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How to Increase Productivity and Cost Efficiency in Internet Infrastructure

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Abstract

Internet data traffic is experiencing an unprecedented surge, swiftly transitioning from gigabit to petabit systems and generating vast quantities of data ripe for analysis and insight extraction. This transformation is set to empower diverse sectors, from smart homes and data centers to the Internet of Things, supercomputing, AI, and quantum computing. At the forefront of this revolution is electronic-photonic integration, a groundbreaking technology that merges mature electronics engineering with integrated photonics, making it indispensable for these advanced applications.

Nicslab collaborates with a broad community of solution providers across telecommunications, industrial sectors, research institutions, energy, and data centers. By delivering integrated hardware subsystems, automation software, and streamlined data interaction, Nicslab's solutions are designed to be intuitive, compact, efficient, and cost-effective.

With its patented "scalable photonic circuits controller," Nicslab offers a unique integrated circuits platform and fabless electronic and photonic chip design services. These enable reliable, low-power, high-performance, and compact electronic-photonic systems across various applications, including instrumentation, AI, telecommunications, data centers, and quantum computing. Trusted by over 75 Tier 1 customers in more than 15 countries—including NVIDIA, NASA, and Fujitsu—Nicslab's agile approach, dedicated team, and commitment to customer feedback have resulted in products that deliver threefold cost savings, up to tenfold power reduction, and twentyfold size reduction over conventional solutions. Positioned as a disruptive force, Nicslab's platform is set to redefine data centers, AI, and quantum applications on a global scale.

Introduction

Electronics stands as one of the 20th century's most remarkable technological achievements, and at the core of this success is the revolutionary integrated circuit (IC). An IC integrates numerous functions and electronic components onto a single silicon chip, offering compactness and affordability [1]. This innovation has enabled a wide array of applications across sectors, including the military [2], consumer electronics [3], telecommunications [4], astronomy [5], biology [6], and quantum electronics [7]. The invention of the transistor, or "transfer resistor," by William Shockley and his colleagues at Bell Laboratories in 1947 [8], laid the foundation for integrated circuits . Shockley, alongside John Bardeen and Walter Brattain, earned the Nobel Prize a decade later for this breakthrough. Jack Kilby of Texas Instruments then introduced the concept of integrating devices and circuit elements onto a single silicon chip [9], which ultimately inspired Moore's Law [10], predicting the density doubling of transistors.

As demand for electronic applications grew, Gordon Moore recognized the need for higher transistor integration, leading to the development of Metal-Oxide-Semiconductor (MOS) technology [11], which facilitated large-scale integration [12]. This era also saw the emergence of the microprocessor [13], establishing a powerful synergy between ICs and software. By the mid-1980s, power dissipation became a critical issue, and CMOS technology provided a solution by significantly reducing standby power dissipation, quickly becoming the standard for very-large-scale integration (VLSI) design. Following Moore's Law, transistor sizes have dramatically shrunk, from tens of microns in the early 1970s to just 2 nanometers in 2021 [14].

Beyond electronics, integration has expanded to other fields, yielding benefits in compactness and affordability. Technologies like integrated sensors [15], microelectromechanical systems (MEMS) [16], and integrated optics have permeated everyday devices, from inkjet printers to smartphones and smartwatches [17].

Modern applications often require specialized electronic platforms optimized for cost, performance, and flexibility. General-purpose processors (Intel Core, ARM, AMD), application-specific processors (digital signal processors, network processors), and microcontrollers (e.g., AVR, 8051) provide flexibility, though typically with limited performance. For higher performance, parallel processing devices like GPUs are an option, while custom circuits or ASICs (Application-Specific Integrated Circuits) deliver higher speeds, lower power dissipation, and reduced costs, though with less flexibility.

In contrast, programmable devices such as Field-Programmable Gate Arrays (FPGAs) [18] offer exceptional flexibility by allowing the internal logic to be interconnected for various digital circuits. FPGAs support large-scale logic circuits of up to millions of gates and are widely used in test equipment, consumer electronics, automotive controllers, computer storage, and high-speed networking [19]. These devices excel in balancing flexibility, speed, power efficiency, and cost, making them competitive solutions [20].

The open-source movement has been instrumental in the success of the electronics community, fostering innovation through accessible platforms like Raspberry Pi [21] and Arduino [22]. These platforms enable cost-effective research and development, democratizing technology for hobbyists, academics, and startups. The vibrant open-source community has propelled rapid prototyping and large-scale production by providing shared hardware and software libraries. These advancements, along with integrated systems, significantly reduce R&D costs and open the door to sophisticated electronics and photonics applications at an affordable scale.

Optics, the study of light, spans physical, nonlinear, quantum, and nano-optics, while photonics involves detecting, generating, or controlling light and radiant energy at the photon level [23]. Photonics integrates with electronics across diverse applications such as defense (e.g., laser weapons), energy (e.g., solar cells), medicine (e.g., laser surgery), and communication (e.g., fiber optics). The impact of fiber optics on modern society is highlighted by the 2009 Nobel Prize awarded to Prof. Charles Kao, often referred to as the "father of fiber optic communications." Fiber optics have fundamentally transformed how we communicate, using light waves within the near-infrared spectrum (around 800–2500 nm). Figure 1 illustrates the current general internet infrastructure.

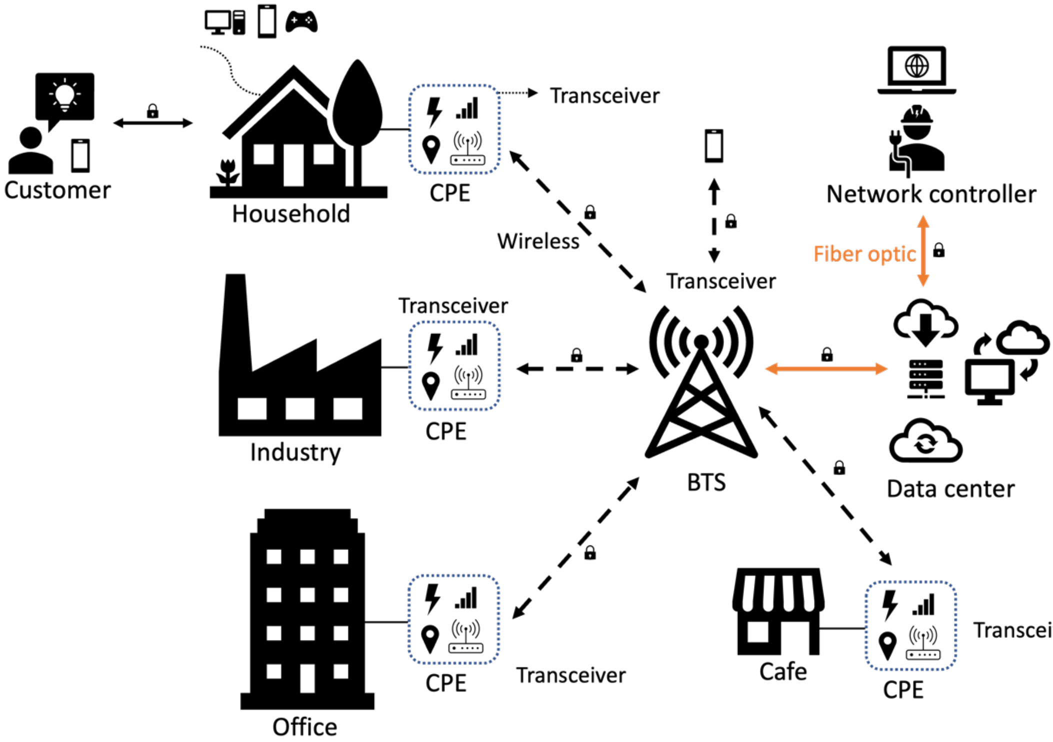

Figure 1. General Internet Infrastructure

In computing, photonics enables high-speed, chip-to-chip optical interconnects and on-chip optical communication. For photonic interconnect communication, essential components include laser diodes, modulators, optical fibers, optical amplifiers, Wavelength-Division Multiplexing (WDM), and photodetectors. While traditional electronic interconnects (such as copper) face limitations like resistance-capacitance (RC) delay, bandwidth constraints (~5 GHz), and higher power consumption, optical interconnects offer a compelling alternative. They can deliver high bandwidth (>40 Gb/s) with comparatively low power consumption [24]. WDM allows multiple data channels within a single fiber or waveguide, each at a distinct wavelength, maximizing data throughput. Dense Wavelength-Division Multiplexing (DWDM), used in high-performance interconnects, supports dozens of wavelengths per waveguide, enabling impressive bandwidth density of 320 Gb/s/μm at only 250 fJ/bit, which greatly enhances energy efficiency over optimized electrical interconnects [25]. This has fueled substantial interest in the emerging field of "silicon photonics."

Although research on integrated photonics has been ongoing for over two decades, only recently has it begun to see substantial real-world applications. A primary challenge has been the reliance on discrete components, which occupy considerable space, suffer from reduced reliability due to multiple interconnections, and demand high packaging costs—an obstacle reminiscent of early electronics in the 20th century. Recent advancements, however, have integrated essential components onto chips, allowing for more sophisticated architectures and functions. Photonic integrated circuits (PICs) leverage optical components and techniques to process optical signals efficiently [26]. Core components in PICs include waveguides, splitters, and fiber couplers, which designers can utilize to construct complex systems like Mach-Zehnder Interferometers (MZIs) and ring resonators for applications such as photonic switches, filters, and modulators [27].

The integration of photonic circuits is pivotal in scaling these technologies for broader application. First, embedding all circuit elements on a single chip minimizes inter-component coupling losses, improving system link gain and energy efficiency. Second, the reduced packaging requirements and potential for large-scale production substantially lower manufacturing costs. Furthermore, the compact size and lightweight nature of PICs make them highly desirable for applications in telecommunications, artificial intelligence, and quantum computing.

Building Blocks for Scalable and Cost-Efficient Photonic Instruments

Achieving robust and efficient equipment has long been a challenge for the industry, and the solution starts at the foundation: electric power. As the primary driver for converting electrical energy to the correct voltage, current, and frequency, power sources are essential in all sectors, including photonics. However, managing multiple devices—such as photonic chips, lasers, modulators, and photodetectors—each with its own power source, often results in bulky, costly, and complex setups. A scalable source measurement control system offers a reliable and efficient solution to these challenges.

Nicslab's source measurement platform provides a versatile suite of subsystem measurement, analysis, and management tools tailored for industries, developers, researchers, engineers, students, and scientists, enabling them to build the applications of the future. Our platform is designed with a transformative vision: to optimize energy generation and consumption, enhance productivity, and drive cost efficiency, ultimately benefiting businesses, communities, and society at large. Figure 2 illustrates the advantages of Nicslab's XDAC source measurement system.

Figure 2. Nicslab's Integrated Source Measurement System

Photonics technology requires seamless integration with the established field of electronics to unlock its full potential—this is achieved through integrated photonics or photonic integrated circuits (PICs). Electronics essentially serve as the driver, routing and manipulating light to enhance photonic applications. Nicslab's source measurement system functions as a photonic driver, simplifying large-scale requirements and replacing bulky, complex, and intricate driver arrangements.

As an integral building block, the XDAC system provides compact, high-speed processing with low energy consumption, resulting in significant cost reductions, including scalable OEM options. The integration of photonic subsystems for PICs enables effective drivers for transceiver systems in data centers, AI deep learning engines, and quantum computing control units. Recent publications highlight the diverse applications of Nicslab's platform, including its use in exoplanet exploration [28], quantum studies [29], and photonic spirals and delay lines [30].

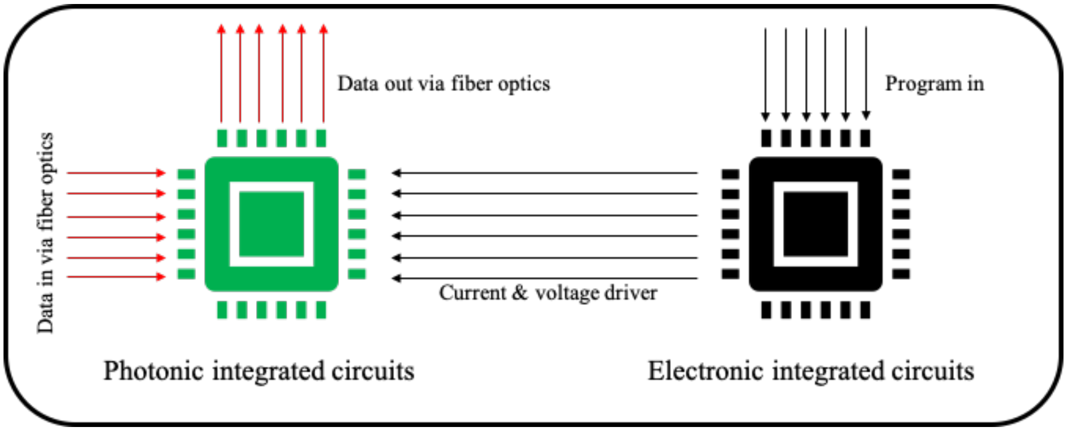

Figure 3. Photonic subsystem integration for photonic integrated circuits

The Nicslab source measurement system is built around three core components:

1. **Source Measurement Hardware & Power Management Software:** This integrated, reconfigurable hardware system, combined with a user-friendly graphical interface, empowers developers to accelerate the creation of photonic solutions. It is designed to be easily customized to meet the availability and compliance requirements of any industry organization.
2. **Software Templates & Algorithms:** Our smart driver device is supported by top-tier control templates and algorithms, offering flexible configuration, compliance, and manageability. This enables seamless integration at any scale, providing unmatched adaptability for diverse applications.
3. **Photonic Subsystem Integration:** This comprehensive suite of integrated hardware drivers and algorithms enables you to build, deploy, and operationalize devices and templates tailored to specific needs. With advanced algorithms and adaptable frameworks, the system delivers intelligent solutions aligned with industrial demands.

Benefit of Scalable Source Measurement System

- **Nicslab's scalable source measurement system** offers advanced instrumentation for rapid development, equipped with templates and algorithms designed to streamline IT infrastructure and enable scalable, integrated solutions.
- **Customize devices effortlessly** for unique applications using a user-friendly, customizable controller.
- **Quickly develop intelligent applications** with extensive APIs tailored to your specific system applications and compliance requirements.

- **Build immersive applications** easily by leveraging control software templates and reconfigurable devices, seamlessly integrating into your app or control station across multiple devices.

- **Utilize comprehensive driver frameworks** used across the telecommunications industry, including power and laser drivers.

- **Choose from a wide range of software tools**, such as Python, C, LabVIEW, and Java, to suit your development needs.

- **Deploy solutions on virtually limitless infrastructure** with full compliance for laboratory and enterprise environments, including support for DevOps capabilities like Continuous Integration and Continuous Delivery.

- **Create impactful and integrated user experiences** that scale effortlessly across diverse instrumentation.

- **Enhance energy efficiency** with smart, cost-effective designs in easy-to-use devices, optimizing both performance and budget.

Create intelligent applications tailored to your organization's specific availability and compliance needs with Nicslab's comprehensive set of flexible customization services. Accelerate automation development using high-level services and a customer-centric approach, ensuring maximum productivity and reliability in targeted scenarios.

Leverage a range of customizable programming templates—including Python, C, Java, and LabVIEW—that support seamless integration and automation. Easily incorporate intelligent features, such as feedback loops, smart switching, and automation, across instruments or workstations for a straightforward setup. Nicslab's source measurement system extends its growing portfolio of APIs, empowering developers to integrate advanced features effortlessly into their applications.

In addition to templates and algorithms, the platform supports various open-source tools like PyCharm, Processing, Arduino, and Raspberry Pi, as well as commercial options like LabVIEW.

Path to Silicon Photonics Heterogeneous Integration

In recent decades, two major advancements have transformed global communication: the widespread adoption of the internet and the resurgence of electronic-photonic circuit integration due to scientific breakthroughs. Silicon has become a preferred material for electronic-photonic integration, largely because of its compatibility with electronics and cost-effectiveness. This research, initiated in the mid-1980s, received significant backing from the U.S. Defense Advanced Research Projects Agency (DARPA), which believed that highly developed electronic-photonic integrated circuits (EPIC) would serve both military and commercial purposes. In 2004, DARPA's microelectronics office launched a major initiative in EPIC, bringing together multiple teams including BAE Systems (for electronic warfare applications), Lincoln Laboratory (high-resolution optical sampling), Luxtera (CMOS photonics technology), UCLA, Caltech, the University of Michigan, Translucent, Brown University, and Stanford University [31].

Photonics and electronics offer complementary advantages: photonics operates at much higher frequencies, while electronics allows for high-density, easily scalable memory. Integrating these technologies provides benefits such as improved accuracy, reconfigurability, and energy efficiency. However, creating reliable electronic-photonic circuits has proven challenging, particularly in achieving synchronized switch timing between electronic and photonic devices and in overcoming manufacturing incompatibilities. As a result, electronic-photonic chips typically feature only a few optical components alongside simple circuits and are limited to niche manufacturing processes. To overcome these challenges, integrated systems must be robust, low-power, compact, and high-performance.

Industries are now accelerating electronic-photonic integration. Companies like Intel, IBM, and Cisco see a cost-driven shift towards optical interconnects, potentially revolutionizing enterprise networks and computing. They are investing in EPIC to enable cost-effective, ultra-fast processing, easing electronic bottlenecks in the next generation of chips. Integration strategies include monolithic integration (all-silicon or group-IV structures) [32] and heterogeneous (hybrid) integration, where III-V and II-IV devices are bonded to silicon. The choice of integration depends on application requirements, with trade-offs in cost and performance. Options range from on-chip silicon lasers and off-chip optical pumping to IBM's innovative "smart partitioning" technique [33], which enhances yield and minimizes costs by allowing wafer-level testing before final assembly, thus expanding application possibilities.

Advances in optical interconnect technology are breaking through current bandwidth limitations and reducing I/O power consumption in electronic memory systems. In 2013, Byun et al. [34] developed an optical interconnect transceiver chip for DRAM, interfacing it with a DDR3 DRAM and an FPGA-based memory controller. Additionally, Beux [35] and colleagues introduced reconfigurable photonic switching, using silicon photonics to implement an Optical Look-Up Table (OLUT) in FPGAs, demonstrating the potential of silicon photonics CMOS technology for on-chip optical computation. Numerous advancements in photonic integrated circuits (PICs) continue to drive progress [36-41]. For example, a recent study integrated over 850 photonic components and 70 million transistors on a single chip, combining memory, logic, and interconnect capabilities in a standard microelectronics process [42].

In 2016, the American Institute for Manufacturing Integrated Photonics (AIM) program brought together industries, government, and universities to build advanced EPIC manufacturing capabilities. This progress opens up diverse applications for EPIC, enabling the development of compact, low-power, and lightweight devices. Beyond high bandwidth and energy efficiency, photonics also presents a promising platform for quantum computing.

Nicslab's Vision on Electronics and Photonics Integrated System

Nicslab recently demonstrated a compact and efficient SMU platform capable of simultaneously driving and measuring 1,080 channels of current and voltage from a central control station (e.g., a PC or laptop) via an Ethernet connection. Users have the flexibility to control current and voltage through either a dedicated graphical user interface (GUI) or Standard Commands for Programmable Instruments (SCPI) [43]. This platform is optimized for sourcing and measuring low-power applications, making it particularly suitable for complex photonic integrated circuits (PICs). Figure 4 illustrates Nicslab's vision for integrating large-scale photonic source measurement systems with PICs.

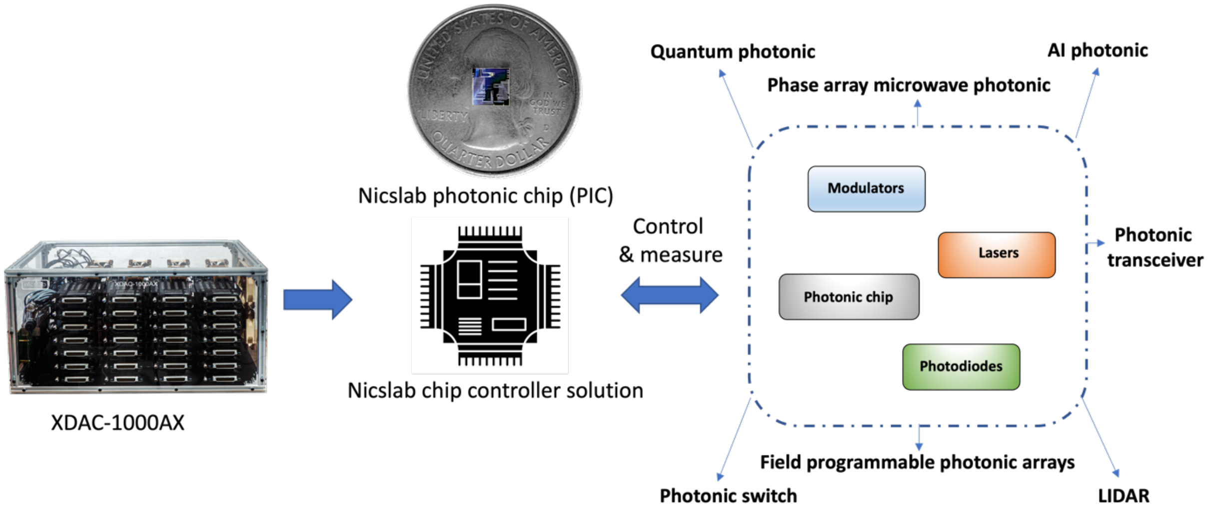

Figure 4. Nicslab product roadmap

Nicslab has developed an integrated SMU system for testing and characterizing photonic integrated circuits (PICs), capable of controlling and measuring up to 1,080 channels simultaneously. This innovative system is designed for scalability, allowing users to expand the number of channels that can be driven and measured in parallel, all from a single PC or laptop connected via Ethernet. The platform supports various signal types, including rectangular, ramp, and sawtooth waveforms, providing flexibility for diverse applications.

Users can interact with the system through either a graphical user interface (GUI) or Standard Commands for Programmable Instruments (SCPI), and they have the freedom to program it using their preferred languages, such as Python, C#, LabVIEW, or MATLAB. The platform also enables users to gather current-voltage (I-V) characteristics of multiple devices under test (DUTs) or apply a constant voltage or current for extended periods, ideal for durability testing. Future miniaturization of this system could result in a driver integrated circuit (IC) that can be heterogeneously integrated with PICs, further expanding its application potential.

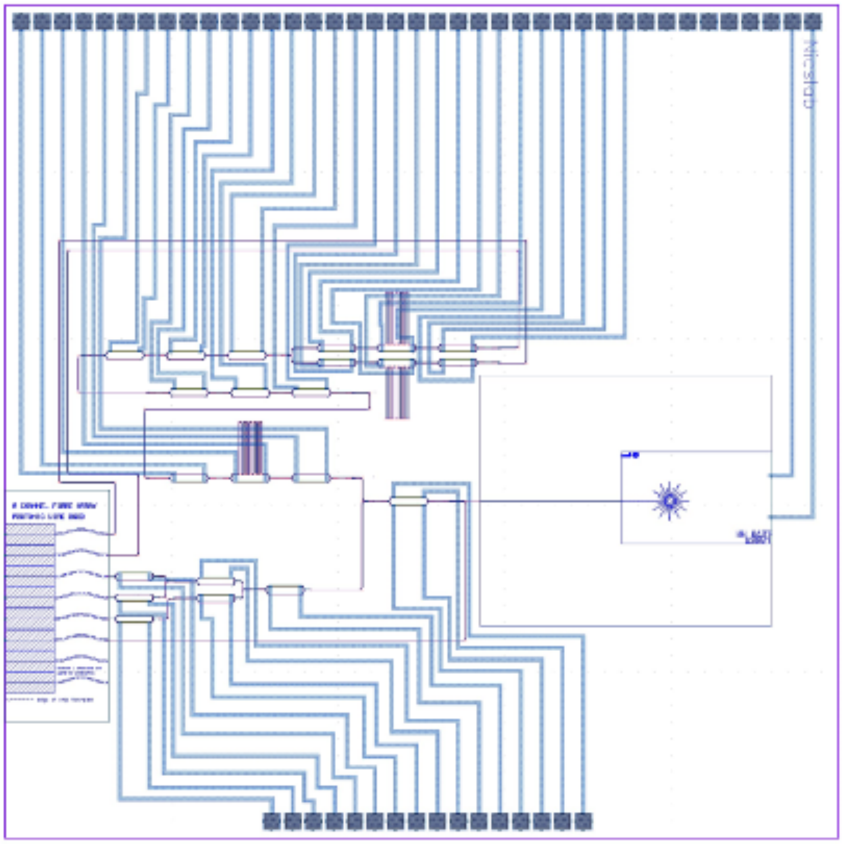

Figure 5. Nicslab’s quantum chip entanglement design

Nicslab’s latest photonic chip designs for quantum and transceiver applications are illustrated in Figures 5 and 6, with the completed tape-out and fabrication shown in Figure 4. The first demonstration on Nicslab's integrated platform is anticipated for rollout in Q4 2025.

Currently, we are advancing the system by simulating the architecture on FPGAs and refining the photonic design through electronic-photonic co-design automation to achieve optimal architecture. Nicslab remains committed to providing specialized optical engines and high-speed interconnects that enable high-density, low-latency connections.

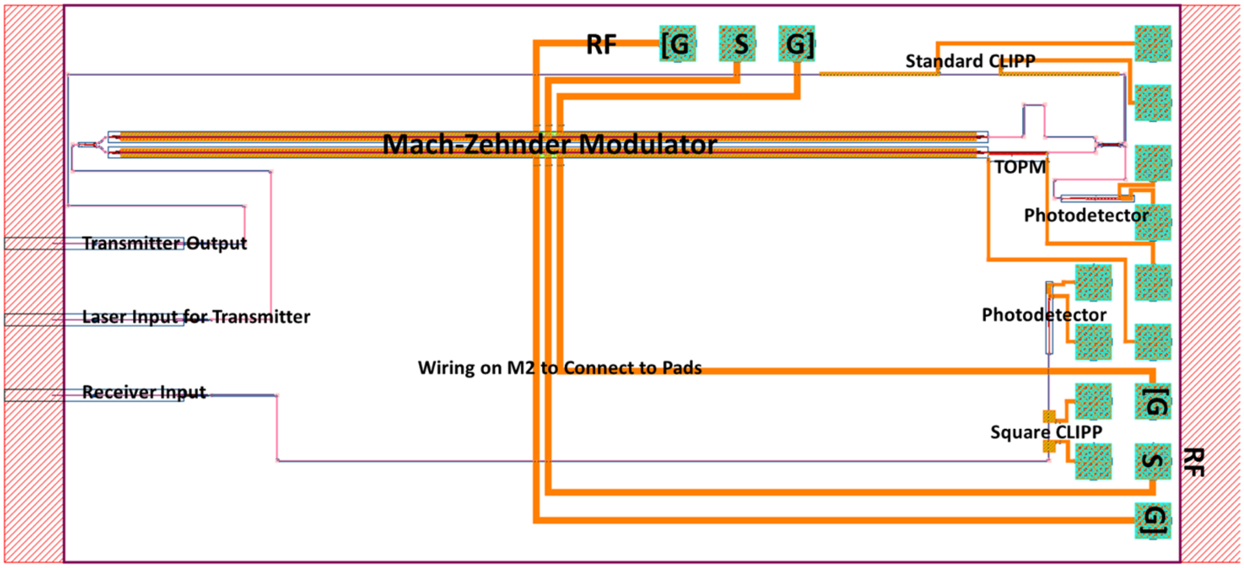

Figure 6. Nicslab photonic integrated circuits transceiver design

The Benefit of Heterogeneous Integration

- Enables the development of devices with performance levels unachievable with III-V materials alone.
- Reduces costs through economy of scale.
- Overcomes scaling limitations in modern processors, particularly by integrating on-chip sources for enhanced long-term efficiency.

Conclusion

Nicslab's photonic source measurement system supports the creation of intelligent applications tailored to each organization's specific availability and compliance requirements. With our standard source measurement system and customizable productivity services, users can build next-generation applications that encompass intelligent instrumentation and intelligent edge processing powered by robust processing units. Our flexible hardware and software templates cater to diverse scenarios, enabling enterprise-grade IT infrastructure that runs smart software at any scale, and providing modern instrumentation tools for industries, developers, researchers, students, engineers, and scientists.

Electronic-photonic integration offers a unique set of advantages for applications across telecommunications, artificial intelligence, and quantum computing. Recently, companies like TSMC have announced advancements that continue Moore's Law, enabling electronic circuits to scale down to 2 nm. This extreme density will allow for more sophisticated integration with CMOS-compatible photonic integrated circuits. However, as progress continues, it's essential to transition electronic functionalities to heterogeneous circuits, preferably on silicon, to achieve greater complexity and lower fabrication costs through high integration density.

Nicslab's platform offers the ultimate advantage of full heterogeneous integration, packaging nanoelectronics and nanophotonic circuits into a single component. This integration bridges the form-factor gap between electronic and photonic circuits, paving the way for a fully packaged system platform that combines high accuracy, reconfigurability, and energy efficiency, driven by the power of nanoelectronics and nanophotonics.

Authors

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