Optics Beyond Communication: Enabling Scalable AI and Quantum Computing

Kaveh Rahbardar Mojaver

Introduction

Over the past few decades, optics has competed with electronics in an ongoing race between photons and electrons to enable higher bandwidth, lower loss, and ultimately more energy-efficient data communication. In the early 2000s, optics was primarily dominant in long-reach links, where transmission losses were too high for electronic communication to be practical. As bandwidth demands grew and more bits were pushed onto communication links, optics became an increasingly better option, even for shorter communication distances. Currently, optics is the clear winner in the photon-versus-electron race, spanning applications from long-haul networks to rack-to-rack connectivity . However, intra-rack and chip-to-chip interconnects are still dominated by electrical links. With bandwidth demands continuing to grow and co-packaged optics emerging, photons are expected to soon become the preferred medium even for these short-reach connections.

Optical communication requires three elements: transceivers to generate and receive signals, an optical medium for photon transmission such as fiber or free space, and optical switching to reroute signals. Electronic switching is well-suited for packet switching, but for circuit switching it consumes significant energy by converting optical signals to electrical form, performing the switching, and then driving transmitters to convert the signals back to optical form. Because these optical–electrical–optical (O–E–O) conversions must be repeated at each switching stage, the associated power consumption scales poorly as network size and bandwidth increase. Optical switching, on the other hand, can accomplish the task much more efficiently by eliminating these O-E-O conversions and confining electrical processing primarily to the network edges. This is the primary reason optical switches are garnering increased interest in recent years.

Beyond communication, optics and electronics also compete in the realm of computing. In this domain, electronics still maintain a strong lead, largely due to their energy efficiency. Today, most computation—whether logic gate operations or vector-matrix operations—is performed electronically, with optics mainly serving as a transport medium. However, the rapid growth of artificial intelligence (AI) and machine learning (ML)—both of which depend heavily on large-scale vector-matrix computations—could shift this balance. As matrix sizes and computational complexity continue to increase, optics may become a serious contender, particularly for specialized analog optical vector-matrix operations. Several proof-of-concept demonstrations have been published at the research level, though industrial-scale deployment has yet to occur.

Another paradigm reshaping computation is quantum computing, which differs fundamentally from classical approaches. Quantum systems have shown the ability to solve certain problems, such as factoring large numbers, far more efficiently than conventional computers. While today's quantum computers remain small-scale, some are already accessible via cloud platforms, and their rapid development has become a priority in the technology roadmaps of many advanced nations. While larger-scale quantum computers in terms of the number of qubits still predominantly use superconducting-based qubits, optical qubits have demonstrated clear advantages in two critical aspects. First, decoherence time—the duration a qubit can maintain its quantum state—is typically in the range of microseconds for superconducting qubits, while photons, which rarely interact with their environment, can theoretically maintain quantum states almost indefinitely in the absence of loss. Second, superconducting qubits must operate at cryogenic temperatures, whereas photons can maintain quantum information at room temperature. In fact, even the quantum computation itself—the manipulation of qubits—can be performed at room temperature in photonic systems, with only photon detection requiring cryogenic cooling. These factors make photonic quantum computing potentially far more energy-efficient compared to superconducting platforms. Here too, there is competition between electronics and photonics, as researchers explore whether photons can offer advantages in quantum architectures.

Figure 1 summarizes the technology roadmap discussed in this section, highlighting which capabilities are available in the near future and which are expected in the longer term .

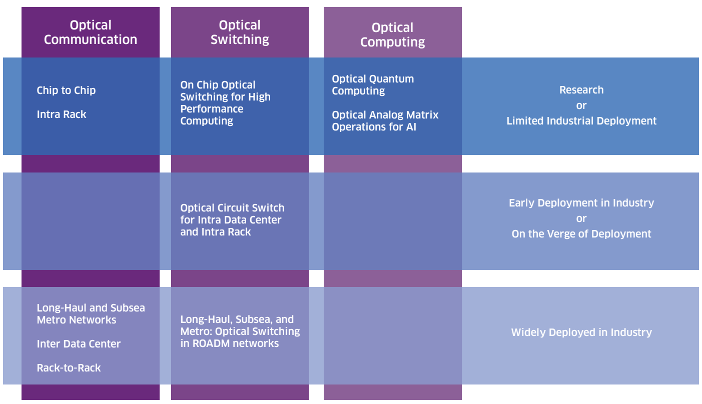

Figure 1: Technology roadmap for optical communication, switching, and computing.

Solutions

Optical circuit switching is currently in a phase of rapid transition toward broad industry deployment. Among the technologies explored for optical switching, micro-electro-mechanical systems (MEMS)-based switches have emerged as the most viable and effective solution to date. MEMS switches demonstrate very low insertion loss, excellent crosstalk performance, and scalability to hundreds of ports, making them well-suited for both data center and telecom applications. However, photonic integrated circuits (PICs) are emerging as strong alternatives, especially as chip-to-chip communication begins to move into the optical domain. In such cases, switching directly within a PIC often makes better sense due to tighter integration and potential cost and footprint benefits . PIC-based switches can also operate at significantly higher speeds than MEMS devices, as they rely on thermo-optic or electro-optic effects rather than mechanically actuated microstructures. This capability is particularly important as optical switching moves into the chip-to-chip and computing space, where faster packet or burst switching is desirable.

Switching in PICs has been demonstrated primarily in two leading material platforms: silicon photonics (SiPho) and indium phosphide (InP). Each has distinct strengths and challenges. Indium phosphide offers access to active gain elements such as semiconductor optical amplifiers (SOAs), enabling light amplification and even near-lossless switching. However, InP waveguides generally suffer from higher propagation loss, lower optical confinement, and larger bend radii, which make it challenging to implement compact switching components like Mach-Zehnder interferometers (MZIs).

Silicon photonics (Sipho) benefits from a mature fabrication ecosystem that enables the integration and management of multiple material platforms for vertically coupled waveguides. In particular, it can leverage silicon nitride (SiN) waveguides for low-loss optical coupling to fiber as well as for achieving very low optical propagation loss on chip. Also, Silicon photonics excels in providing high-confinement waveguides, as well as high-extinction-ratio MZIs, making it a strong platform for scalable, low-footprint switching fabrics. The main drawback is that silicon is an indirect bandgap material, meaning it cannot efficiently amplify light—no intrinsic gain is available. To combine the strengths of both platforms, hybrid SiPho/InP integration has been widely investigated. In this approach, routing and passive switching are handled by silicon photonics, while amplification is provided by InP-based SOAs. The challenge, however, lies in the interface losses when transferring light between the two media. These coupling losses require additional optical gain, which in turn introduces amplified spontaneous emission (ASE) noise, ultimately degrading signal integrity . Also, SOAs are not transparent across optical bands and must be carefully designed for specific wavelength ranges, which limits operational flexibility. Taken together, the limitations of both SiPho and SiPho/InP hybrid approaches suggest that no single architecture has yet emerged as a clear solution, and that fundamentally different switching approaches and system architectures may ultimately be required as the industry moves forward. An alternative hybrid approach combining SiPho with MEMS-based switching can significantly reduce optical loss and often eliminates the need for SOAs altogether, albeit at the cost of slower switching speeds compared to purely SiPho-based solutions.

Conclusion

Optics has steadily moved beyond its traditional role in communication to become a key enabler of scalable AI and quantum computing. From MEMS-based switches to hybrid silicon photonics and indium phosphide platforms, and from AI acceleration to photonic quantum qubits, the technology roadmap shows that photons are set to play an increasingly critical role. As integration challenges are addressed, optics will continue to push the boundaries of speed, efficiency, and scalability in both communication and computing.

North America
Toll Free: 844 810 LITE (5483)

Outside North America
Toll Free: 800 000 LITE (5483)

China
Toll Free: 400 120 LITE (5483)

aiquantumcomputing-wp-oc-ae 30179748 000 0126