic neural network, realized as a practical evaluation platform, and supported by hardware and software that are designed to work together.

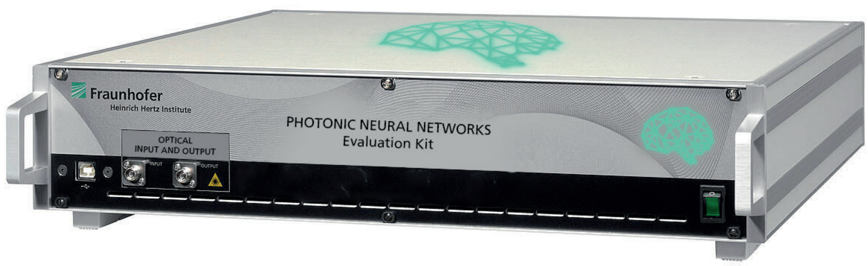


Figure 9: Illustration of a potential evaluation kit with one optical input and output. The 9inch rack box includes the packaged photonic neural network (e.g. Figure 5 left), its supporting electronics, and a communication interface. Customizations are possible such as number of input and output ports are possible.