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Review

On-chip silicon photonic signaling and processing: a review

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ABSTRACT

The arrival of the big data era has driven the rapid development of high-speed optical signaling and processing, ranging from long-haul optical communication links to short-reach data centers and high-performance computing, and even micro-/nano-scale inter-chip and intra-chip optical interconnects. On-chip photonic signaling is essential for optical data transmission, especially for chip-scale optical interconnects, while on-chip photonic processing is a critical technology for optical data manipulation or processing, especially at the network nodes to facilitate ultracompact data management with low power consumption. In this paper, we review recent research progress in on-chip photonic signaling and processing on silicon photonics platforms. Firstly, basic key devices (lasers, modulators, detectors) are introduced. Secondly, for on-chip photonic signaling, we present recent works on on-chip data transmission of advanced multi-level modulation signals using various silicon photonic integrated devices (microring, slot waveguide, hybrid plasmonic waveguide, subwavelength grating slot waveguide). Thirdly, for on-chip photonic processing, we summarize recent works on on-chip data processing of advanced multi-level modulation signals exploiting linear and nonlinear effects in different kinds of silicon photonic integrated devices (strip waveguide, directional coupler, 2D grating coupler, microring, silicon-organic hybrid slot waveguide). Various photonic processing functions are demonstrated, such as photonic switch, filtering, polarization/wavelength/mode (de)multiplexing, wavelength conversion, signal regeneration, optical logic and computing. Additionally, we also introduce extended silicon+ photonics and show recent works on on-chip graphene-silicon photonic signal processing. The advances in on-chip silicon photonic signaling and processing with favorable performance pave the way to integrate complete optical communication systems on a monolithic chip and integrate silicon photonics and silicon nanoelectronics on a chip. It is believed that silicon photonics will enable more and more emerging advanced applications even beyond silicon photonic signaling and processing.

1. Introduction

The origin of silicon photonics can be dated back to Soref's very early works in 1980s [1,2]. Fig. 1 shows the advantages, materials, device classification, and applications of silicon photonics. With 30 years of development, especially the rapid breakthrough in the last decade, silicon photonics has become one of the most suitable platforms for integrated optics owing to its low power consumption, low cost, small footprint, and most importantly, complementary metal-oxidesemiconductor (CMOS) compatibility [3–6]. Fabricating very low cost photonic devices using the mature integrated circuit industry is the most important motivation for silicon photonics researchers. In addition, the refractive index of silicon is about 3.5 at telecommunication wavelengths, which is greatly larger than silica (~1.414), leading to high index contrast of the silicon waveguide. Such strong light confinement of silicon waveguides makes it possible to integrate a great number of optical devices in a millimeter level. The high index contrast of the silicon waveguide also provides strong light-matter interactions, which make it possible to observe evident optical nonlinearities, such as four-wave mixing, self-phase modulation, cross-phase modulation, and so on [7]. The typical materials adopted in silicon photonics include silicon-on-insulator (SOI), SiN, GeSi, Ge-on-Si, silicon nanocrystal (Si-nc), and so on. SOI is the most commonly used material in silicon photonics. SiN is the most suitable material for passive devices, owing to its ultra-low loss (several dB/m). GeSi can be used for low-energy electro-absorption modulators, while Ge-on-Si is always used for high-speed on-chip detectors. Si-nc is considered to be a great material for nonlinear photonics applications. Silicon photonic devices can be divided from three different aspects of considerations. According to the waveguide structure of the devices, they can be divided into optical I/O, waveguide, ring resonator, Mach-Zehnder interferometer (MZI), multimode

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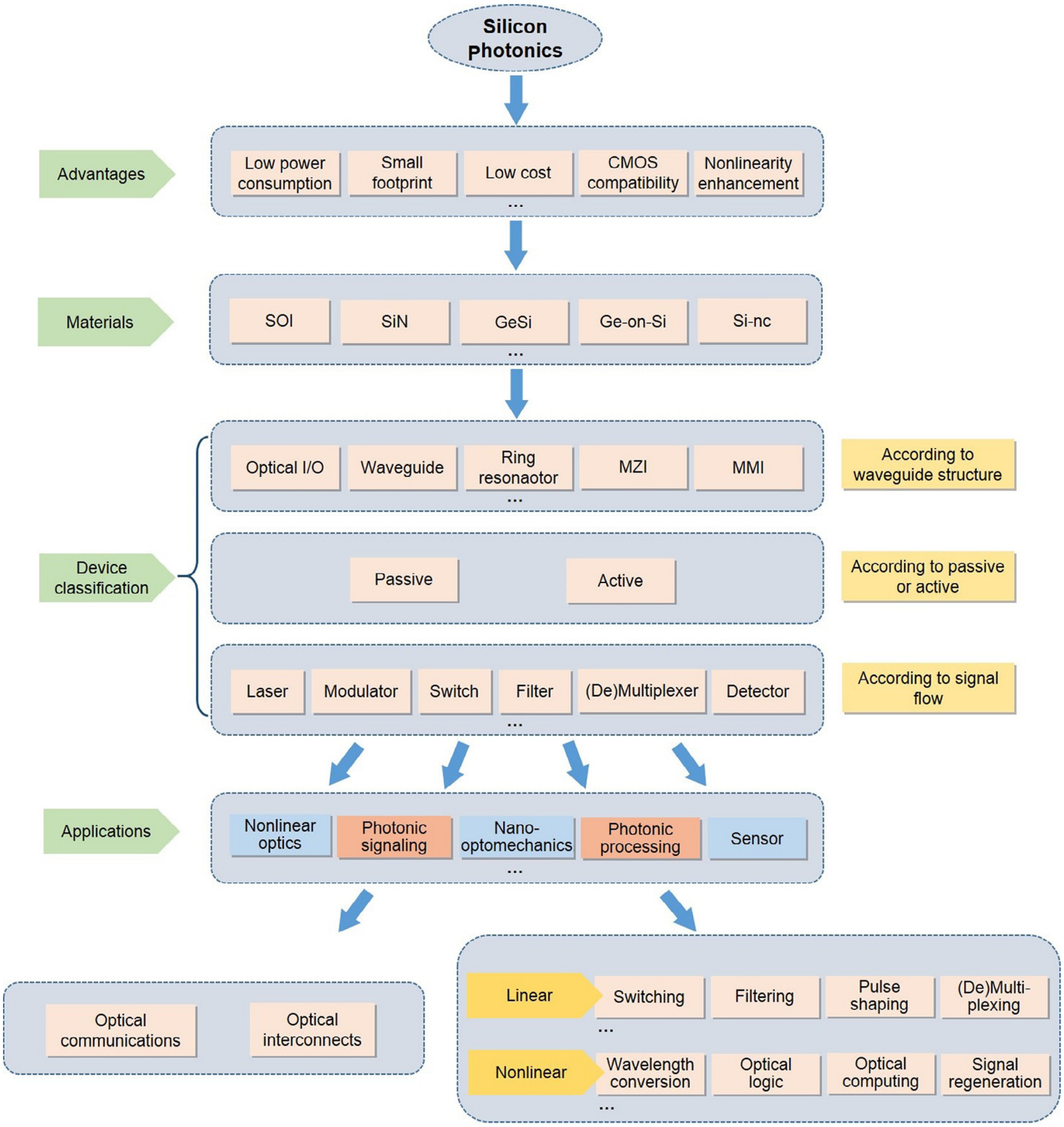

Fig. 1. (Color online) Advantages, materials, device classification, and applications of silicon photonics.

interferometer (MMI), and so forth. Also, silicon photonic devices can be divided into passive and active devices. Another point of view is the signal flow. Light is generated from a laser, and modulated by a modulator, processed by passive devices, such as switch, filter and (de)multiplexer, and finally detected by a detector. According to such signal flow, silicon photonic devices can be also classified by laser, modulator, switch, filter, (de)multiplexer, detector, and so on. The applications of silicon photonics include nonlinear optics [7–18], photonic signaling [6,19–36], nano-optomechanics [37–40], photonic processing [41], sensors [42–46], mid-infrared optics [47–51], terahertz technology [52,53], and so on.

The dominant applications for silicon photonics are photonic signaling and photonic processing. Generally, photonic signaling can be divided into optical communications and interconnects, owing to the application scenario, especially the communication distance of the link, as shown in Fig. 2. Data transmission in the distance from deep-space mission to access network can be classified into optical communications, while data center and high-performance computing applications from rack-to-rack transmission to on-chip transmission can be classified into optical interconnects. In optical communications and interconnects, high baudrate data signal is directly modulated onto the optical carrier for long-haul or short-reach data transmission. Photonic processing technologies are of great importance in optical communication systems because they can overcome the electronics bottlenecks, offering ultra-fast signal processing. In general, photonic processing technologies can be divided into two classes, i.e. linear and nonlinear photonic signal processing. Linear photonic signal processing includes switching [54,55], filtering [56–60], optical pulse shaping [61,62], differentiation [63–66], wavelength/mode/polarization (de)multiplexing [67–71], and so on. Nonlinear photonic signal processing exploits various nonlinear phenomena. There are a lot of optical material platforms for nonlinear photonic signal processing, including highly nonlinear fibers (HNLFs) [72–82], semiconductor optical amplifiers (SOAs) [83–85], chalcogenide waveguides [86], and periodically poled lithium niobate (PPLN) waveguides [87–101]. Based on these material platforms, a number of widely used functionalities have been demonstrated, including optical multiplexing and demultiplexing, wavelength conversion, optical logic and computing, signal regeneration, equalizer, optical switch, optical memory, and so on. However, devices based on the aforementioned material platforms have relatively large footprint, and are lack of abilities for massive