A silicon photonic-electronic neural network that could enhance submarine transmission systems

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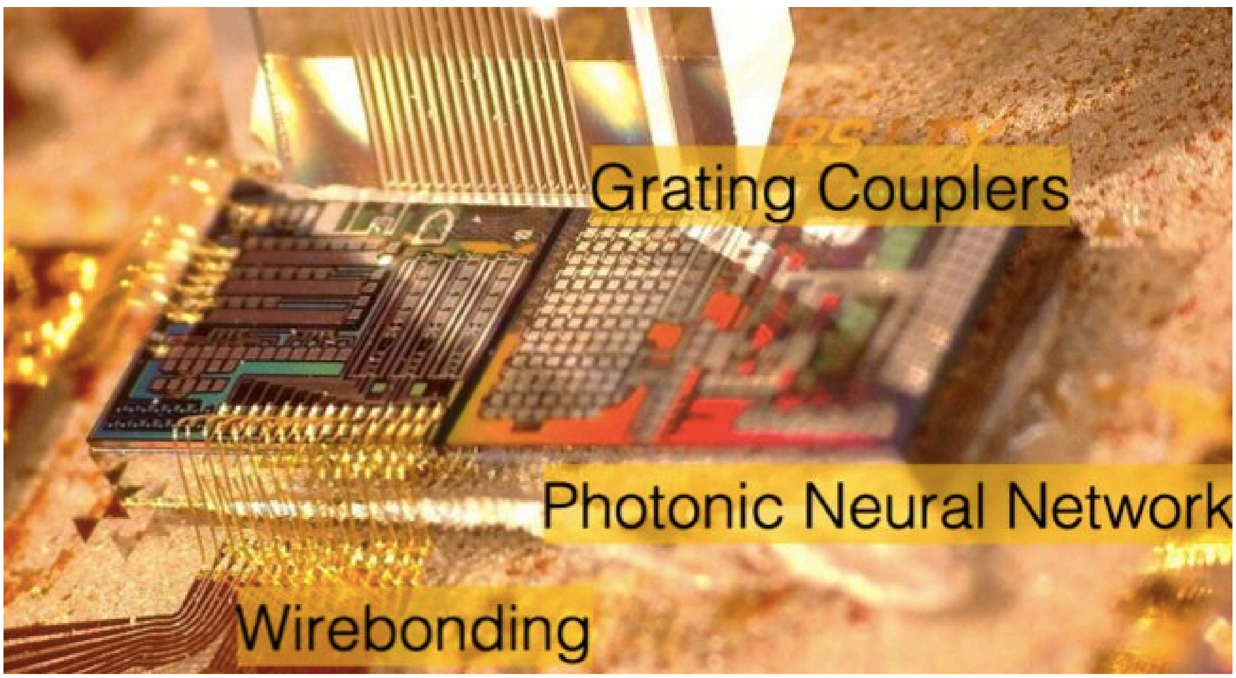

Credit: Huang et al.

We are currently witnessing an explosion of network traffic. Numerous emerging services and applications, such as cloud services, video streaming platforms and the Internet of Things (IOT), are further increasing the demand for high-capacity communications. Optical communication systems, technologies that transfer information optically using fibers, are the backbone of today's communication networks of fixed-line, wireless infrastructure and data centers.

Over the past decade, the growth of the internet was enabled by a technique known as digital signal processing (DSP), which can help to reduce transmission distortions. However, DSP is currently implemented using CMOS integrated circuits (ICs), thus it relies heavily on Moore's Law, which has approached its limits in terms of power dissipation, density and feasible engineering solutions.

As a result, distortions caused by a phenomenon known as fiber nonlinearity cannot be compensated by DSP, as this would require too much computation power and resources. Fiber nonlinearities remain the major limiting effect on long-distance transmission systems.

Researchers at Princeton Lightwave Lab and NEC Laboratory America have recently created a new neural network hardware that could help to overcome this limitation, compensating for the adverse effects of fiber nonlinearity. This neural network, presented in a paper published in *Nature Electronics*, is run on a silicon-based photonic-electronic system composing of a few neurons, which can, in principle, outperform commercial DSP chips in throughput, latency and energy use."

"The research on 'neuromorphic photonics' at Princeton began with a discovery by our supervisor, Prof. Paul Prucnal, and neuroscientist David Rosenbluth," Chaoran Huang, one of the researchers who carried out the study, told *Tech Xplore*. "These two researchers found that photonic devices and biological neurons are governed by identical differential equations, yet 'photonic neurons' have a time scale of roughly picosecond to nanosecond whereas biological neurons have a time scale of roughly one millisecond."

The previous work by Prof Prucnal and Rosenbluth inspired the team to start developing highly performing, photonics-based neuromorphic hardware. Ideally, this hardware would be able to execute artificial neural networks at a nanosecond scale, thus significantly faster than conventional electronics-based systems.

Subsequently, some of the researchers in the team created a new optical network-based architecture based on the broadcast-and-weight protocol. This promising architecture allowed them to build large-scale optical networks, comprised of photonic neurons and tunable micro-ring resonators, which implement the so-called synaptic weights. In this architecture, photonic neurons and micro-ring resonators are connected by optical waveguides on silicon chips.

"These advancements give our photonic neural network the scalability to execute real-world applications," Huang explained. "Since then, we've been looking for AI applications where photonics can outperform electronics. We and our collaborators in NEC Laboratory America's Optical Networking + Sensing Department created a photonic processor capable of processing high-speed optical communication signals, in order to solve the pressing limitations of DSP capacity in the post-Law Moore's Law age."

DSPs are hardware components that can be found inside numerous smart devices. Over the past few decades, DSPs have fueled the development of many systems connected to the internet. The upscaling of DSP implementations on CMOS semiconductor circuits, however, strongly relies on Moore's Law. This is a crucial limitation, as conventional semiconductors have now reached their limit in terms of power dissipation and density.

"DSP capacity may find it increasingly difficult to sustain the continuous exponential expansion of internet traffic in the post-Law Moore's Law age," Huang said. "We solve this problem using a neural network implemented in hardware on an integrated photonic chip enabled by silicon photonics, which can process optical signals in real-time i.e., predicting and compensating for fiber nonlinearities in over a 10,000 km trans-pacific submarine transmission link."

The photonic neural network developed by Huang and her colleagues is based on high-quality waveguides and photonic devices, such as photodetectors and modulators originally designed to be used in optical communications. This ultimately allows the network to support fiber communication rates, which could enable real-time processing using newly developed optical networks. The silicon neural network created by the researchers is also fully programmable and is based on the so-called broadcast-and-weight protocol, which was introduced in one of their previous papers.

"This protocol uses the concept of wavelength division multiplexing (WDM) to enable scalable interconnections between photonic neurons," Huang explained. "Neurons in this architecture produce optical signals with distinct wavelengths. These photonic neurons are multiplexed into a single waveguide and broadcast to all others. Weights are applied to signals encoded on multiple wavelengths using groups of tunable wavelength filters."

Credit: Huang et al.

The protocol proposed by the researchers alters the transmission of signals through a filter by tuning the filter along its transmission edge, essentially multiplying signals with a desired weight. The resulting 'weighted' signals are then sent to a photodetector that can receive signals of multiple wavelengths in parallel and sum them together.

The photocurrent generated during this initial process drives an optical modulator that converts electrical photocurrent into optical power. This means that in the team's photonic network, optical modulators take on nonlinear activation functions, serving as artificial neurons.

"Typically, the interconnectivity of neural networks is the source of most of the computational load," Huang said. "This problem can be addressed in two ways by our photonic-electronic neural network. First, weight addition operations can be performed in parallel and without requiring any logic operations. Thus, they exhibit distinct, favorable trends in terms of energy dissipation, latency, crosstalk, and bandwidth, when compared to electronic neuromorphic circuits."

In addition to performing weight addition operations in parallel, the network created by Huang and her colleagues has an improved interconnectivity, as it can carry many signals simultaneously. This is enabled by a process known as wavelength multiplexing.

"A network could support N additional neuron connections without adding any physical wires by associating each node with a color of light," Huang explained. "In electronic neuromorphic circuits, in contrast, one more neuron adds *N* more connections—a prohibitive situation if *N* is large."

Its unique qualities make the silicon photonic-electronic neural network ideal for creating large systems containing hundreds of artificial neurons on individual chips, using only a few interconnection waveguides. This could have notable implications for the creation of a variety of communication and processing devices.

"While there has been some impressive work on photonic neural networks (see recent papers in Nature here and here), these systems solve toy problems like recognizing digits)," Huang said. "Our work shows perhaps first practical demonstration of a photonic neural network for a task that is nontrivial and that has far-reaching consequences. In our recent paper, we showed how a neural network implemented in hardware on an integrated photonic chip enabled by silicon photonics can process optical signals in real-time."

In their paper, the team evaluated the potential of the new network they developed for reducing the adverse effects of fiber nonlinearity on the performance of a trans-pacific optical-fiber transmission system spread across 10,080 km. In their tests, they found that it could compensate for optical fiber nonlinearities and improve the quality factor of the signal produced by the system.

A characterizing feature of the network developed by Huang and her colleagues is that it utilizes high quality waveguides and photonic devices. This significantly enhances its performance, making it a promising solution to address the optical network capacity limits associated with the slowing down of Moore's Law.

In the future, the new neural network created by this team of researchers could help to enhance the performance of optical communication tools. So far, Huang and her colleagues only used their network to address signal distortions in a single wavelength channel. However, they believe that it could also be applied to multiple WDM optical fiber systems.

"We now plan to use this unique architecture to process multiple WDM channel in parallel and in the optical domain," Huang said. "This would result in bandwidth increase over THz, significantly beyond the capability of DSP. This unique feature help with inter-channel nonlinear compensation in a WDM communication system, which DSP struggles with, while offering low-energy operation by eliminating power-hungry ADCs (which may consume more than 40% of the energy in some transmission systems."

Due to their advantageous characteristics, such as low latency and low power consumption, photonic neural networks could ultimately have a broad range of valuable applications. For instance, they could be used to improve the performance of machine learning, nonlinear programming and signal processing tools. In their next studies, Huang and her colleagues plan to assess the performance of their photonic-electronic neural network on some of these additional applications.

More information: Chaoran Huang et al, A silicon photonic–electronic neural network for fibre nonlinearity compensation, *Nature Electronics* (2021). DOI: 10.1038/s41928-021-00661-2

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