

# Principle And Application of Silicon Photonic Technology in Communication and Artificial Intelligence

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**Abstract.** Silicon photonics, the innovative approach to fabricating integrated photonic systems on complementary metal-oxide-semiconductor (CMOS) platforms, has garnered significant attention over the past two years due to its potential to revolutionize data centers by offering solutions that are faster, more secure, and energy-efficient. This technology merges the scalability and precision of microelectronics with the benefits of photonic technology's high speed and low power consumption, thereby surpassing traditional discrete device solutions in efficiency and performance. Silicon optical technology, in particular, boasts superior data transmission capabilities, with optical signals achieving rates that electrical signals cannot match. Moreover, as traditional copper circuits approach their physical limitations, enhancing bandwidth becomes increasingly challenging. This article highlights the advantages of silicon photonics and explores its applications in the realms of Light Detection and Ranging (LiDAR) and quantum communication. It presents a comprehensive analysis of two distinct LiDAR methodologies and offers new insights into quantum communication, underscoring the transformative potential of silicon photonics in these advanced technological domains.

**Keywords:** Silicon photonic technology; LiDAR; complementary metal oxide semiconductor; quantum communication.

## 1. Introduction

As early as the 1990s, IT practitioners began to look for a successor to the traditional semiconductor industry and photonic technology was once considered the most promising technology. These days, silicon photonics technology is cited as being important for the development of transceivers with high aggregate bitrates. This is mostly because these photonic integrated circuits may be realized using CMOS fabrication technology, which can result in lower costs when produced in large quantities. Using the super-scale logic of CMOS technology, the feature of high precision manufacturing, and the merits of high speed and low power consumption of photonic technology, the original separation of many optical and electrical components is shrunk into an independent microchip to achieve high integration, low cost, and high-speed optical transmission. These days, silicon photonic technology products are widely available. It consists of high-performance silicon modulators, high-efficiency fiber-to-chip coupling architectures, low-loss waveguide circuits, and germanium p-i-n photodiodes that can operate at 28 Gbps and higher [1]. Thus far, the integration of the laser source has primarily relied on the flip-chip integration of III-V semiconductor devices. This approach is not scalable, resulting in significant expenses associated with the production of transceivers. Until now the laser source integration mostly depended on flip-chip integration of III-V semiconductor devices, which is not an extensible method, adding substantial cost to the transceiver fabrication. Although optical connectivity applications are the primary driver of silicon photonics development, other application areas are also growing. They are of interest because of the possible cheap cost of silicon photonic sensors, particularly in the context of sensing silicon photonics. Spectroscopic sensors have remarkable selectivity and enable real-time, calibration-free operation by monitoring the absorption characteristics of any material [2]. Nowadays in China, there are design problems such as incomplete structure, low degree of automation, non-uniform industrial standards, and shortage of equipment in silicon photonic chip technology. And there is a great mismatch in the packaging of silicon photonic chips. At the same time, the industry is also facing related device problems. In the future, silicon photonics technology will continue to develop in the field of

communication and will be widely used in other fields, such as lidar, image projection, photon computing, and biosensing. The concepts, benefits, and drawbacks of silicon photonic technology will be covered in this essay along with its uses in communication and a few other areas.

## 2. Working Mechanism of Silicon Photonic Technology

In silicon photonics technology, two waveguide platforms are required. Two platforms have been developed, the most advanced of which uses silicon-on-insulator (SOI) waveguides and the other on silicon nitride waveguides. The operational wavelength range of SOI-based spectrometers is limited to the region of 1.1  $\mu\text{m}$  to 4  $\mu\text{m}$ . Silicon begins to absorb at wavelengths less than 1.1  $\mu\text{m}$ , and silicon oxide begins to absorb at wavelengths more than 4  $\mu\text{m}$ . Thus, silicon nitride is used as the waveguide layer instead of silicon when developing photonic integrated circuits for wavelengths less than 1.1  $\mu\text{m}$ . Depending on the wavelength range of interest, the spectrometer can use a variety of sources and detection materials. With flip-chip technology, these sources/detectors can be introduced as separate units, or the right materials can be heterogeneously combined. To some extent, the latter is still being investigated in terms of wafer-scale demonstration. Nonetheless, highly performant CMOS imager wafers have the potential to enable applications of silicon nitride-based spectroscopy on wafer-scale detectors because silicon is an efficient detector with a wavelength below 1.1  $\mu\text{m}$ .

Considerable progress has been achieved in both waveguide platforms to realize optical wavelength demultiplexers, which are crucial elements in dispersive optical spectroscopy. Silicon photonics technology has also made Fourier transform infrared spectrometers (FTIR or FTS) a reality [3]. In this case, a spatially changing interferogram is recorded, therefore the spectrometer does not need to be adjusted. In general,  $\text{Si}_3\text{N}_4$ -based spectrometers outperform SOI in terms of optical crosstalk and insertion loss. This can be attributed to the  $\text{Si}_3\text{N}_4$  platform's lower refractive index contrast than SOI, which lessens the susceptibility to sidewall roughness and phase noise. Another option for implementing the sample interface is to use silicon photonics technology. In this approach, the evanescent field of a waveguide interacts with the sample. The evanescent field for contrast material platforms with medium to high refractive index, such as  $\text{Si}_3\text{N}_4$  and SOI, is situated between 30 and 100 nm from the waveguide's surface. As a result, measurements of molecules or chemical reactions near the waveguide are simple. The interaction length with the sample can be extended by using resonating structures or a longer waveguide [3].

Due to obstacles in making the spectrometer broadband when operated, such as the strong waveguide dispersion of both SOI and  $\text{Si}_3\text{N}_4$  PICs and the scarcity of integrated broadband sources, Si photonics technology spectrometers typically target specific spectral features or combine multiple spectrometers on a single chip, each covering a different wavelength range.

## 3. Advantages of Silicon Technology

Silicon photonics technology is highly integrated. This technology uses silicon as the substrate of integrated chips. Silicon-based materials are low-cost and have good ductility, and optical devices can be made using the mature silicon CMOS process. Compared with traditional solutions, silicon photonics technology has higher integration and more embedded functions, which is conducive to improving the integration of the chip. The waveguide transmission performance of this technology is excellent. Silicon has a band gap of 1.12 eV, corresponding to a light wavelength of 1.1 microns. Therefore, silicon is transparent for the 1.1-to-1.6-micron communication band, with superior waveguide transmission properties. Furthermore, the refractive index of silicon is as high as 3.42, which has a larger refractive index compared to silica to ensure that the silicon waveguide can have a small waveguide bending radius.

The potential for cost reduction is huge. Traditional GaAs/InP substrates are expensive to produce because of the limited growth characteristic of wafer materials. In recent years, with the significant improvement of the transmission rate, the need for larger three-group wafers grows and the cost of

chips will be further increased. Silicon-based materials have less cost and can be manufactured in large sizes compared with group III semiconductors. Thus, chip costs can be greatly reduced.

## **4. Feasibility and Application of Silicon Photonic Technology**

### **4.1. Intelligent Driving**

At present, vehicle-mounted radar has become a relatively mature technology route, LiDAR requires multiple laser emission sources and receivers, or the use of multiple signal control. The high integration of silicon light and the phase modulation ability of the electro-optical effect are very suitable for LiDAR applications. At present, several teams such as MIT and OURS have launched LiDAR products based on silicon light. With the maturity of driverless and assisted driving applications, LiDAR is expected to become an important field of silicon light application [4].

#### **4.1.1 Silicon-based phased array LiDAR**

Phased array LiDAR mainly uses the phase difference between the beams to control the beam direction. Compared with the traditional mechanical beam scanning device, the phased array LiDAR greatly reduces the size and energy consumption. The materials commonly used to realize the optical-controlled phased array are lithium niobate, liquid crystal, and piezoelectric ceramics. The phased array made of lithium niobate mainly uses the Purker effect and the Kerr effect to realize the control of the optical waveguide phase by an electric field. The speed of beam scanning is very fast, up to the order of picosecond. However, the operating voltage is high, the power consumption is very large, and the scanning Angle is small. In addition, relatively large phase shifter spacing, small aperture filling factor, and large insertion loss also hinder its development. The advantages of liquid crystal technology are low driving voltage, low power consumption, long service life, and large scanning Angle. The disadvantages are poor thermal stability, limited operating wavelength range, and slow response speed, which is usually on the order of milliseconds. Piezoelectric ceramics have a high electro-optical coefficient, wide transmission spectrum, low loss, and low price, and the speed of photo-controlled scanning is fast, which is generally on the order of nanoseconds. However, the required working voltage is very high about 1 kV and the cost is high, which is not suitable for civil use [5].

#### **4.1.2 Silicon-based optical switch array LiDAR**

In 2018, C. CHAINTOUTIS from the University of Athens proposed to realize beam steering based on optical antennas and lenses at different positions on the chip. Although this method is implemented on the InP platform, it is the first in this form of lidar. The beam emitted by the optical antenna at different positions can be deflected in different directions by passing through the lens above. Different from the OPA scheme, this scheme does not require multiple dimming phases and only needs to switch the beam to the antenna at a specific position on the chip. The scheme is simple and does not require a large-scale drive circuit [5].

### **4.2. Quantum Communication**

Quantum communication requires the preparation, manipulation, and analysis of entangled photons, and silicon optical technology is very suitable for complex optical path control and high integration. The Peking University team published a quantum entanglement chip design based on silicon light in Science in March 2018. Quantum communication has a wide range of applications in long-distance trunk lines, secure devices such as finance, and data center encryption. A quantum communication chip based on silicon light is expected to become an important technical solution in the future. At present, the commercialization of silicon photonics technology is more mature in the field of data centers, high-performance data exchange, long-distance interconnection, 5G infrastructure, and other optical connections, 800G and later silicon optical modules are more cost-

effective. Shortly, high-speed information transmission will be supported by silicon optical chips in large data centers.

### 4.2.1 Quantum error correction

Although quantum information processors have many natural advantages, they still face a basic difficulty, and that is an error. When the product of logical operation and qubit error rate comes to some extent, logical operation will lose its reliability. At the same time, due to the quantum non-cloning theorem, qubits cannot be copied. And it is impossible to eliminate errors through repetition like classical processors. Thus, the realization of a practical quantum processor requires efficient quantum error correction. The common process of quantum error communication is shown below (Fig. 1). Errors in optical quantum technology can arise from photon loss, incorrect logical operations, and quantum state quality. Many strategies have been devised to increase photon fault tolerance, including initiatives to lower manufacturing errors to provide high-performance optical components. Thus far, there have been confirmed instances of topological quantum light sources and quantum interference processes on silicon photonic circuits.

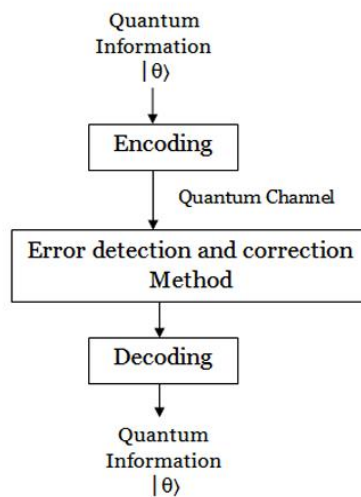


Fig. 1 Quantum error detection and correction process [6].

### 4.2.2 Quantum key distribution

Quantum key distribution (QKD), which is based on the principles of quantum physics, seeks to securely exchange information between sender and recipient. Many quantum coding protocols, including BB84, two-state, and the Einstein Podolsky-Lawson protocol, have been established after decades of development, with QKD emerging as the cornerstone of quantum networks. Nonetheless, it has been demonstrated theoretically that all current repeater-less QKD realizations and protocols are limited in their performance by a fundamental rate-distance constraint known as the linear limitation [7]. Remarkably, twin-field (TF) QKD, a recently suggested technology, can surpass linear bound without using quantum repeaters [8]. The TF QKD is shown below (Fig. 2).

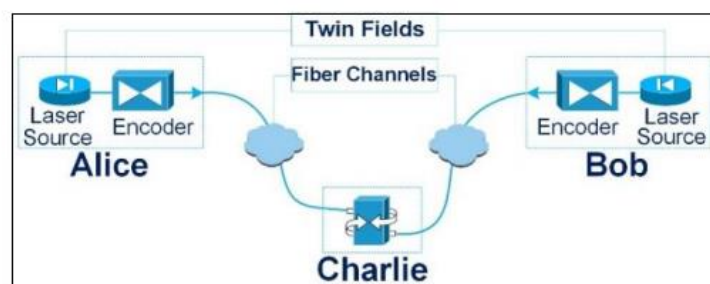
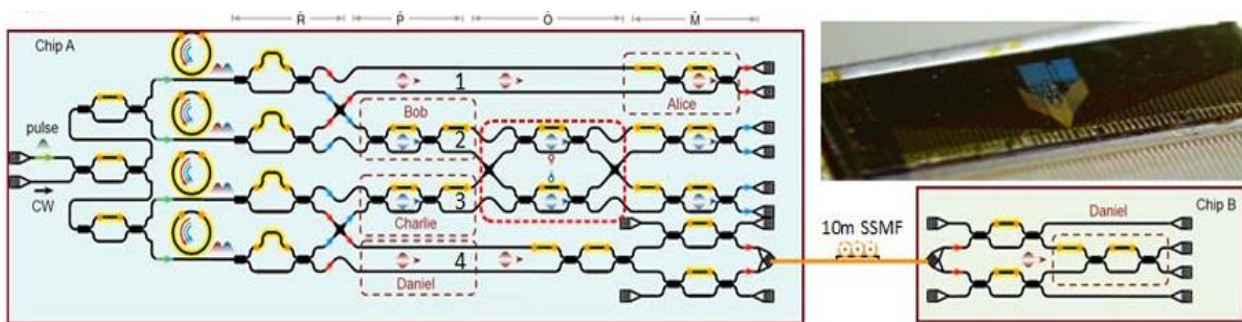


Fig. 2 Quantum error detection and correction process [9].

### 4.2.3 Quantum Teleportation

The goal of quantum teleportation is to move a particle's quantum state from itself to another particle. This technology serves as the foundation for distributed quantum computing and scalable quantum networks. It transfers quantum information held in quantum states via quantum entanglement, a novel type of communication [10]. Three particles are involved (A, B, and C), and we consider particles B and C to be Baer entangled. Particle A's quantum state can be transferred to particle B by measuring the Baer state between A and C. By employing a high number of cascade gates, linear optical quantum information processors can be scaled effectively via quantum teleportation.

Of course, quantum teleportation methods can also be implemented with silicon waveguides. Specifically, multiphoton entangled quantum states can be directly manipulated by strong spontaneous four-wave mixing (SFWM) in silicon waveguides. Photons obtained in quantum states are first transmitted to another device equipped with a quantum photon connection via route polarization interconversion, and then state chromatography measurements are used to reconstruct the quantum states before the teleportation operation is verified. This achievement lays the foundation for integrated photonic quantum computing and communication systems on a wide scale. The silicon chip-to-chip quantum teleportation and silicon on-chip quantum entanglement switching schematics are shown below (Fig. 3).



**Fig. 3** Schematic on-chip quantum entanglement switching and silicon chip-to-chip quantum teleportation. The synthetic silicon chip is displayed in the inset [10].

## 5. Conclusion

A lot of scientific advances frequently fail to close the knowledge gap between research and marketable products. Silicon photonics, however, defied the norm. Utilizing decades of research and billions of dollars invested in silicon semiconductor device processing, silicon photonics enables low cost, robust processing, and high yield. In addition to being a superb optical material, silicon is a useful platform for large-scale photonic integrated circuits and has transparency in commercially significant infrared wavelength bands. Thus, silicon photonics is expected to meet the world's growing bandwidth requirements. It is a component of a newly formed ecosystem that also consists of integrators, foundries, and designers.

In terms of design process flow, the CMOS platform provides powerful process capability for silicon optical technology. This is why silicon photonic technology can play its great potential in many fields. As the core component of autonomous driving technology, Lidar has been widely concerned. Among them, silicon-based integrated all-solid-state lidar known as the next generation of products, will replace the existing mechanical or microelectromechanical system (MEMS) lidar. Beyond that, significant progress has been made in silicon photonic devices for quantum information processing; integrated programmable multi-photon and high-dimensional quantum information processors have also been demonstrated. Photon sources, quantum state manipulation, and detection can all be integrated on a chip and are anticipated to be implemented on the same chip. In the area of quantum information processing, silicon photonics technology will have more opportunities as

manufacturing techniques advance. Naturally, there are still a lot of material flaws in silicon photonic devices. Notwithstanding these difficulties, silicon photonics will be crucial in the future.

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