

The Fundamental Structure of Silicon Photonic Chips and Applications in Optical Communication

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Abstract. With the rapid advancement of modern technologies such as the Internet of Things (IoT) and artificial intelligence (AI), the demand for data processing and transmission in human society has experienced exponential growth, driving an unprecedented surge in broadband network capacity requirements. As its core support, optical communication is facing major challenges. Silicon-based photonic chips, characterized by small size, light weight, and low power consumption, are key devices to break through the bottlenecks of optical communication systems. This paper enumerates the composite structures of silicon-based photonic chips and discusses different types of structures. It compares different types of Mach-Zehnder interferometers, micro-ring resonators, Positive-Intrinsic-Negative photodiodes, Avalanche photodiodes, silicon-based quantum dot lasers, and explores their performance as well as their applications in optical communication. In addition, it provides an outlook on the future of silicon-based photonic chips and optical communication.

Keywords: Mach-Zehnder interferometers, micro-ring resonators, positive-intrinsic-negative photodiode, avalanche photodiodes, quantum dot laser

1. Introduction

Optical communication networks, as the backbone networks supporting information interaction in modern society, have their main advantages in relatively strong data transmission capabilities, stability, and reliability [1,2]. Although traditional optical communication network technologies have achieved remarkable progress in the past few decades, they still seem inadequate when facing the increasingly growing data transmission demands and complex and changeable transmission environments [3]. Especially during the data transmission process, the existence of some faulty data leads to a decline in the data transmission quality of optical communication networks. Therefore, exploring new optical communication network data transmission technologies and improving the data transmission performance of optical communication networks have become current research hotspots and difficulties.

Microelectronics technology, dominated by silicon materials, has achieved remarkable accomplishments over the past half-century and has always been the driving force for the development of the modern information society. The development of microelectronic chips follows Moore's Law. However, as the process nodes of microelectronic chips approach the atomic level, the

impact of quantum effects on chip performance intensifies, and Moore's Law is facing failure. People use multi-core processors to improve performance and reduce power consumption. However, the signal transmission speed of the bus restricts the processing capability of the processor. Traditional electrical interconnection cannot meet the needs of future high-speed data communication due to reasons such as electromagnetic interference and time delay. Optical communication has characteristics such as anti-electromagnetic interference, high transmission rate, low power consumption, and low time delay. As a medium for information interconnection, light has inherent advantages compared to electrical signals [4-8]. In the 1970s, Miller from the Bell Laboratories in the United States proposed the concept of integrated optics [9], whose goal is to integrate optical devices and electrical devices simultaneously on the same chip. However, in its early stages, constrained by the maturity of materials and processes, it remained in the laboratory phase for a long time. At the beginning of the 21st century, with the evolution of CMOS processes toward the nanoscale, the surge in demand for Internet bandwidth, and the impetus from companies such as Intel and Luxtera, silicon photonics technology entered a period of accelerated industrialization. This paper will talk about the structure and performance of silicon-based photonic chips.

This paper addresses the bottleneck of optical communication systems amid surging data demands from IoT and AI. It enumerates composite structures of silicon photonic chips, discusses various structures, compares performances of Mach-Zehnder interferometers (MZIs), micro-ring resonators (MRRs), positive-intrinsic-negative photodiodes (PIN PDs), avalanche photodiodes (APDs), silicon-based quantum dot lasers (QDLs), and explores their applications in optical communication, with an outlook on the future.

2. The fundamental structures of silicon-based photonic chip

2.1. Slot-waveguide

Slot-waveguide is a conventional structure, first presented by Almedia and his colleagues in 2004 [10]. This structure can guide and strongly confine light within a nanoscale low-refractive-index material through total internal reflection, achieving a confinement level that conventional waveguides cannot reach. As shown in Figure 1, the slot-waveguide architecture is characterized by a pair of high-refractive-index (n_H) strip waveguides (rails) that are spatially separated by a subwavelength-scale, low-refractive-index slot region, where the slot width (w) is a critical design parameter governing optical confinement.

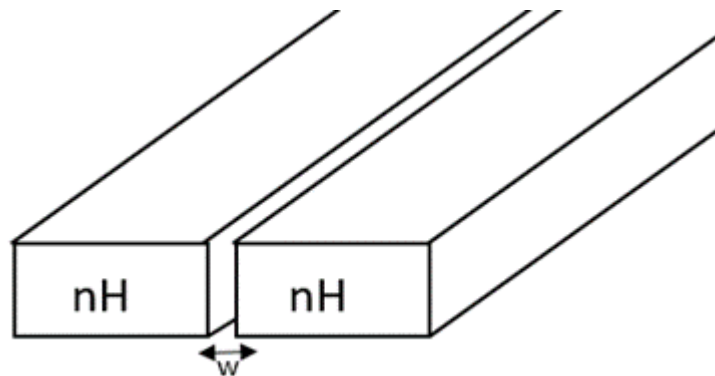


Figure 1. The structure of the slot-waveguide.

2.2. Ridge waveguide

The structure of the ridge waveguide is derived from the improvement of the traditional rectangular waveguide. Its cross-section, built upon the rectangular waveguide, is added with "ridge-like protrusions". In essence, it regulates the confinement and distribution of the electromagnetic field by changing the morphology of the internal boundary of the waveguide. As shown in Figure 2, A typical feature of a ridge waveguide is that there is a ridge with a high refractive index which is lithium niobate in the figure, with a relatively higher refractive index compared to the surrounding air, SiO₂ insulating layer, and the area above and on both sides of the ridge is a medium with a low refractive index such as air, SiO₂. Through this difference in refractive index, light can be confined and propagated.

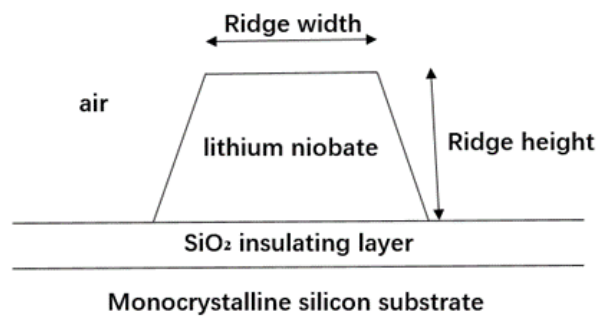


Figure 2. The structure of the ridge waveguide.

2.3. MZI

The basic structure of a Mach-Zehnder interferometer includes an input port for introducing external light. It is followed by a first-stage beam splitter, such as a directional coupler, multimode interference coupler, or a semi-transparent and semi-reflective mirror in free space, which splits the light equally into two beams. These two beams enter the interferometer arms respectively, and the arms can integrate modulation units to change the optical path. Then, through a second-stage beam combiner of the same type as the splitter, the two beams interfere, and finally, the interfered light signal is output from the output port. As shown in Figure 3, it is the structure of MZI.

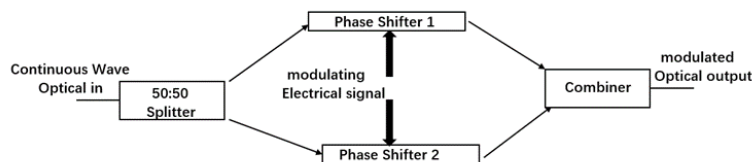


Figure 3. The structure of MZI.

2.4. MRR

Micro-ring resonators feature a core structure of a circular or racetrack-shaped waveguide coupled with input/output waveguides. The ring waveguide, typically made of high-refractive-index materials like silicon, enables light to circulate via total internal reflection. Evanescent field

coupling between the ring and bus waveguides enables resonant light to be filtered or modulated, with the resonance wavelength determined by the ring circumference and effective refractive index. Figure 4 shows the structure of MRR.

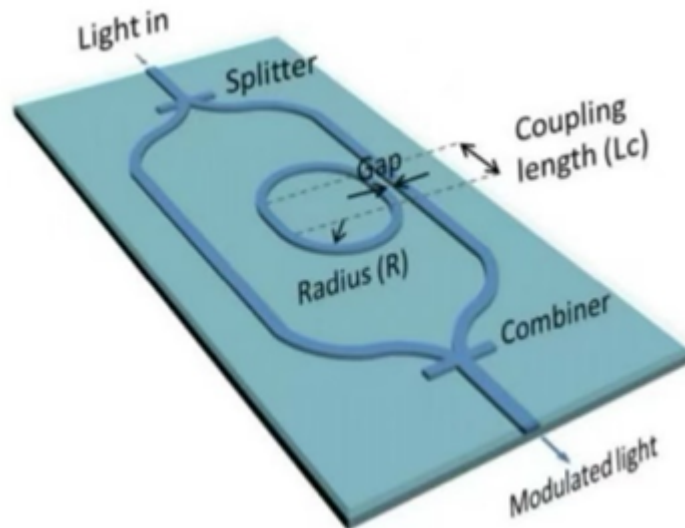


Figure 4. The structure of MRR [11].

2.5. PIN PD

A Positive-Intrinsic-Negative photodiode is structured with 3 layers. The p-type (positive) layer is fabricated using semiconductor materials, such as silicon and gallium arsenide, doped with acceptor impurities, which introduce an excess of holes as the majority charge carriers. The intrinsic region is composed of undoped semiconductor materials exhibiting exceptionally high purity levels, with characteristic impurity concentrations below 10^{13} cm^{-3} [12]. Common material systems include silicon (Si), germanium (Ge), and ternary compounds such as indium gallium arsenide ($\text{In}_x\text{Ga}_{1-x}\text{As}$), selected for their well-defined bandgap characteristics and superior carrier mobility in the intrinsic state. The negative layer is usually made of semiconductor materials doped with donor impurities. For instance, impurities like phosphorus and arsenic are doped into silicon or gallium arsenide, making this layer have more free electrons and show negative charge characteristics.

The function of the positive layer is mainly responsible for collecting the holes drifting from the I layer. The intrinsic layer is used for absorbing the photon energy, generating a large number of electron-hole pairs, and the Negative layer is used to collect the electrons drifting from the intrinsic layer.

2.6. APD

Avalanche photodiode has many structures, such as a read diode structure, a separate absorption, grading, and multiplication structure (SAMG structure), and a separate absorption and multiplication structure (SAM structure). For example, the SAMG structure is made of a P-N junction, which is fabricated within the InP window layer. The avalanche region is made of N-type InP, and a bandgap-graded InGaAsP transition layer is inserted between the heterointerface of N-InP and N-InGaAs. The work principle of the SAMG structure uses InGaAs as the light absorption layer because it has a high absorption coefficient for light at $1.3 \mu\text{m}$ and $1.55 \mu\text{m}$. The separation of the avalanche region and the absorption region can prevent the tunnel breakdown of the InGaAs homojunction from

occurring before avalanche breakdown. Meanwhile, the characteristic of InP material that the hole ionization coefficient is greater than the electron ionization coefficient is utilized to achieve avalanche multiplication of carriers.

2.7. Silicon-based QDL

The silicon-based quantum dot laser is architecturally composed of five fundamental components: (1) a substrate layer, typically silicon or silicon-on-insulator (SOI); (2) an active region incorporating quantum dot (QD) nanostructures as the optical gain medium; (3) a waveguide structure for optical mode confinement and propagation; (4) a resonator cavity for establishing optical feedback and enabling lasing action and (5) electrodes for carrier injection and device operation. This paper will talk about these fundamental components in detail.

The substrate typically utilizes silicon (Si) owing to its low-cost availability, well-established microfabrication protocols, and seamless integration with standard photonic and electronic platforms.

Quantum dot materials mainly fall into two categories: SiGe quantum dots and III-V quantum dots. For example, Si Ge quantum dots formed on silicon substrates through "self-assembled growth" (Stranski-Krastanov mode) [13]. The difference in lattice constants between SiGe and Si (germanium atoms have a larger radius than silicon) leads to stress accumulation, eventually forming discrete quantum dots. Although SiGe has an indirect bandgap, the three-dimensional confinement of quantum dots can enhance carrier recombination probability and improve luminous efficiency.

Common types of waveguides include: Ridge waveguide and slot-waveguide. This paper has talked about the structures of these 2 types in detail in 3.1 and 3.2. Both of these structures are improvements on the traditional structure. The common structure of a Resonator is a Fabry-Perot (FP) cavity, which uses the cleaved surfaces of silicon-based materials as mirrors and has a simple structure but a relatively wide linewidth.

Electrodes, crucial for carrier injection and device functionality, generally consist of metal-semiconductor contact structures. Precisely, they are fabricated by depositing metal layers (such as titanium, platinum, and gold) with optimized thicknesses and sequences on the semiconductor surface. These metal layers form ohmic or Schottky contacts as required. Through rational design of the electrode shape (like strip-shaped or interdigitated electrodes) and distribution, efficient and uniform injection of carriers (electrons and holes) into the active region is achieved. This precisely regulates the population inversion condition within the active region.

3. Functional characterization of silicon photonic chips in optical communication systems

3.1. Main components of optical communication systems and function

The core functions of Optical Communication Systems rely on four key structural categories. These structures work synergistically to perform essential tasks such as generating, transmitting, modulating, and detecting optical signals. Below are the four core structures and their functions:

Light source structure is the origin of optical signals, providing the optical carrier required for optical communication and efficiently guiding optical signals into the on-chip optical path system. Waveguide structure can confine and guide the transmission of optical signals, and implement routing functions such as switching, splitting, and combining of optical paths. The modulator structure can impose electrical signal information onto an optical carrier and achieve the conversion

of an electrical signal to an optical signal. The detector structure can convert optical signals reaching the chip's end into electrical signals.

3.2. The performance of silicon-based quantum dot laser

Silicon-based quantum dot lasers are a new type of light source that combines quantum dot structures with silicon-based materials. Their performance inherits the unique advantages of quantum dots while needing to address the inherent challenges of silicon-based materials, showing great potential in the field of optoelectronic integration.

In terms of threshold current, silicon-based quantum dot lasers can be as low as the sub-milliamp level, thanks to quantum dots' discrete energy levels that confine carriers and reduce non-radiative recombination. For emission wavelength, they cover near-infrared to mid-infrared, which is enabled by the tunable quantum dot size. The electro-optical conversion efficiency can reach up to over 30% in laboratory settings, due to the high probability of radiative recombination of carriers in quantum dots. Regarding temperature stability, the operating temperature can reach above 100°C with a small threshold drift, as quantum dot energy levels are less sensitive to temperature than bulk materials. And for modulation speed, high-speed modulation of over 10Gbps has been achieved, benefiting from the short carrier relaxation time of quantum dots.

3.3. The performance of 2 types of waveguide structures

There are many different structures of waveguides, such as ridge waveguides and slot waveguides. This paper has given a detailed introduction to the structures of these 2 types in 3.1. Compared with the ridge waveguides, the slot waveguides have lower transmission loss due to the dispersed field distribution. Both of them need to couple with other components, but the coupling efficiency differs. The ridge waveguides have a higher coupling efficiency because the fields of the ridge waveguides are concentrated at the ridge edges, making them easy to couple with probes, microstrip lines. Table 1 below will compare the performance of the ridge waveguide and slot waveguide.

Table 1. The performance of the ridge waveguide and slot-waveguide.

Performance Parameter	Ridge waveguide [14]	Slot-waveguide [15]
Transmission loss	Typical value in the millimeter-wave band is 0.1-1 dB/cm	With high-quality craftsmanship, the loss is approximately 1-10 dB/cm
Single-mode Bandwidth	Can cover multiple continuous waveguide frequency bands	Have a wide single-mode bandwidth, which can cover multiple octaves;
Coupling performance	With high coupling efficiency	confining in the slot, so coupling requires matching the slot structure, making the design more complex.

3.4. The performance of two types of modulator structures

In Sections 3.2 and 3.3, this paper discusses the structure of MZIs and MRRs. The performance of MZI varies depending on its application fields and material selection. MZIs are suitable for high-speed, broadband, and low-sensitivity scenarios, while MRRs are suitable for high-density integration and narrowband filtering/multiplexing scenarios. The performance differences between the two stem from their structural nature: MZIs are based on interference, and MRRs are based on resonance. Table 2 below compares the performance of these two types of modulator structures.

Table 2. The performance of MZI and MRR.

Performance Parameter	MZI [16]	MRR [17,18]
Insertion Loss (dB)	Silicon-based waveguide: 3-5 dB. LiNbO ₃ waveguide: <1 dB	Silicon-based: < 3 dB Silicon nitride:<0.1 dB
Modulation Rate and Bandwidth	Silicon-based MZIs can reach 44 Gbps. Commercial LiNbO ₃ modulators have a bandwidth of 11 GHz, supporting 12.5 Gbps.	Bandwidth is limited by the resonance linewidth, usually only a few hundred MHz to several GHz.
Temperature Sensitivity	low temperature sensitivity	high temperature sensitivity

3.5. Performance analysis of different detectors

In 3.4 and 3.5, this paper has explained the structure of PIN Photodiode and APD. PIN PD features a high response speed. This is because its intrinsic layer is relatively wide, allowing photogenerated carriers to drift rapidly within it, enabling a quick response to changes in optical signals. The dark current of APD is relatively high. Since APD needs to apply a relatively high reverse bias voltage to trigger the avalanche multiplication effect during operation, the high reverse bias voltage increases the number of carriers generated by thermal excitation. PIN PD has excellent linearity because its working principle is based on the photovoltaic effect, and the photocurrent has a linear relationship with the incident light power. Table 3 below compares the performance of these two types of detector structures.

Table 3. The performance of PIN PD and APD.

Performance Parameter	PIN PD [19]	APD [19]
Response Speed	High(GHz level)	Medium-high (hundreds of MHz to GHz)
Dark Current	Low	Relatively high
Linearity	Excellent	Poor
Gain	None(1:1)	Yes (10-1000 times)

4. Conclusion

This study investigates the structures, performance, and applications of silicon-based photonic chips in optical communication. Key structures, including slot-waveguides, ridge waveguides, MZIs, MRRs, PIN PDs, APDs, and QDLs, are analyzed. Performance comparisons reveal distinct strengths: quantum dot lasers exhibit low threshold currents and broad wavelength coverage; slot-waveguides show lower transmission loss than ridge waveguides, while the latter offer higher coupling efficiency; MZIs excel in high-speed modulation, whereas MRRs are suited for dense integration; PIN PDs provide fast response and linearity, while APDs offer gain despite higher dark current.

These findings are significant as silicon-based photonic chips address bottlenecks in traditional optical communication, such as bandwidth limits and electromagnetic interference, by leveraging silicon's compatibility with mature microelectronics. They support the surging data demands of IoT and AI, bridging the gap between electrical and optical interconnections. Performance optimization

should be prioritized, with particular emphasis placed on the reduction of propagation losses and enhancement of the thermo-optic stability in microring resonators in the future.

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