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How to Increase Productivity and Cost Efficiency in Internet Infrastructure

Andri Mahendra Ph.D.

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Content

Abstract

The internet data traffic is undergoing a dramatic explosion, rapidly transitioning from gigabit system to petabit system that generating a massive amount of data that can be analyzed to extract valuable information. This new reality will empower all aspects of life from smart home, data center, internet of things, supercomputer, AI, and quantum computing. Electronic-photonic integration, an emerging technology that combines mature electronics engineering and integrated photonics, holds powerful and substantial roles for these applications.

Photonics and electronics have complementary advantages: photonic system operates frequencies several orders of magnitude higher than electronics, whereas electronics offers extremely high density and easily built memories. The integrated photonic-electronic systems lead to advantages in accuracy, reconfigurability, and energy efficiency. However, it has been challenging to develop reliable and accurate electronic photonic integrated circuits systems. The challenges for such systems are to realize efficient and accurate switch timing between electronic and photonic devices. Another challenge is due to manufacturing incompatibilities between electronics and photonics. Thus electronic-photonic chips typically contain only a few optical devices adjacent to simple circuits and are constrained to niche manufacturing processes. All these challenges require robust, low power, compact, and high-performance integrated systems.

Nicslab's electronic and photonic circuits platform uniquely addresses the above-mentioned challenges with its patent-pending "scalable photonic circuits controller" and provides fabless electronic and photonic chip design service to achieve reliable, low power, high performance, and compact integrated electronic photonic system for several applications. Nicslab products currently in market with 40+ customers in over 10 countries including NVIDIA, Fujitsu and leading research labs. With Nicslab's agile strategy, strong team and laser focus on customer feedback, the products offer 3x cost saving with potential 10x power saving and 100x faster speed compared to copper based solutions. Nicslab's platform is poised to disrupt the data center, AI, and quantum to the masses.

Introduction

Electronics, perhaps more than any other field of technology, is one of the greatest success stories of the 20th century. One of the revolutionary devices of electronics is the integrated circuit or IC. IC is a device that integrates many sets of functionalities and electronic components on one chip of silicon. It is small size and low cost [1], thus shows an unlimited number of opportunities to be applied in a variety of applications such as military [2], consumer electronics [3], telecommunication [4], astronomy [5], biology [6] and quantum electronics [7]. The enabling technology behind the Integrated Circuits (IC) was the invention of transfer resistor, or transistor, in 1947 by William Shockley and his colleagues at Bell Laboratories [8]. Based on this invention, Shockley and two Bell Labs colleagues, John Barden and Walter Brattain were awarded the Nobel Prize a decade later. This breakthrough was quickly followed by the invention of planar transistors [9] by Jack Kilby, a research engineer at Texas Instruments in the late 1950s. He introduced the concept of integrating device and circuit elements onto a single silicon chip. This was the origin of the density doubling law known as Moore's Law [10]. Integrated circuits with planar transistors extended operating and cost benefits of transistors to mass-produced electronic circuits, laying the foundations for the field of microelectronics. As the requirement of electronic applications increased, Gordon Moore recognized that the product developments were needed for larger transistor integration. Metal-oxide semiconductor (MOS) technology [11] appeared as the most effective technique to achieving larger scales of integration [12]. During this time, the most significant product to be introduced was the microprocessor [13]. This started the tremendous coupling of IC and software technology. However, power dissipation was becoming an important issue by the mid-1980s. The solution was to apply complementary metal-oxide-semiconductor (CMOS) technology. This technology reduces the standby power dissipation in logic circuits to almost zero [12]. CMOS technology rapidly became the standard for very-large-scale integration (VLSI) design. Following Moore's Law, over the years, the sizes of transistors have reduced from 10s of microns in the early 1970s up to 2 nanometers in 2021 [14].

After the success of IC for electronic devices, there have been many attempts of integration to other technologies to obtain the same benefits of compact and low-cost IC. Other technologies include integrated sensors [15], microelectromechanical systems [16], and integrated optics [17]. These integrated systems can be found now in our daily life such as inkjet printers, smartphones, smartwatches, etc.

Today, many applications require different electronic platforms for specific systems and need to be optimized in terms of cost, performance, and flexibility. Implementation of software using the basic electronic platforms for computing such as general-purpose processors or GPP (Intel core, ARM, AMD), application-specific processors (digital signal processor, network processor), and microcontroller (AVR, 8051) give more flexibility. However, the performance of such systems is usually low. Another option is to use massive parallel processing electronic devices such as Graphical Processing Unit (GPU) offering better performance. Implementation in hardware with custom circuits or ASICs (Application Specific Integrated Circuits) provide an even higher speed of operation, lower power dissipation, and lower cost but less flexible and no programmability.

On the other hand, programmable electronic devices such as Field Programmable Gate Arrays (FPGAs) [18] offer higher flexibility by allowing flexible logic inside the device to be interconnected to implement arbitrary digital circuits. This type of device provides the realization of relatively large logic circuits up to million equivalent gates in size. FPGAs are used in many applications, such as test equipment, consumer products like DVD players and high-end television sets, controller circuits for automobile factories, computer equipment like large tape and disk storage systems, internet routers, and high-speed network switches. FPGAs contain three main types of resources: I/O blocks for connecting to the pins of the package, logic blocks, and interconnection between switches and wires [19]. Programmable connections exist in all of the resources. The interconnection wires are structured as horizontal and vertical routing channels between rows and columns of logic blocks and organized in a two-dimensional array. The routing channels consist of wires and programmable switches that enable the logic blocks to be interconnected in many ways [20]. These make this device very competitive in the aspect of balance between flexibility, speed, power efficiency, and development cost.

One of the keys to the long-term success of the electronic computing community, and in particular of the hardware and software, has been open source licensing. Open source platforms such as Raspberry Pi [21] and Arduino [22] enable research and development at a modest cost, allowing anyone to do cutting-edge, creative work in a process that can instantly go into large-scale production. These open-source platforms nowadays also contain FPGAs and powerful mobile processors such as ARM core processors. Countless successful companies have been formed by leveraging these platforms. What has emerged is a vibrant community of companies and academics using the open-source hardware and software library that have been developing over the past 25 years in the electronic computing industry, and repurposing them to build electronic system prototypes. The promise of open-source hardware and software not only lies in open libraries but also in integrating multiple functions into a single system enabling rapid prototyping, and verifying all the functionalities before integrating these into the system on chip or chip stack. Doing so has radically driven down the cost of research and development, and will create the opportunity for a variety of fundamentally new applications of electronics and photonics, where high complexity systems can be built at a very modest cost.

Optics is the science of light which includes physical optics, nonlinear optics, quantum optics, and nano-optics while photonics is the technology of detecting, generating, or controlling light and other forms of radiant energy which quantum unit is the photon [23]. Photonics usually involves the interplay between electronics and optics. This technology has been applied in diverse applications such as defense (laser weapon), energy (solar cells), medicine (laser surgery), sensing (fiber sensor), data storage (CD/Blu-ray), entertainment (laser shows), bio (optical tweezers), nano (integrated photonics), space science (adaptive science), human-machine interface (CMOS camera) and communication (fiber-optic communication). The Nobel Prize award 2009 in Physics to Prof. Charles Kao regarded as the "father of fiber optic communications" emphasizes the great changes in modern society. Fiber optics have played a main role in initiating the Information Age and changed the way we receive information and communicate. Fiber optic communications systems use light waves in the near-infrared region of the electromagnetic spectrum (from about 800 nm to 2500 nm).

In computing, photonics is used for chip-to-chip optical interconnects and on-chip optical interconnect communications. To enable photonic interconnect communications, several components are required such as laser diodes, modulators, optical fibers, optical amplifiers, Wavelength-Division Multiplexing (WDM), and photodetectors. In electronics, electrical interconnect (copper) provides resistance-capacitance (RC) delay, bandwidth limitation (~5GHz) and higher power consumption compare to optics. Optical interconnects can give high bandwidth (> 40 Gb/s) with relatively low power consumption [24]. WDM applies many independent data channels in the same fiber or waveguide, at different wavelengths. In high-performance interconnects, Dense Wavelength-Division Multiplexing (DWDM) is used with dozens of wavelengths per waveguide. Simulation and experimental results suggest that it can provide bandwidth density on the order of 320 Gb/s/μm at only 250 fJ/bit, a considerably improved energy efficiency over-optimized electrical interconnect [25]. Optical interconnect is motivating the new field in research and development of "silicon photonics".

While research into integrated photonic has been active for the past two decades, its application to real-world systems has gathered serious attention only in the past couple of years. The main obstacle was the fact that the majority of integrated photonic systems have been relying on discrete components, occupying large volumes, suffering from reduced reliability due to various interconnection; and requiring high packaging costs. This situation is somewhat reminiscent of electronics in the early twentieth century. In recent years, many essential components have been integrated into chips, leading to more complex architectures and functionalities. Most photonic integrated systems, whether they are performing signal processing, or simply data transfer, make use of the same basic components. One definition of photonic integrated circuits is the use of optical components and techniques with integration for processing optical signals [26]. Common components for optical signal processing are waveguides, splitters, and fiber couplers. From these, photonic integrated circuit designers can build Mach Zehnder Interferometer (MZI) and ring resonators which, in turn, can be used to build photonic switches, filters, modulators, etc [27].

In the same way, the integration of photonic circuits is the key to bringing these technologies into large-scale applications. First, the possibility of integrating all circuit elements onto a single chip would reduce inter-component coupling losses, which is of utmost importance for increasing the system link gain as well as achieving a more energy-efficient circuit. Second, photonic integrated circuits need significantly less packaging together with the possibility for large-scale production would significantly drive down manufacturing costs. In addition, the inherently low size and weight benefits of photonic integrated circuits would make them attractive in a vast range of applications, such as in telecommunication, artificial intelligence, and quantum computing.

Path to Silicon Photonics Heterogeneous Integration

The past few decades saw two major advances which changed the way humans communicated, the first was the use of the internet for communication. The second was a resurgence in electronic and photonic circuit integration, brought about by scientific breakthroughs which have had a major impact on the world as we know it today. One of the dominant choice materials for electronic photonic integration is silicon, mainly because of the potential attraction of integration with electronics in a cost-effective manner. Such research began in the mid-1980s. U.S Government through Defence Advanced Research Project Agency (DARPA) believed that highly developed electronics photonic integrated circuits will meet both military and commercial needs. In 2004, the DARPA microelectronics office made a major investment also known as the electronic photonic integrated circuits project (EPIC) to develop electronic photonic integrated circuits which consist of several teams. The teams were the BAE systems team (electronic warfare application-specific EPIC), the Lincoln Laboratory team (high-resolution optical sampling technology), the Luxtera team (CMOS photonics technology), UCLA (nonlinear silicon photonics), California Institute of Technology (optical signal amplification in silicon), University of Michigan (CMOS-compatible quantum dot lasers grown directly on Si/SiGe), Translucent (low-cost buried photonic layer beneath CMOS), Brown University (all-silicon periodic nanometric superlattices toward a silicon layer) and Stanford University (germanium quantum wells on silicon substrate for optical modulation) [28].

Industries are now pursuing electronic photonic integration at an accelerated rate. Intel, IBM, Cisco, and other major companies, foresee a cost-driven transition to optical interconnect that could revolutionize enterprise networks and servers. These companies chose to invest in electronic photonic integrated circuits because it could be enabling cost-effective ultrafast processing and alleviate the electronic bottlenecks in a new generation of chips and computers. This will link up computing and communication. There is two different approaches to integration, monolithic and heterogeneous integration. Monolithic refer to all-silicon fabrication or all-in group-IV heterostructures [29]. III-V and II-IV devices bonded to Si illustrate heterogeneously (also known as hybrid integration). Both monolithic and heterogeneous integration is useful. We can select the type of integration depends on what is the requirement or need with the applications. Some of these options provide trade-offs in terms of cost and performance. For both integration types, some useful options are electrical silicon laser on-chip, an off-chip laser that optically pumps silicon Raman laser on-chip, heterogeneous integration of electrical III-V laser on-chip, and off-chip lasers of various kinds that communicate via fiber optics with electronic photonic integrated circuits without laser. Another technique that has been developed recently by the IBM team is using smart partitioning [30]. This technique maintains enough electrical content on the photonics chip as it is necessary for fully functional wafer level testing and chip disposition before assembly. Not only optimizing yield and minimize cost, but smart partitioning can also open up a broader range of applications.

Progress in optical interconnect technology is a positive indication to break the current trade-offs between bandwidth and the capacity of electrical memory system interconnection, and to decrease the I/O power consumption. In 2013, Byun et al. [31] presented an optical interconnect transceiver chip for DRAM optical interface. The chip was fabricated on the bulk-Si wafer using DRAM-compatible processes. The chip verification was performed by interfacing between a DDR3 DRAM and an FPGA-based memory controller. Moreover, Beux [32] et al. proposed the implementation of reconfigurable photonic switching. Since high-performance FPGAs computation capacity is related directly to proportional to the size and expressive to the power of LUT (Look Up Table), Optical Look Up Table (OLUT) shows promise in the future design of FPGAs. This work adopted silicon photonics technology to replace a traditional LUT with an optical core implementation. The demonstration exhibits the potential of silicon photonics CMOS technology suited for optically assisted on-chip computation. Many efforts in photonics integrated circuits implementation are advancing [33–38]. Furthermore, reference [39] reported an electronic-photonic system on a single chip integrating over 850 photonic components and 70 million transistors that work together to equip with memory, logic, and interconnect functions, using a standard microelectronics foundry process. This represents the new era of chip-scale electronic-photonic systems. The investment also has started in 2016 combining industries, government, and universities efforts to build advanced electronic photonic manufacturing capability which also known as American Institute for Manufacturing Integrated Photonics (AIM) program. With this potential, a broad range of applications could benefit from this technology and program to create small, low power and lightweight device. In addition to high bandwidth and energy efficiency advantages, photonics is also proposed as one physical representation of quantum computing.

Building Blocks for Scalable and Cost-Efficient Internet Infrastructure

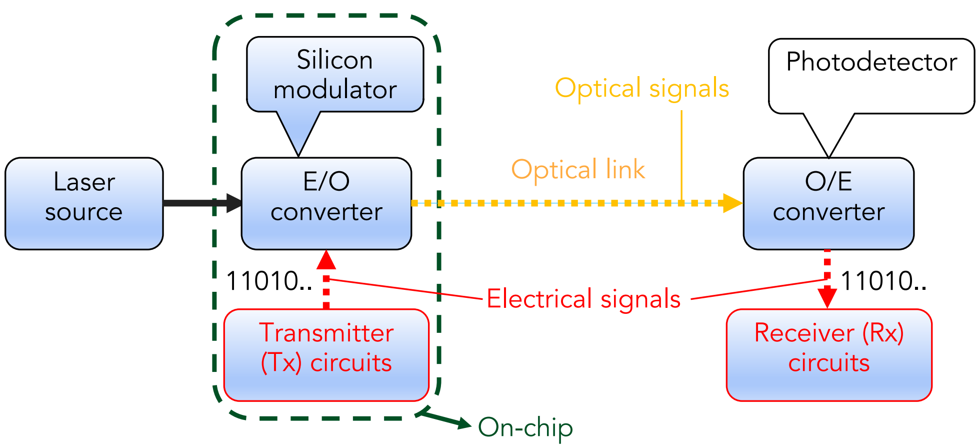

Figure 1. General transmission link in optical communication

General transmission links in optical communication consist of several components including lasers that provide a modulation source and the external modulator device as shown in Fig. 1.

From this figure, the external modulator transmitter is connected with an optical link and receiver with optical to the electrical converter. This scheme exists in the current data center or cloud infrastructure.

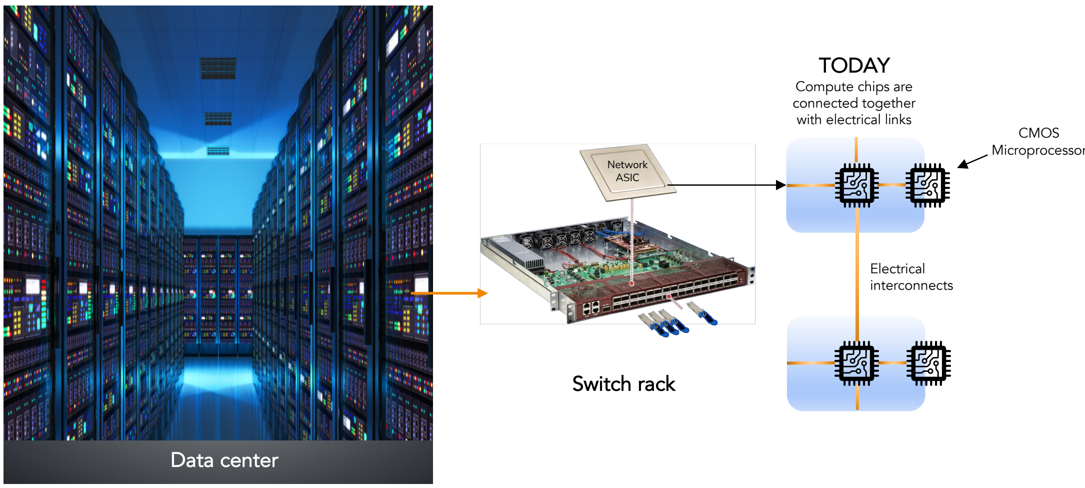

Figure 2. Optical Semiconductors are Crucial for Data Infrastructure

The cloud data explosion has been accelerated by AI applications requiring scalable and cost-efficient CMOS technologies with optics and 3D package capabilities to continue scaling functional densities and interconnect supporting cloud data requirements in networking compute and storage. Copper interconnects can no longer handle the speed and bandwidth required to support the cloud data explosion. As the data rate per I/O in link increases, the insertion loss on copper PCB traces and cables increase rapidly resulting in reduced link performance. Fig. 2 shows how the optical semiconductor is critical for data infrastructure in the data center.

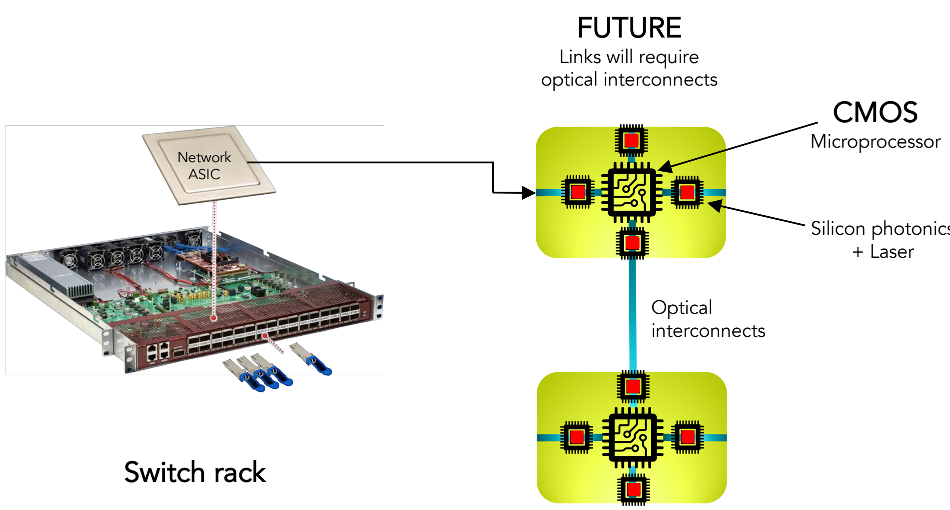

Figure 3. Chip scale electronic and photonic integrated circuits with co-packaging + heterogeneous integration

The speed and energy efficiency problems can be solved with a heterogeneous integration of optical and electronic components [40, 41]. Current optical transceivers consist of several individual components with multiple assembly steps that make them complex with silicon photonics. Nicslab provides a fully integrated solution that enables high performance, low-power, low-cost platform addressing the growing bandwidth needs for Terabit speed and beyond. Fig. 3 depicts the illustration on the chip-scale electronic and photonic integrated circuits with co-packaging (put optic as close as possible to CMOS microprocessor) including heterogeneous integration.

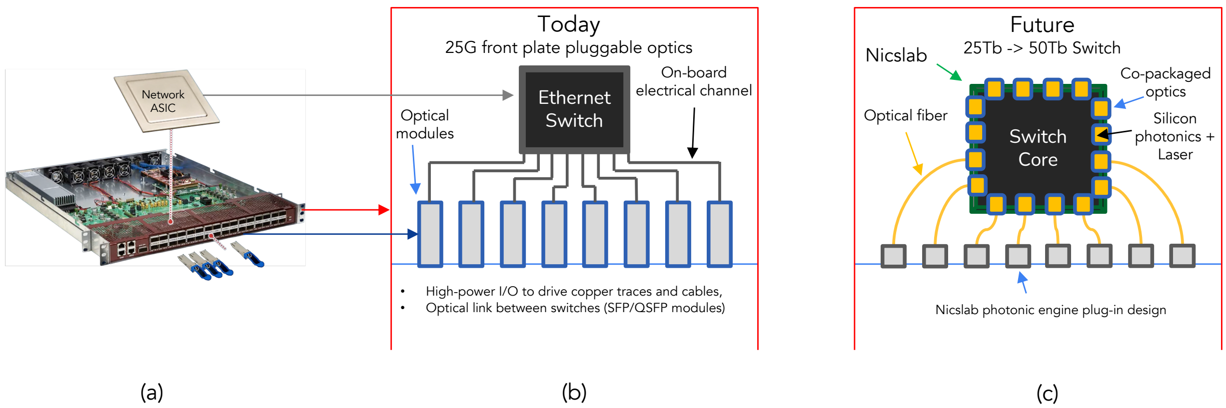

Figure 4. Heterogeneous integration to reduce energy consumption and increase internet speed/capacity

We are actively developing the system by simulating the architecture on FPGAs and working on a photonic design by using photonic design automation to get the best architecture. Nicslab's heterogeneous integration of optical and electronic components will enable a 10x power-saving and 16x faster speed compared to current pluggable solutions while improving the rack density for high radix ethernet switches, and artificial intelligence applications coupled with disaggregated computing, driving the need for dedicated high-speed connectivity between CPUs, GPUs, and networking storage elements. Nicslab will continue to offer specialized optical engines and high-speed interconnects that facilitate high density and low latency connections. Fig. 4 exhibits how potential heterogeneous integration can reduce energy consumption and increase internet speed/capacity in the future.

The Benefit of Heterogeneous Integration

- Reduce cost due to economy of scale.
- Allow for some or even better-performing devices than has previously been seen demonstrated utilizing only III-V materials.
- Scaling limitation in the modern processor with on-chip sources in long term for higher efficiency.

Conclusion

Electronic photonic integration provides a wide range of unique advantages which powerful for a variety of applications, including telecommunications, artificial intelligence, and quantum computing.

Recently IBM announced the capability of continuing Moore's Law that enabling electronic circuits to be scaled down to 2 nm. This will enable extremely high dense electronic circuits which allow much more sophisticated integration with CMOS compatible photonic integrated circuits. Nevertheless, as progress is made in these areas, the crucial point is to migrate electronics functionalities to heterogeneous circuits, preferably in silicon, to achieve more complex devices and reduce fabrication costs through high integration density. Nicslab platform has the ultimate benefit of full heterogeneous electronic and photonic integration with the possibility for packaging of both nanoelectronics and nanophotonic circuits into a single component. Integration can reduce the current gap in form-factor between the electronic and photonic circuits, and lead to a fully-packaged system platform with high accuracy, reconfigurability, and energy efficiency brought about through the power of nanoelectronics and nanophotonic circuits. The first design of Nicslab's heterogeneous electronic photonic integrated circuits is expected to be rolled out in 2022 for data center interconnects and quantum computing use cases.

Authors

Andri Mahendra Ph.D. is a CEO/CTO at Nicslab; email: andri@nicslab.com; www.nicslab.com. He holds Ph.D. in Electronics and Photonics from the University of Sydney, Australia. He has more than 5 years of experience in the South Korea Semiconductor industry, working at IBM T. J. Watson in New York, the USA with the Silicon Integrated Nanophotonic team and also on USYD/Lockheed Martin project.

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