Photonic Integrated Circuits

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Abstract

Photonic integrated circuits play a critical role in integrating photonic computing into traditional digital computing, as well as advancing newer applications such as quantum computing.
The global telecommunications network depends heavily on the optical fiber network for the transmission of information. This paper discusses the use of photonic integrated circuits in long and short-range communications applications such as intra-rack interconnects in data centers, optical information processing, and integrating photonic quantum circuits on PICs.
This paper describes what photonic circuits are, and how they can be integrated in existing networks, how doing so will impact power consumption, material considerations for fabricating these chips, as well as the devices that need to be integrated onto a chip to ensure telecommunication applications, and move forward with realizing linear optical quantum computation.

Introduction

Traditionally, optical networks are bulky and vulnerable to environmental factors, making them less-than-ideal for integration with digital circuits or quantum processes. Scaling down these components makes optical networks more compact, faster, and more cost-effective. Photonic integrated circuits refer to the integration of optical circuit components (such as waveguides, filters, amplifiers, detectors, generating sources, etc), onto a chip, analogous to an electronic integrated circuit. These circuits allow the transmission and modulation of optical information, and find use in telecommunication, computer interconnects, and upcoming computing technologies such as quantum computing.

In telecommunications and in digital computing, photonics can help support higher data rates and increased bandwidth of information transmission, allowing for faster compute times since transmission occurs at the speed of light, faster and more integrity in connectivity, and lower power consumption due to scale. Silicon photonics, being easier to manufacture and integrate into existing CMOS technology, can support transmission speeds of more than 100 Gb/s [1]. On-chip photonic signal processing will help reduce the network complexity of modulating electronic/optical signals for long-range secure communication[2].

This paper describes in-depth some key components that must be scaled onto a PIC to realize the telecommunication applications of photonic circuits. Realizing linear optical quantum computing is also discussed, but the main application discussed remains long and short-range classical (digital) telecommunications.

Results

Optical waveguides are used to route photons on the chip, and are used for on-chip signaling and detecting. They function as a scaled-down version of an optical fiber and work by restricting the transmission of energy in one direction.

The most common form of the waveguide is a **strip or channel waveguide**, which offers a tight bending radius, and is formed by bordering a strip of material with a higher refractive index with a material of lower refractive index. This way, total internal reflection (TIR) occurs forms guided modes, confining light to move only laterally and bidirectionally [3].

The strip waveguide suffers from many scattering losses, and thus, other configurations, such as slot and rib waveguides are used to lower photon loss.

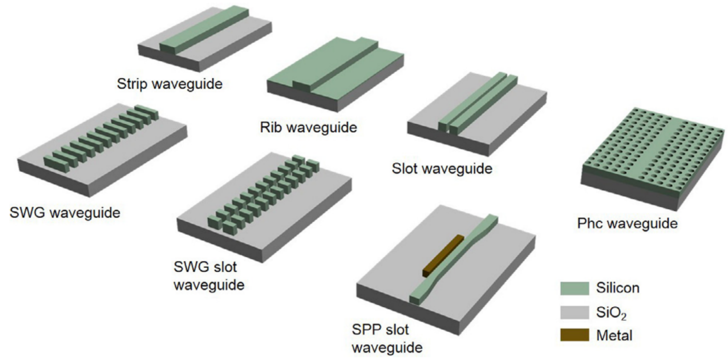

Fig. 1. Different configurations of waveguides formed on a silicon wafer with an SiO_2 cladding. Photonic Crystal (Phc) waveguides can be formed by selectively removing lines from a Phc lattice. [3]

As shown in Fig. 1., a slot waveguide is formed by introducing a slot in between the strip, usually filled with material of a lower refractive index, or unfilled and left as an air gap. The sharp difference in refractive indices of the slot and its surrounding strip confines light more strongly and reduces photon loss by preventing photons from moving orthogonally to the waveguide. Other waveguide configurations are built upon the structure of a strip and slot waveguide, e.g. the **SWG or SWG slot waveguide**. Waveguides made using photonic crystals or Surface Plasmon Polaritons have even stronger light confinement [3].

A grating couples light beams into and out of waveguides and is useful for optical interconnects. A subwavelength grating (SWG) may be formed by placing strips of silicon with a SiO_2 cladding, with the pitch of the strips equal to the wavelength in the waveguide. A slot may be formed going through the strips for stronger light confinement, forming an **SWGS (Subwavelength grating slot)**. Gratings require vertical confinement as well as lateral confinement, which makes Silicon a better choice than InP, since InP's native oxide can only confine light laterally.

Filters can be implemented using a Fabry-Perot (FP) cavity structure with Sagnap-loop mirrors (SLM) for resonance, as well as MZIs. Fig. 2. Shows 3 micro-heaters, which are used to tune the phaseshifts of the waveguide by changing the reflection coefficients of the SLMs. Filters help tune wavelength and operation bandwidth by adjusting their phase shifters. Their tuning efficiency is ~0.017 nm/mW.

An optical switch is used to connect optical fibers to each other and route data packets between the inputs and outputs of these fibers. Optical switches can either be all-optical, which forward the light signal without conversions or transformations, or OEO switches, which perform an optical-electronic-optical conversion before forwarding the data packets.

Before the emergence of MEMS-based (microelectromechanical system) switches, thermo-optic switches were based on MZIs (Mach-Zehdner Interferometer), but were low in port number. MEMS-based switches are now the most common optical switches, as they offer higher port counts, large bandwidth, low insertion loss and extinction ratios, and broadband operation [3].

They can be realized in 2D and 3D configurations. The 3D configuration offers more port count switches, with a mirror scaling of $\sqrt{N}$ compared to the 2D configuration requiring N^2 micro-mirrors for an NxN dimension switch. Furthermore, the crosstalk in 3D switches is inherently low, compared to the lowest measured crosstalk of <-50 dB in 2D switches. Crosstalk occurs in these switches due to unwanted diffraction of input light beams.
The port count in a 3D switch is determined by the diameter of beams and mirror rotation angle, whereas in a 2D switch, it is determined by the size of the mirrors.

Micromirrors are monolithically integrated as a microarray in the silicon substrate in a 2D switch, either by surface micro-machining or bulk micro-machining. The mirror angles can be rotated by electrostatic or electromagnetic force. When the mirrors are positioned horizontally (in line with the incoming light beams), the beams pass through them; when they are positioned vertically, the light beams get reflected to a corresponding output port, as shown in Fig. 3. This way, the mirrors route input beams to different output ports. In 3D mirrors, micromirrors can rotate on any two axes, allowing us to manipulate the output optical path. Thus, 3D switches offer more port count than 2D switches. Other switches include technologies such as liquid crystal on silicon (LCOS), semiconductor optical amplifiers (SOA), Mach-Zehdner interferometers (MZI), and micro-ring resonators (MRR) [4].

Photonic processing can be carried out by using grating couplers and microrings for multiplexing and demultiplexing operations. The grating can couple the x and y polarization of the signal into two waveguides. Wavelength demultiplexing can be carried out using two microrings of different resonating frequencies. Since coherent optical communications are very important in realizing long-range communications, it is important to have efficient, high-functioning QAM modulators integrated onto a chip.

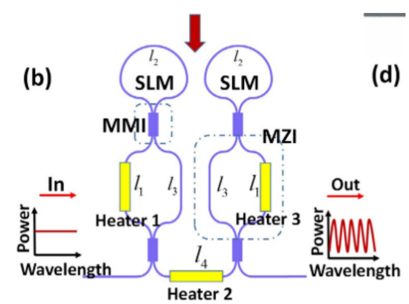

Fig. 2. Schematic of a silicon photonic comb. [3]

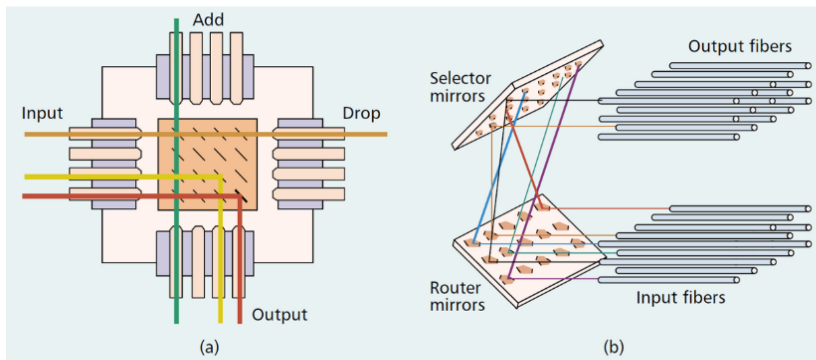

Fig 3. 2D and 3D micromirrors. These can be fabricated by either etching mechanical structures onto a silicon substrate (bulk micromachining) or by depositing epitaxial layers such as polysilicon, silicon nitride, and SiO_2, which are then patterned and selectively removed (surface micromachining). [4]

Discussion

In telecommunications, two broad applications of photonic integrated circuits are in **short and long-range communication**. Specifically in short-range communication, which is any communication within 2 km, there is a great potential for using PICs for optical connections within boards on a computing rack in a data center. Data centers require high-speed intra-network connections and routing, which can be facilitated by the use of Si photonics since it can support a high bitrate (>100 Gb/s of transmission) [2].

The current technology used for short-range connections is VCSELs (Vertical-Cavity Surface-Emitting Lasers), which are inexpensive but have a low bandwidth distance product (~2 GHz) over multimode fibers, which limits their connection distances to ~100m. This, along with the difficulty in producing single mode VSCELs, makes using PICs for short-range connections beneficial for newer data centers [2, 3].

PIC solutions for short-range inter-rack connections include using a Parallel Single-Mode fiber (PSM), which has a laser and grating integrated onto it. The laser beams, after being coupled to the PIC via the gratings, get split four ways to four 10 Gb/s on-off-keying MZMs (Mach-Zehdner interferometer modulators).

Another solution is to use WDM (Wavelength Division Multiplexing), in which four OOK modulated wavelengths of 25 Gb/s each are multiplexed in the transmitter and demultiplexed at the receiver. This involves only 2 fibers, as compared to the 8 fibers needed in PSM, but it also requires 4 lasers, which make the circuit bulkier. Other methods include PAM (Polarization Amplitude Modulation) and DP (Dual Polarization) transmission [3].

Reducing the number of fibers used in a data center will greatly reduce the visual complexity of interconnects in the data center. WDM-based techniques will be the most efficient and cost-effective way of implementing low-fiber number interconnects. Moreover, utilizing multimode fibers, while expensive, will prevent having to cross waveguides, and will allow a convenient demultiplexing using a star coupler [2, 4].

On the other hand, long-range communications require intradyne coherent transmission because installing long fiber lines is expensive and can lead to many faults along the fiber line. Intradyne coherent receivers can receive WDM, PDM, and high-order constellations with good performance due to receiving the complete optical field from the fiber, which is acted upon by a digital signal processor [3]. Since the world depends on long-range communication, QPSK modulators are in high demand and can be fabricated using various MRRs. This way, PICs can be used for optical processing can be carried out to aid long-range communication, and routing and OEO conversion to allow short-range interconnects in data centers.

Quantum computation is another area in which photonic integrated circuits could play a big role in development. Due to the existing infrastructure for photonic transmission (optical fiber cable network), the photonic quantum key distribution could bring forth a new era of secure transmission. Moreover, quantum computing architectures such as ion trap computers could use ion-photon interconnects [5] for non-local computation; photonic quantum computers, on the other hand, will benefit the most from the integration of lasing, detecting, modulating, and routing devices onto chips. Quantum memories require low-loss waveguides and low-loss passive components to ensure fidelity of the qubit is maintained before computation. Current problems in Linear Optical Quantum Computation are lossy memories, probabilistic generation of photons (using parametric down conversion), and faulty detectors (bucket or number-resolving) [6] , to name a few.

Silicon-based PICs would require integration with other materials (III-V materials) to overcome the indirect bandgap that makes silicon a non-ideal platform for lasing. Integration with InP or III-V materials allows lasing to occur on the same monolith [7]. Moreover, in linear photonic quantum computing, quantum gates using birefrignent plates, waveguides, beamsplitters, and interferometers can be fabricated on integrated chips as well, which would allow scaling up the number of qubits and number of operations that can be carrier out in one set up of the computer.

Conclusion

The pre-existing, mature infrastructure used to build CMOS devices and its ease of integration with Silicon PICs makes Silicon a strong contender in the PIC space. Indium's rarity and the consequent higher cost also boosts the use of silicon instead of InP in fabricating photonic integrated circuits. Currently, InP is commonly used in more specialized applications which require lasing and detection, such as in quantum computing. Developments in the Si+ fabrication space will create new options for quantum computing researchers to use hybrid platforms for photonic quantum networks.

These reasons, and the ability to manufacture these devices with moderate to high integration, make Silicon PICs a better fit for telecommunications and network interconnect applications [2], and push Si+ PICs to the forefront of the race to realize photonic quantum computation using PICs (hybrid).

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