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.

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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-oxide-semiconductor (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 ultralow 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...
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

Fig. 1. (Color online) Advantages, materials, device classification, and applications of silicon photonics.
integration. The development of silicon photonics offers the possibility to perform photonic signal processing on an ultracompact silicon chip [54–71,102–114]. Silicon-on-insulator (SOI) platform is quite suitable for linear photonic signal processing for its low loss and ultracompact footprint. Moreover, nonlinearities enhanced by the tight light confinement of SOI waveguide also facilitate photonic signal processing functionalities assisted by optical nonlinearities.

Very recently, with the ever increasing demand for high-speed data transmission and management in fiber-optic communications, data centers, high-performance computing, inter-chip and intra-chip optical networks, photonic signaling and processing technologies using advanced multi-level modulation signals have attracted a lot of attention [115–117]. Moreover, optical signaling and processing based on photonic integrated circuits have distinct advantages of low interconnect latency, large bandwidth, free of electromagnetic interferences, and low power consumption. In particular, among various kinds of photonic integration platforms, silicon photonics is considered to be the most promising platform for on-chip photonic signaling and processing for its low cost and CMOS compatibility for mass production. In this scenario, a laudable goal would be to combine advanced multi-level modulation signals, photonic integrated circuits and silicon photonics together to enable on-chip silicon photonic signal and processing. The main research topics include on-chip signaling (transmission, transmission/interconnects) and processing. For on-chip transceivers, a lot of photonic integrated devices providing laser sources, signal modulation and detection have been demonstrated, including lasers [118–121, modulators [122–126] and detectors [127–130]. For on-chip signaling or data transmission/interconnects, different kinds of photonic integrated devices have been considered, including strip waveguide [131–133], microring [134,135], slot waveguide [136], photonic crystal waveguide [137,138], subwavelength grating waveguide [6,139,140], and hybrid plasmonic waveguide [141–147]. For on-chip processing, various photonic integrated devices have been reported, such as strip waveguide [105,111,112], 2D grating coupler [69], microring [103,104,107,108], and silicon-organic hybrid slot waveguide [106].

In this paper, we review the recent progress in silicon-based on-chip photonic signaling and processing for handing high-speed advanced multi-level modulation signals on photonic integration platforms. For on-chip photonic signaling, we first briefly introduce the development of silicon-based lasers, modulators, and detectors. After that, we present recent works on on-chip data transmission of advanced multi-level modulation signals. Various silicon photonic integrated devices (microring, slot waveguide, hybrid plasmonic waveguide, subwavelength grating slot waveguide) are taken into consideration. For on-chip photonic processing, we present recent works on on-chip data processing of advanced multi-level modulation signals. Both linear and nonlinear effects in different kinds of photonic integrated devices (strip waveguide, directional coupler, 2D grating coupler, microring, silicon-organic hybrid slot waveguide) are used to facilitate various photonic processing functions such as photonic switch, filtering, (de)multiplexing, wavelength conversion, signal regeneration, optical logic and computing. In addition, we also introduce extended silicon photonics and present recent works on on-chip graphene-silicon photonic signal processing. Finally, we briefly discuss some other emerging advanced applications beyond silicon photonic signaling and processing.

2. Lasers, modulators and detectors on silicon platforms

As mentioned above, photonic signaling and processing are two important application areas of silicon photonics. Lasers, modulators and detectors are the main required basic devices for silicon photonic signaling and processing applications. In this section, we review the history and development of silicon based lasers, modulators and detectors [118–130,148–223].

2.1. Lasers

The most challenging problem in silicon photonics is to develop a practical on-chip laser source. There have been a lot of works on this topic in recent years [118–121,148–178]. Silicon is an indirect bandgap material, which lacks of emitting efficiency essentially [148]. Current research efforts mainly focus on four kinds of technologies: stimulated Raman scattering (SRS), Erbium (Er) doping, germanium epitaxial, and III–V based laser. Table 1 shows a brief summary of the general behaviors of the four kinds of lasers in silicon photonics. The idea of developing SRS in silicon waveguides for light amplifying and lasing was first proposed in 2002 [149]. Subsequently, several demonstrations of silicon Raman-based lasers have been reported [118–120,150]. However, due to the intrinsic optical-pumping mechanism of SRS, silicon Raman lasers could not meet the needs of the practical applications in optical communications and interconnects. Another developing technology for silicon photonics lasers is rare-earth doping. Commonly used materials include Er-doped Si-rich materials and Er compound materials [151–155]. Er is used as an atomic luminescent center when constructing Er doping light source. However, the light emission of Er doping sources have very low efficiency because of its lack of erbium excitation efficiency [156]. Although many research efforts have been applied to Er doping lasers, these sources are still impracticable for real applications. Ge-on-Si on-chip laser is more realistic, compared with Er doping laser. Although Ge is also an indirect band semiconductor, the band structure of Ge can be engineered, which allows it to operate at approximately 1,550 nm band. The first Ge-on-Si laser was proposed theoretically in 2007 [157]. There are three most commonly used methods to engineer the band structure of Ge, i.e. n-type doping [158], tensile strain [159], and germanium-tin (GeSn) alloy [160]. The development of Ge-on-Si laser light is very fast owing to the successful bandgap engineering of Ge. A great milestone of...
Table 1
A summary of silicon-based lasers.

<table>
<thead>
<tr>
<th>Year</th>
<th>Classification</th>
<th>Output power</th>
<th>Threshold pump power/current</th>
<th>Linewidth</th>
<th>Image</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>SRS</td>
<td>40 μW</td>
<td>400 mW</td>
<td>–</td>
<td><img src="image1.png" alt="Image" /></td>
<td>[118]</td>
</tr>
<tr>
<td>2005</td>
<td>SRS</td>
<td>9 mW</td>
<td>180 mW</td>
<td>80 MHz</td>
<td><img src="image2.png" alt="Image" /></td>
<td>[119]</td>
</tr>
<tr>
<td>2006</td>
<td>III–V based laser (bonding)</td>
<td>1.8 mW</td>
<td>65 mA</td>
<td>–</td>
<td><img src="image3.png" alt="Image" /></td>
<td>[172]</td>
</tr>
<tr>
<td>2006</td>
<td>Er doping</td>
<td>10 μW</td>
<td>43 μW</td>
<td>–</td>
<td><img src="image4.png" alt="Image" /></td>
<td>[152]</td>
</tr>
<tr>
<td>2007</td>
<td>SRS</td>
<td>10 mW</td>
<td>26 mW</td>
<td>&lt;100 kHz</td>
<td><img src="image5.png" alt="Image" /></td>
<td>[120]</td>
</tr>
<tr>
<td>2009</td>
<td>III–V based laser (bonding)</td>
<td>12.7 mW</td>
<td>1 kA/cm²</td>
<td>–</td>
<td><img src="image6.png" alt="Image" /></td>
<td>[173]</td>
</tr>
<tr>
<td>2012</td>
<td>Germanium epitaxial</td>
<td>1 mW</td>
<td>280 kA/cm²</td>
<td>&lt;1.2 nm</td>
<td><img src="image7.png" alt="Image" /></td>
<td>[161]</td>
</tr>
<tr>
<td>Year</td>
<td>Classification</td>
<td>Output power</td>
<td>Threshold pump power/current</td>
<td>Linewidth</td>
<td>Image</td>
<td>Ref.</td>
</tr>
<tr>
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<td>-----------</td>
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<td>------</td>
</tr>
<tr>
<td>2014</td>
<td>III–V based laser (direct mounting)</td>
<td>20 mW</td>
<td>39 mA</td>
<td>27 MHz</td>
<td><img src="image1.png" alt="Image" /></td>
<td>[174]</td>
</tr>
<tr>
<td>2014</td>
<td>III–V based laser (hetero-epitaxial)</td>
<td>100 mW</td>
<td>200 A/cm²</td>
<td>–</td>
<td><img src="image2.png" alt="Image" /></td>
<td>[167]</td>
</tr>
<tr>
<td>2014</td>
<td>Er doping</td>
<td>27 µW</td>
<td>0.5 mW</td>
<td>&lt;20 pm</td>
<td><img src="image3.png" alt="Image" /></td>
<td>[175]</td>
</tr>
<tr>
<td>2015</td>
<td>Germanium epitaxial</td>
<td>–</td>
<td>325 kW/cm²</td>
<td>–</td>
<td><img src="image4.png" alt="Image" /></td>
<td>[162]</td>
</tr>
<tr>
<td>2016</td>
<td>III–V based laser (hetero-epitaxial)</td>
<td>105 mW</td>
<td>62.5 A/cm²</td>
<td>2.4 nm</td>
<td><img src="image5.png" alt="Image" /></td>
<td>[176]</td>
</tr>
<tr>
<td>2017</td>
<td>III–V based laser (hetero-epitaxial)</td>
<td>95 µW</td>
<td>43 µA</td>
<td>&lt;0.1 nm</td>
<td><img src="image6.png" alt="Image" /></td>
<td>[177]</td>
</tr>
<tr>
<td>2018</td>
<td>III–V based laser (transfer-printing)</td>
<td>2 mW</td>
<td>18 mA</td>
<td>–</td>
<td><img src="image7.png" alt="Image" /></td>
<td>[178]</td>
</tr>
</tbody>
</table>
ge-on-si laser is the demonstration of the first electrically pumped Ge-on-Si laser [161]. Another important progress is the demonstration of optically pumped GeSn laser using CMOS processing [162]. With further improvement, Ge-on-Si laser can be a competitive candidate for on-chip lasers in silicon photonics. However, III-V based laser is still considered to be the most practical on-chip sources in silicon photonics up to now, owing to the direct bandgap structure of III-V semiconductors. There are three main integration approaches to realize III-V based lasers: mounting integration, bonding based heterogeneous integration, and direct epitaxial growing. The main disadvantage of direct mounting integration is the end coupling between silicon waveguide and III-V material, where submicron precision alignment is needed. For the heterogeneous integration based on bonding, the light generated in the III-V material is evanescently coupled into the silicon waveguides. Thus, it is free of the consideration of lattice match limitations. High-quality bonding, with ultra-thin bonding layers has been demonstrated, which is suitable for the fabrication of hybrid III-V/Si lasers. These lasers show the best performance as far. However, this approach is not a perfect integration approach, which has some limitations such as high cost, no mass production, and so on. The third approach is direct epitaxial growing. The main issue of direct hetero-epitaxial growth is high-density threading dislocations, related to the large lattice mismatch between III and V materials and silicon. Various methods have been proposed to lower the threading dislocations, such as inserting a buffer layer [163,164], epitaxial lateral overgrowth technique [165,166], and utilizing quantum dots (QDs) [167–170]. Until now, it is possible to fabricate InAs/GaAs QD silicon lasers with large output power (>100 mW) and high temperature stability (>100 °C) using hetero-epitaxial growth approach [167,171]. In addition to the three main hybrid integration approaches discussed above, it should be noted that there are still some other novel process which may be possible for hybrid III-V/Si integration. For example, very recently Zhang et al. [178] proposed a transfer-printing-based method to integrate distributed feedback (DFB) laser on an SOI substrate.

2.2. Modulators

The performance of silicon-based optical modulators has been improved dramatically in the last decade owing to the significant research efforts from both academic institutions and corporations [122–126,179–200]. Table 2 shows a brief summary of silicon-based optical modulators in the last decade. Early demonstrations of silicon modulators are mainly based on metal–oxide–semiconductor (MOS) capacitor or pin diode. The first silicon modulator with modulation bandwidth up to GHz, which is based on MOS capacitor, was fabricated by Intel Corporation in 2004 [179]. In 2005, Xu et al. [180] demonstrated the first sub-wavelength waveguide based silicon modulator using a silicon microring resonator (MRR) constructed by a forward-biased pin diode. The device footprint of this modulator is only about $10^2 \, \mu \text{m}^2$. After these two precursory works, silicon optical modulators have attracted many research attentions. In 2007, Liu et al. [183] proposed a silicon modulator based on vertical pn diode structure. The utilization of pn diode greatly improves the speed of the silicon modulators owing to the fast free carrier effect (FCE) in the pn junction. To simplify the fabrication process of modulators, subsequent research efforts based on pn junctions mainly focus on lateral pn junctions. Based on lateral pn junctions, the modulation speed of on-off keying (OOK) signal can be as high as 70 Gbit/s now [195]. Due to the wide use of coherent optical communications, I-Q modulator is highly desired. In 2012, Dong et al. [190] reported the first I-Q modulator on silicon. 50 Gbit/s quadrature phase-shift keying (QPSK) signal was successfully modulated using this modulator. A record bitrate of 321.4 Gbit/s based on polarization-division multiplexing 16-ary quadrature amplitude modulation (PDM-16-QAM) using a nested 1-Q modulator was demonstrated in 2016 [197]. Another consideration of silicon modulators is the operating wavelength. In addition to the well developed 1.55 μm band, optical modulators operating at 1.3 μm band (O-band) for potential optical interconnects applications have been reported [192,194]. Moreover, owing to the great potential of using mid-infrared wavelength for future optical networks, silicon modulators working around 2 μm have also been demonstrated [191,200]. Results show that silicon modulators at 2 μm can be more compact and lower power consumption than 1.55 μm band [200].

2.3. Detectors

Detector is another key device for silicon-based photonic signaling and processing applications. Ge-on-Si detectors are the most widely studied devices for optical signal detection on silicon platforms [127–130,201–223]. Initially, high-performance Ge-on-Si photodetectors were all the normal-incidence detectors, where light was launched into the detectors through fiber coupling or free space [201–208]. To achieve compact circuits on a silicon chip, waveguide-integrated Ge-on-Si detectors have developed rapidly in the last decade. Compared to the normal-incidence detectors, the absorption length of waveguide-based detectors increases. As a consequence, the trade-off between quantum efficiency and bandwidth for normal-incidence detectors vanishes. Thus the waveguide-based detectors can achieve high-speed operation and high quantum efficiency simultaneously. Furthermore, the device footprint of waveguide-based detectors is much smaller than normal-incidence detectors, so the dark current of waveguide-based detectors can also maintain at a relatively low level. After the first report of waveguide-based detectors, the performance of silicon photonic detectors has been improved rapidly. Table 3 summarizes several reported demonstrations on waveguide-based Ge-on-Si detectors. Three coupling schemes between the silicon waveguide and Ge detector are possible depending on the relative position of silicon waveguide and Ge detector region. In the first configuration, silicon waveguide is lied on the top of the Ge detector. The light is coupled to the Ge detector through evanescent wave [209]. The second configuration is to butt-couple the silicon waveguide to the Ge detector [210–214]. Although butt-coupling has large coupling efficiency, the most popular configuration of waveguide-based Ge-on-Si detectors is the third configuration, where the silicon waveguide is located underneath the Ge detector, because of its ability of integration in a CMOS process [210,215–221]. As shown in Table 3, most of the recently demonstrated high performance Ge-on-Si detectors are based on the bottom-coupling configuration. Using a new silicon-contacted scheme, state-of-the-art waveguide-based Ge-on-Si detectors can achieve high responsivity (around 1 A/W), high bandwidth (around 70 GHz), and low dark current (<0.01 μA) simultaneously [220,221].

3. On-chip silicon photonic signaling (transmission/interconnects)

In this section, we first introduce several kinds of silicon waveguide structures, and then review their applications in on-chip signal photonic signaling [135,136,146,147,224,225].

3.1. Silicon waveguide structures

There are various kinds of silicon photonic devices used for on-chip signaling or on-chip signal transmission/interconnects.
<table>
<thead>
<tr>
<th>Year</th>
<th>Structure</th>
<th>Doping</th>
<th>Speed</th>
<th>Modulation voltage</th>
<th>Loss</th>
<th>Modulation format</th>
<th>Working wavelength</th>
<th>Image</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>MZI</td>
<td>MOS</td>
<td>1 Gbps</td>
<td>6 V</td>
<td>6.7 dB</td>
<td>OOK</td>
<td>~1550 nm, broadband</td>
<td><img src="179" alt="Image" /></td>
<td>[179]</td>
</tr>
<tr>
<td>2005</td>
<td>MRR</td>
<td>pin</td>
<td>1.5 Gbps</td>
<td>6.9 V</td>
<td>&lt;0.5 dB</td>
<td>OOK</td>
<td>~1550 nm, ~0.1 nm width</td>
<td><img src="180" alt="Image" /></td>
<td>[180]</td>
</tr>
<tr>
<td>2005</td>
<td>MZI</td>
<td>MOS</td>
<td>10 Gbps</td>
<td>1.4 V</td>
<td>10 dB</td>
<td>OOK</td>
<td>~1550 nm, broadband</td>
<td><img src="181" alt="Image" /></td>
<td>[181]</td>
</tr>
<tr>
<td>2007</td>
<td>MRR</td>
<td>pin</td>
<td>12.5 Gbps</td>
<td>3.5 V</td>
<td>&lt;0.5 dB</td>
<td>OOK</td>
<td>~1550 nm, ~0.1 nm width</td>
<td><img src="182" alt="Image" /></td>
<td>[182]</td>
</tr>
<tr>
<td>2007</td>
<td>MZI</td>
<td>Vertical pn</td>
<td>30 Gbps</td>
<td>6.5 V</td>
<td>7 dB</td>
<td>OOK</td>
<td>~1550 nm, broadband</td>
<td><img src="183" alt="Image" /></td>
<td>[183]</td>
</tr>
<tr>
<td>2009</td>
<td>MRR</td>
<td>pn</td>
<td>&gt;10 Gbps</td>
<td>2 V</td>
<td>2 dB</td>
<td>OOK</td>
<td>~1550 nm, broadband</td>
<td><img src="184" alt="Image" /></td>
<td>[184]</td>
</tr>
<tr>
<td>2010</td>
<td>MZI</td>
<td>pn</td>
<td>10 Gbps</td>
<td>5 V</td>
<td>–</td>
<td>OOK</td>
<td>~1550 nm, broadband</td>
<td><img src="185" alt="Image" /></td>
<td>[185]</td>
</tr>
<tr>
<td>2010</td>
<td>MZI</td>
<td>pn</td>
<td>12.5 Gbps</td>
<td>6 V</td>
<td>2.5 dB</td>
<td>OOK</td>
<td>~1550 nm, broadband</td>
<td><img src="186" alt="Image" /></td>
<td>[186]</td>
</tr>
<tr>
<td>2011</td>
<td>MZI</td>
<td>pn</td>
<td>25 Gbps</td>
<td>6 V</td>
<td>5 dB</td>
<td>OOK</td>
<td>~1550 nm, broadband</td>
<td><img src="187" alt="Image" /></td>
<td>[187]</td>
</tr>
</tbody>
</table>

(continued on next page)
<table>
<thead>
<tr>
<th>Year</th>
<th>Structure</th>
<th>Doping</th>
<th>Speed</th>
<th>Modulation voltage</th>
<th>Loss</th>
<th>Modulation format</th>
<th>Working wavelength</th>
<th>Image</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>MRR</td>
<td>pn</td>
<td>44 Gbps</td>
<td>3 V</td>
<td>–</td>
<td>OOK</td>
<td>~1550 nm, ~0.2 nm width</td>
<td><img src="image1.png" alt="image" /></td>
<td>[124]</td>
</tr>
<tr>
<td>2012</td>
<td>MZI</td>
<td>pn</td>
<td>50 Gbps</td>
<td>5 V</td>
<td>~4 dB</td>
<td>OOK</td>
<td>~1550 nm, broadband</td>
<td><img src="image2.png" alt="image" /></td>
<td>[188]</td>
</tr>
<tr>
<td>2012</td>
<td>MRR</td>
<td>pn</td>
<td>20 Gbps</td>
<td>6 V</td>
<td>~10.5 dB</td>
<td>QPSK</td>
<td>~1550 nm, ~0.1 nm width</td>
<td><img src="image3.png" alt="image" /></td>
<td>[189]</td>
</tr>
<tr>
<td>2012</td>
<td>MZIs</td>
<td>pn</td>
<td>50 Gbps</td>
<td>12 V</td>
<td>–</td>
<td>QPSK</td>
<td>~1550 nm, broadband</td>
<td><img src="image4.png" alt="image" /></td>
<td>[190]</td>
</tr>
<tr>
<td>2012</td>
<td>MZIs</td>
<td>pn</td>
<td>112 Gbps</td>
<td>12 V</td>
<td>~10 dB</td>
<td>PDM-QPSK</td>
<td>~1550 nm, broadband</td>
<td><img src="image5.png" alt="image" /></td>
<td>[34]</td>
</tr>
<tr>
<td>2012</td>
<td>MZI</td>
<td>pin</td>
<td>3 Gbps</td>
<td>1.08 V</td>
<td>9 dB</td>
<td>OOK</td>
<td>~2165 nm, broadband</td>
<td><img src="image6.png" alt="image" /></td>
<td>[191]</td>
</tr>
<tr>
<td>2013</td>
<td>MZI</td>
<td>pn</td>
<td>60 Gbps</td>
<td>6.5 V</td>
<td>1.9 dB</td>
<td>OOK</td>
<td>~1550 nm, broadband</td>
<td><img src="image7.png" alt="image" /></td>
<td>[125]</td>
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<tr>
<td>2013</td>
<td>MZI</td>
<td>pn</td>
<td>50 Gbps</td>
<td>1.5 V</td>
<td>5.5 dB</td>
<td>OOK</td>
<td>~1300 nm, broadband</td>
<td><img src="image8.png" alt="image" /></td>
<td>[192]</td>
</tr>
<tr>
<td>2013</td>
<td>MZIs</td>
<td>pn</td>
<td>224 Gbps</td>
<td>5 V</td>
<td>~10 dB</td>
<td>PDM-16-QAM</td>
<td>~1550 nm, broadband</td>
<td><img src="image9.png" alt="image" /></td>
<td>[193]</td>
</tr>
<tr>
<td>2014</td>
<td>MRR</td>
<td>pn</td>
<td>40 Gbps</td>
<td>4.8 V</td>
<td>7 dB</td>
<td>OOK</td>
<td>~1310 nm, ~0.37 nm width</td>
<td><img src="image10.png" alt="image" /></td>
<td>[194]</td>
</tr>
<tr>
<td>2014</td>
<td>MZI</td>
<td>pn</td>
<td>70 Gbps</td>
<td>5.32 V</td>
<td>~3.3 dB</td>
<td>OOK</td>
<td>~1550 nm, broadband</td>
<td><img src="image11.png" alt="image" /></td>
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<table>
<thead>
<tr>
<th>Year</th>
<th>Structure</th>
<th>Doping</th>
<th>Speed</th>
<th>Modulation voltage</th>
<th>Loss</th>
<th>Modulation format</th>
<th>Working wavelength</th>
<th>Image</th>
<th>Ref.</th>
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<tr>
<td>2015</td>
<td>MZI</td>
<td>pn</td>
<td>112 Gbps</td>
<td>2.2 V</td>
<td>4.5 dB</td>
<td>PAM-4</td>
<td>~1550 nm, broadband</td>
<td><img src="image1.png" alt="Image" /></td>
<td>[196]</td>
</tr>
<tr>
<td>2016</td>
<td>MRR</td>
<td>pn</td>
<td>45 Gbps</td>
<td>2.2 V</td>
<td>&lt;1 dB</td>
<td>PAM-8</td>
<td>~1550 nm, ~0.1 nm width</td>
<td><img src="image2.png" alt="Image" /></td>
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<tr>
<td>2016</td>
<td>MZIs</td>
<td>pn</td>
<td>321.4 Gbps</td>
<td>–</td>
<td>–</td>
<td>PDM-16-QAM</td>
<td>~1550 nm, broadband</td>
<td><img src="image3.png" alt="Image" /></td>
<td>[197]</td>
</tr>
<tr>
<td>2017</td>
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<td>90 Gbps</td>
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<td>–</td>
<td>OOK</td>
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<tr>
<td>2017</td>
<td>MZI</td>
<td>pn</td>
<td>128 Gbps</td>
<td>4 V</td>
<td>4.3 dB</td>
<td>PAM-4</td>
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<td><img src="image5.png" alt="Image" /></td>
<td>[199]</td>
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### Table 3
A summary of waveguide-based Ge-on-Si detectors.

<table>
<thead>
<tr>
<th>Year</th>
<th>Responsivity</th>
<th>Bandwidth</th>
<th>Dark current</th>
<th>Coupling scheme</th>
<th>Image</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>1 A/W</td>
<td>4.5 GHz @3 V</td>
<td>0.0002 μA @1 V</td>
<td>Butt</td>
<td><img src="image6.png" alt="Image" /></td>
<td>[210,211]</td>
</tr>
<tr>
<td>2006</td>
<td>0.2 A/W</td>
<td>1.5 GHz @4 V</td>
<td>–</td>
<td>Bottom</td>
<td><img src="image7.png" alt="Image" /></td>
<td>[210]</td>
</tr>
<tr>
<td>2007</td>
<td>1.08 A/W</td>
<td>7.2 GHz @1 V</td>
<td>1 μA @1 V</td>
<td>Top</td>
<td><img src="image8.png" alt="Image" /></td>
<td>[209]</td>
</tr>
<tr>
<td>2007</td>
<td>0.89 A/W</td>
<td>31.3 GHz @2 V</td>
<td>0.17 μA @2 V</td>
<td>Bottom</td>
<td><img src="image9.png" alt="Image" /></td>
<td>[215]</td>
</tr>
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</table>

(continued on next page)
<table>
<thead>
<tr>
<th>Year</th>
<th>Responsivity</th>
<th>Bandwidth</th>
<th>Dark current</th>
<th>Coupling scheme</th>
<th>Image</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>0.85 A/W</td>
<td>26 GHz @1 V</td>
<td>3 μA @2 V</td>
<td>Bottom</td>
<td><img src="image1.png" alt="Image" /></td>
<td>[216]</td>
</tr>
<tr>
<td>2009</td>
<td>1.1 A/W</td>
<td>32 GHz @1 V</td>
<td>1.3 μA @1 V</td>
<td>Butt</td>
<td><img src="image2.png" alt="Image" /></td>
<td>[212]</td>
</tr>
<tr>
<td>2009</td>
<td>1 A/W</td>
<td>42 GHz @1 V</td>
<td>0.018 μA @1 V</td>
<td>Butt</td>
<td><img src="image3.png" alt="Image" /></td>
<td>[213]</td>
</tr>
<tr>
<td>2011</td>
<td>0.95 A/W</td>
<td>36 GHz @1 V</td>
<td>0.046 μA @1 V</td>
<td>Bottom</td>
<td><img src="image4.png" alt="Image" /></td>
<td>[217]</td>
</tr>
<tr>
<td>2012</td>
<td>0.8 A/W</td>
<td>&gt;67 GHz @2 V</td>
<td>4 μA @1 V</td>
<td>Butt</td>
<td><img src="image5.png" alt="Image" /></td>
<td>[214]</td>
</tr>
<tr>
<td>2013</td>
<td>0.75 A/W</td>
<td>60 GHz @2 V</td>
<td>3 μA @1 V</td>
<td>Bottom</td>
<td><img src="image6.png" alt="Image" /></td>
<td>[218]</td>
</tr>
<tr>
<td>2015</td>
<td>0.85 A/W</td>
<td>60 GHz @4 V</td>
<td>0.061 μA @0.5 V</td>
<td>Bottom</td>
<td><img src="image7.png" alt="Image" /></td>
<td>[219]</td>
</tr>
<tr>
<td>2015</td>
<td>1 A/W</td>
<td>&gt;70 GHz @1 V</td>
<td>0.1 μA @1 V</td>
<td>Bottom</td>
<td><img src="image8.png" alt="Image" /></td>
<td>[220]</td>
</tr>
</tbody>
</table>
Fig. 3 shows some frequently used silicon waveguide structures. Silicon strip waveguide, also known as channel waveguide, is the most commonly used waveguide structure (i.e. building block). Such waveguide is typically used for compact optical routing as it offers tight bending radius. The rib waveguide is widely used for electrooptic devices such as modulators because it allows electrical connections to be made on the side of the waveguide. Slot waveguide is developed to flexibly control the nonlinearity of strip/rib waveguide by adding one degree of freedom in the cross section. It confines light in the low refractive index region (slot) based on the surface science (i.e. electric field discontinuity at the high index contrast dielectric-dielectric interface). It is noted that the slot region can be horizontal or vertical. By placing nonlinear material in the slot region, stronger nonlinearities can be achieved in a silicon slot waveguide than conventional strip or rib waveguide. Photonic crystal (PhC) waveguides have also been suggested for enhancing nonlinearities. Light-matter interaction is enhanced due to the slowdown of the light in these structures. Subwavelength grating (SWG) waveguide utilizes a periodic grating like structure to guide the optical mode. Compared with strip/rib waveguide guide, SWG waveguide offers added degrees of freedom to customize the guided mode in z-axis, thus the effective index, mode profile and dispersion of the waveguide can be tailored flexibly. By introducing a longitudinal slot in an SWG waveguide, one can further realize a SWG slot (SWGS) waveguide. With one more degree of freedom than SWG waveguide, the SWGS waveguide with low index air or SiO₂ slot region can be designed to achieve much lower nonlinearity. Additionally, the surface plasmon polariton (SPP), another wide recognition in the field of surface science, can be combined with the strip/slot waveguide to form the SPP slot waveguide structure (hybrid plasmonic waveguide) with even tighter light confinement.

We evaluate the performance of high-speed on-chip signal transmission of silicon strip waveguides (e.g. microring formed by strip waveguides), silicon slot waveguides, hybrid SPP slot waveguides, and SWGS waveguides [135,136,146,147,224,225]. Advanced multi-level modulation signals are employed in the experiment.

3.2. Microring resonator

We first characterize the performance of high-order orthogonal frequency-division multiplexing offset quadrature amplitude modulation (OFDM/OQAM) m-QAM signals in strip waveguides [135]. A silicon microring resonator (strip waveguide structure) is adopted. The experimental setup for OFDM/OQAM m-QAM transmission in a silicon microring is shown in Fig. 4. The bus waveguide with dimensions of 500 nm wide and 220 nm thick is shown in Fig. 4a. Fig. 4b depicts the scanning electron microscope (SEM) image of the microring structure. The radius and height are 50 μm and 220 nm, respectively. The zoomed-in coupling region is depicted in Fig. 4. The coupling gap between the bus waveguide and bending waveguide of the microring is about 240 nm. A vertical grating coupler is used to couple the signal into the chip. Another vertical grating coupler is used to couple the light out of the chip, as shown in Fig. 4d. The free spectral range of the microring is about 1.87 nm, and the linewidth is about 0.2 nm. There are eight external cavity lasers (ECLs) at the transmitter. The wavelengths of the eight lasers are 1,557.63, 1,555.76, 1,553.89, 1,552.02, 1,550.15, 1,548.28, 1,546.41 and 1,544.54 nm, respectively. An I/Q modulator is used to modulate the eight carriers. An erbium-doped fiber amplifier (EDFA) is also used at the transmitter side to amplify the signal. After the on-chip signal transmission through the silicon microring resonator, the light is amplified by another EDFA, detected by a coherent receiver, and off-line processed by MATLAB software.

The measured BER of signal transmission as a function of the received optical signal to noise ratio (OSNR) is plotted in Fig. 5a-d. The OSNR penalty is assessed to be around 1.7 dB for OFDM/OQAM 64-QAM/128-QAM, at a BER of $2 \times 10^{-3}$ (enhanced forward error correction (EFEC) threshold). The OSNR penalty is 3.1 dB for OFDM/OQAM 256-QAM, at the same threshold. For OFDM/OQAM...
512-QAM, 3.3-dB OSNR penalty is observed at a BER of $2 \times 10^{-2}$ (20% overhead FEC threshold). The corresponding constellations are also shown in the insets.

3.3. Slot waveguide

For on-chip signal transmission through a silicon microring, the wavelength of the signal is aligned to the microring resonance to avoid unwanted filtering impairment, i.e. the silicon microring has a narrow bandwidth. Silicon strip waveguide without forming a microring structure has a broad transmission bandwidth. Slot waveguide is an evolution of strip waveguide with reduced nonlinearity by confining light in the low-index air slot region. We then design and fabricate a silicon slot waveguide for on-chip broadband signal transmission [136]. The measured SEM images of the fabricated silicon slot waveguide are depicted in Fig. 6. There are three parts, i.e. mode converter for strip-to-slot conversion, slot waveguide, and mode converter for slot-to-strip conversion. The width of the air slot region is 100 nm, and the height of the air slot region is 220 nm. The loss of the mode converter is about 0.5 dB. The propagation loss of the slot waveguide is $24 \pm 5$ dB/cm, which mainly comes from the roughness of the slot sidewall.

We then evaluate the on-chip signal transmission using a 2-mm-long silicon slot waveguide. The signal used here is wavelength-division multiplexing (WDM) signal with 161 channels. Each WDM channel carries a 11.2-Gbit/s OFDM 16-QAM signal. The measured output spectrum after transmission is shown in Fig. 7a. Fig. 7b shows the measured BER performance. The BERs of all the channels are less than $3 \times 10^{-3}$. Fig. 8a shows the radio frequency (RF) spectrum of the OFDM signal after demodulation. Fig. 8b shows the results of single channel measurements for three wavelengths (1,565.84, 1,549.27 and 1,533.82 nm).

On-chip signal transmission with different waveguide lengths is also examined. We study the BER performance of the on-chip signal transmission with 4 lengths of the silicon slot waveguide. The
Fig. 5. (Color online) Measured BER for OFDM/QAM m-QAM transmission in a silicon microring. (a) 64-QAM. (b) 128-QAM. (c) 256-QAM. (d) 512-QAM. Reprinted with permission from Ref. [135], Copyright 2016 Chinese Laser Press.

Fig. 6. (Color online) Measured SEM images of the fabricated silicon slot waveguide. (a) Layout of the whole slot waveguide structure. (b) and (d) Grating coupler. (d) and (e) Mode converters for strip-to-slot conversion and slot-to-strip conversion. (f) and (g) Bending region. (h) and (i) Slot region. Reprinted with permission from Ref. [136], Copyright 2015 The Optical Society.
Fig. 7. (Color online) Measured spectrum and BER for on-chip signal transmission through a silicon slot waveguide (161 channel WDM signals). (a) Output spectrum after transmission. (b) BER and OSNR. Reprinted with permission from Ref. [136], Copyright 2015 The Optical Society.

Fig. 8. (Color online) Measured RF spectrum and BER performance. (a) Received RF spectrum of the demodulated signal. (b) Measured BER curves at three typical wavelengths. Reprinted with permission from Ref. [136], Copyright 2015 The Optical Society.

Fig. 9. (Color online) Measured BER curves and constellations after transmission in 1-mm (slot 1), 2-mm (slot 2), 3.1-mm (slot 3), and 12.2-mm-long (slot 4) slot waveguides, respectively. (a) BER curves. (b) Constellations. Reprinted with permission from Ref. [136], Copyright 2015 The Optical Society.
lengths are chosen to be 1, 2, 3.1 and 12.2 mm (slot 1 to slot 4), respectively. The BER curves are shown in Fig. 9a. The observed OSNR penalties of the four silicon vertical slot waveguides are 1, 2, 3.2 and 4.5 dB, respectively. The increased OSNR penalty under a longer waveguide could be ascribed to the nonlinear distortion contributed from the partial mode distribution in the silicon region and increased loss. Fig. 9b shows the constellations for each slot waveguide.

3.4. Hybrid SPP slot waveguide

Another kind of evolving slot waveguide is a vertical hybrid SPP slot waveguide. Compared with pure dielectric slot waveguide, it offers even stronger light confinement. Fig. 10a illustrates the schematic diagram of the designed hybrid SPP slot waveguide [146,147], which is connected with input and output silicon strip waveguide via coupling tapers. Fig. 10b shows simulated electric field (x component $E_x$) evolution in the hybrid SPP slot waveguide based on the finite difference time domain (FDTD) method. One can clearly see the mode conversion from strip mode (within silicon region) to the hybrid SPP slot mode tightly confined in the air slot region. We then fabricate the designed hybrid SPP slot waveguide on an SOI platform using several steps of electron-beam lithography (EBL), inductively coupled plasma (ICP) etching and electron beam evaporation (EBV). Fig. 11a shows the measured microscope image of the hybrid SPP slot waveguide layout. The measured SEM images are shown in Fig. 11b–d. One can see from Fig. 11c that the width of silicon waveguide is 270.5 nm and the air gap is only 46.6 nm. We further demonstrate 1.8-Tbit/s on-chip broadband signal transmission (161 WDM channels each carrying 11.2-Gbit/s OFDM 16-QAM signal) using the fabricated hybrid SPP slot waveguide. The measured experimental results are shown in Fig. 12. The measured output spectrum, BER and constellations indicate favorable on-chip signal transmission performance.

3.5. SWGS waveguide

As mentioned above, the SWGS waveguide with low index air or SiO$_2$ slot region, adding increased degree of freedom and flexibility for tailoring mode with much lower nonlinearity, is also a promising candidate for on-chip optical interconnects. We design an SWGS waveguide on silicon platform [224], as shown in Fig. 13. A slot is introduced into the SWG waveguide to form the SWGS waveguide structure. The mode guiding mechanism of the SWGS waveguide can be regarded as the combination of slot mode and SWG Bloch mode. The effective nonlinear coefficients as a function of the wavelength for strip waveguide, slot waveguide, SWG waveguide and SWGS waveguide are shown in Fig. 14a, where the cladding layer is SiO$_2$. It can be clearly seen that the SWGS waveguide features lower nonlinearity than the other types of waveguides. We also calculate the effective nonlinear coefficients when the cladding layer is air, as shown in Fig. 14b. One can clearly see from Fig. 14 that the SWGS waveguide has much lower nonlinearity. Very recently, we also design and fabricate SWGS waveguides at 2 µm for on-chip signal transmission [225]. Fig. 15a–c shows measured microscope images of the fabricated SWGS waveguides. The measured experimental results (spectrum, BER curves) are shown in Fig. 15d and e. The obtained results indicate the successful implementation of on-chip data transmission (5-Gbit/s OOK signal) on SWGS waveguides.

4. On-chip silicon photonic processing

In this section, we review various demonstrations of on-chip silicon photonic processing, including photonic switch, filtering,
Fig. 12. (Color online) Measured experimental results. (a) and (b) Output spectrum, (c) and (d) BER and OSNR vs. wavelength, (e) BER curves for two wavelength channels ($\lambda_1 = 1,548.195$ nm, $\lambda_2 = 1,551.801$ nm), and (f)–(j) constellations for on-chip broadband signal transmission (161 WDM channels each carrying 11.2-Gbit/s OFDM 16-QAM signal) through hybrid SPP slot waveguides. Reprinted with permission from Ref. [147], Copyright 2017 The Optical Society.

Fig. 13. (Color online) Concept of SWGS waveguide. (a) Various silicon waveguides. (b) Strip waveguide. (c) Slot waveguide. (d) SWG waveguide. (e) and (f) SWGS waveguide. Reprinted with permission from Ref. [224], Copyright 2017 The Optical Society.
polarization/wavelength (de)multiplexing, mode (de)multiplexing, wavelength conversion and signal regeneration, optical logic and computing [67–71,102–112,226–255].

The developing of silicon photonics offers the possibility to perform photonic signal processing on an ultra-compact silicon chip. A brief summary of demonstrated silicon-based photonic signal processing techniques is provided below.

Fig. 14. (Color online) Effective nonlinear coefficients of four types of silicon waveguides. (a) SiO₂ cladding. (b) Air cladding. Reprinted with permission from Ref. [224], Copyright 2017 The Optical Society.

Fig. 15. (Color online) Experimental results of fabricated SWGS waveguides at 2 µm for on-chip data transmission. (a)–(c) Measured microscope images of the fabricated SWGS waveguides. (d) Measured spectrum at 2 µm. (e) Measured BER performance for on-chip data transmission (5-Gbit/s OOK signal) on SWGS waveguides. Reprinted with permission from Ref. [225], Copyright 2018 De Gruyter.
processing functions since 2006 is listed in Table 4. Note that Table 4 only shows the photonic signal processing works using silicon-based devices. Recent advances in nonlinear signal processing in silicon nitride devices are not included. Photonic signal processing based on silicon nitride is also a promising research area, particularly stoichiometric silicon nitride. For example, silicon-rich nitride waveguides for ultra-broadband nonlinear signal processing (e.g. wavelength conversion, radio-frequency spectrum analyzer) have been demonstrated [240]. Remarkably, both linear and nonlinear photonic signal processing functions are summarized in Table 4. Grating-based devices and MRR are usually used for polarization/wavelength/mode (de)multiplexing. The most widely used devices for nonlinear photonic signal processing are nonlinear waveguides. MRR is also used for nonlinear photonic signal processing for its nonlinearity enhancement in the resonant structure. Another important perspective is the modulation format. It is noted that the modulation formats used in early demonstrations are almost binary OOK or differential phase shift keying (DPSK) with one bit information in a symbol. Beyond binary modulation format, advanced multi-level modulation formats (m-PSK, m-QAM) have also been widely used in modern fiber-optic communication systems to enhance the transmission capacity. Recently, some silicon-based photonic signal processing functions employing advanced multi-level modulation formats have been demonstrated. In this section, after introducing the silicon-based photonic switch, one of the most important photonic processing functions, we present some of our recent progress in various on-chip photonic signal processing functions using advanced multi-level modulation formats.

4.1. Photonic switch

Silicon photonic switch, which can route signals from multiple input ports to multiple output ports, is a critical component for both long-haul fiber-optic communications, data center and high-performance optical interconnects. Large port number switch fabrics, with low cross talk, low insertion loss, and fast switching time are highly desired to facilitate robust data signal management at network nodes. Table 5 lists several reported demonstrations on silicon-based photonic switch. Generally, on-chip silicon photonic switches can be divided into two categories, i.e. thermo-optic (TO) and electro-optic (EO). Usually, TO switches possess low crosstalk and low insertion loss, while EO switches have fast response of reconfigurability. Early researches on silicon photonic switches mainly focused on TO switches. In 2005, Chu et al. [241] demonstrated compact 1×C2N silicon photonic switches based on cascaded MZIs. After that, the port number of silicon photonic switches increased dramatically. For example, Tanizawa et al. [247] reported a fully packaged 32×32 silicon photonic TO switch using land grid array (LGA) packaging technology. Recently, an ultra-large scale TO silicon photonic switch was demonstrated with very low crosstalk and moderate insertion loss [248].

<table>
<thead>
<tr>
<th>Year</th>
<th>Functionality</th>
<th>Key component</th>
<th>Modulation format</th>
<th>Image</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>Wavelength conversion</td>
<td>Nonlinear waveguide</td>
<td>OOK</td>
<td><img src="image" alt="Image" /></td>
<td>[226]</td>
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<tr>
<td>2007</td>
<td>Optical buffer</td>
<td>MRR</td>
<td>OOK</td>
<td><img src="image" alt="Image" /></td>
<td>[102]</td>
</tr>
<tr>
<td>2008</td>
<td>Signal regeneration</td>
<td>Nonlinear waveguide</td>
<td>OOK</td>
<td><img src="image" alt="Image" /></td>
<td>[227]</td>
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<tr>
<td>2010</td>
<td>Wavelength conversion</td>
<td>MRR</td>
<td>OOK</td>
<td><img src="image" alt="Image" /></td>
<td>[228]</td>
</tr>
<tr>
<td>Year</td>
<td>Functionality</td>
<td>Key component</td>
<td>Modulation format</td>
<td>Image</td>
<td>Ref.</td>
</tr>
<tr>
<td>------</td>
<td>--------------------------</td>
<td>---------------</td>
<td>-------------------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>2010</td>
<td>Wavelength (de)multiplexing</td>
<td>Nonlinear waveguide</td>
<td>OTDM-DPSK</td>
<td><img src="image1.png" alt="Image" /></td>
<td>[229]</td>
</tr>
<tr>
<td>2011</td>
<td>Wavelength conversion</td>
<td>Nonlinear waveguide</td>
<td>OTDM-DPSK</td>
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<td>[230]</td>
</tr>
<tr>
<td>2011</td>
<td>Optical logic</td>
<td>PhC waveguide</td>
<td>–</td>
<td><img src="image3.png" alt="Image" /></td>
<td>[231]</td>
</tr>
<tr>
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<td>Nonlinear waveguide</td>
<td>DPSK</td>
<td><img src="image4.png" alt="Image" /></td>
<td>[232]</td>
</tr>
<tr>
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<td>Echelle grating</td>
<td>–</td>
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<td>[67]</td>
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<tr>
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<td>OOK</td>
<td><img src="image6.png" alt="Image" /></td>
<td>[103]</td>
</tr>
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<td>MRR</td>
<td>DPSK</td>
<td><img src="image7.png" alt="Image" /></td>
<td>[104]</td>
</tr>
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</table>

(continued on next page)
<table>
<thead>
<tr>
<th>Year</th>
<th>Functionality</th>
<th>Key component</th>
<th>Modulation format</th>
<th>Image</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
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<td>AWG, PBS, adiabatic coupler</td>
<td>–</td>
<td>[68]</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>Polarization/wavelength (de)multiplexer</td>
<td>2D grating, MRR</td>
<td>OFDM 64/128-QAM</td>
<td>[69]</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>Wavelength conversion</td>
<td>Nonlinear waveguide</td>
<td>16-QAM</td>
<td>[233]</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>Wavelength conversion</td>
<td>Nonlinear waveguide</td>
<td>OFDM 16/32/64/128-QAM</td>
<td>[105]</td>
<td></td>
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<tr>
<td>2015</td>
<td>Wavelength multicasting</td>
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<td>[234]</td>
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<td>2015</td>
<td>Mode (de)multiplexing</td>
<td>Grating-assisted coupler</td>
<td>OFDM 256-QAM</td>
<td>[71]</td>
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<tr>
<td>2015</td>
<td>Optical computing</td>
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<td>8-PSK</td>
<td>[109]</td>
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<tr>
<td>Year</td>
<td>Functionality</td>
<td>Key component</td>
<td>Modulation format</td>
<td>Image</td>
<td>Ref.</td>
</tr>
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<td>------</td>
<td>---------------------------------------</td>
<td>---------------------------------------</td>
<td>-------------------------</td>
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<td>2015</td>
<td>Optical packet switching</td>
<td>Nonlinear waveguide</td>
<td>OOK, OTDM</td>
<td><img src="image1" alt="image" /></td>
<td>[110]</td>
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<td>2015</td>
<td>Multi-channel wavelength conversion</td>
<td>Nonlinear waveguide</td>
<td>Nyquist 16-QAM</td>
<td><img src="image2" alt="image" /></td>
<td>[111]</td>
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<tr>
<td>2016</td>
<td>Wavelength conversion</td>
<td>Nonlinear waveguide (Amorphous silicon waveguide)</td>
<td>BPSK, QPSK</td>
<td><img src="image3" alt="image" /></td>
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<td>2016</td>
<td>Optical logic</td>
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<td>DPSK</td>
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<td>Signal regeneration</td>
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<tr>
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<td>Signal regeneration</td>
<td>Nonlinear waveguide</td>
<td>DPSK</td>
<td><img src="image6" alt="image" /></td>
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<td>2017</td>
<td>Optical logic</td>
<td>Stub photonic lattice</td>
<td></td>
<td><img src="image7" alt="image" /></td>
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<td>Mode-selective wavelength conversion</td>
<td>Multimode silicon waveguide</td>
<td>OFDM-QPSK</td>
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<td>Year</td>
<td>Type</td>
<td>Port number</td>
<td>Key component</td>
<td>Crosstalk</td>
<td>Insertion loss</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td>-------------</td>
<td>---------------</td>
<td>-----------</td>
<td>----------------</td>
</tr>
<tr>
<td>2005</td>
<td>TO</td>
<td>1, 1 × 2, 1 × 4</td>
<td>MZI</td>
<td>–</td>
<td>15–22 dB</td>
</tr>
<tr>
<td>2008</td>
<td>TO</td>
<td>4 × 4</td>
<td>MRR</td>
<td>–20 dB</td>
<td>–1.3 dB</td>
</tr>
<tr>
<td>2009</td>
<td>EO</td>
<td>2 × 2</td>
<td>MZI</td>
<td>–17 dB</td>
<td>0.8 dB</td>
</tr>
<tr>
<td>2011</td>
<td>EO</td>
<td>4 × 4</td>
<td>MZI</td>
<td>–9 dB</td>
<td>5.8 dB</td>
</tr>
<tr>
<td>2012</td>
<td>TO</td>
<td>8 × 8</td>
<td>MZI</td>
<td>–30 dB</td>
<td>4 dB</td>
</tr>
<tr>
<td>2015</td>
<td>TO</td>
<td>8 × 8</td>
<td>MZI</td>
<td>–35 dB</td>
<td>7.2 dB</td>
</tr>
</tbody>
</table>

Table 5
A summary of silicon-based photonic switch.
silicon photonic EO switch with 2×2 port number was demonstrated in 2008 [243]. The switching time of the device was 4 ns. Now, the start-of-art silicon photonic EO switch has 1.2 ns switching time, and can operate up to 32 inputs and 32 outputs [251]. Another consideration is the combination of EO and TO [252]. EO is used for fast switching operation and TO can be used for device alignment. Such kind of silicon photonic switch can increase the performance of crosstalk and insertion loss of pure EO switches while maintain fast switching time. Very recently, beyond silicon photonic switches based on TO and EO effects, microelectromechanical systems (MEMS)-actuated matrix switch on silicon platform was demonstrated showing impressive performance in terms of port number, bandwidth, insertion loss and extinction ratio [250]. A 64×64 digital silicon photonic switch with a low on-chip insertion loss (3.7 dB) and broadband operation (300 nm: 1400–1700 nm) was designed and fabricated. The measured switching time was 0.91 μs, and the extinction ratio was larger than 60 dB. The matrix switch with 4096 MEMS-actuated vertical adiabatic couplers was integrated on a 8.6 mm × 8.6 mm chip [250]. In the future, the performance of silicon photonic

Table 5 (continued)

<table>
<thead>
<tr>
<th>Year</th>
<th>Type</th>
<th>Port number</th>
<th>Key component</th>
<th>Crosstalk</th>
<th>Insertion loss</th>
<th>Switching speed</th>
<th>Image</th>
<th>Ref.</th>
</tr>
</thead>
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<tr>
<td>2015</td>
<td>TO</td>
<td>32 × 32</td>
<td>MZI</td>
<td>−20 dB</td>
<td>19.7 dB</td>
<td>–</td>
<td><img src="247" alt="Image" /></td>
<td>[247]</td>
</tr>
<tr>
<td>2016</td>
<td>TO</td>
<td>64 × 64</td>
<td>MZI</td>
<td>−30.7 dB</td>
<td>12 dB</td>
<td>–</td>
<td><img src="248" alt="Image" /></td>
<td>[248]</td>
</tr>
<tr>
<td>2016</td>
<td>EO</td>
<td>16 × 16</td>
<td>MZI</td>
<td>−10 dB</td>
<td>14 dB</td>
<td>3.2 ns</td>
<td><img src="249" alt="Image" /></td>
<td>[249]</td>
</tr>
<tr>
<td>2016</td>
<td>MEMS</td>
<td>64 × 64</td>
<td>Adiabatic coupler</td>
<td>−60 dB</td>
<td>3.7 dB</td>
<td>0.91 μs</td>
<td><img src="250" alt="Image" /></td>
<td>[250]</td>
</tr>
<tr>
<td>2017</td>
<td>EO</td>
<td>32 × 32</td>
<td>MZI</td>
<td>−17.9 dB</td>
<td>16.5 dB</td>
<td>1.2 ns</td>
<td><img src="251" alt="Image" /></td>
<td>[251]</td>
</tr>
<tr>
<td>2018</td>
<td>EO, TO</td>
<td>16 × 16</td>
<td>MZI, MRR</td>
<td>−20.5 dB</td>
<td>10.6 dB</td>
<td>1.65 ns</td>
<td><img src="252" alt="Image" /></td>
<td>[252]</td>
</tr>
</tbody>
</table>
switches still need to be further enhanced (port number, bandwidth, insertion loss, crosstalk, stability) to realize practicable large-scale photonic switches.

4.2. Filtering

Filtering is one of the most basic linear signal processing functions. Many kinds of on-chip silicon photonic filters have been demonstrated in the last decade. Some of these filters are reconfigurable, and can perform versatile functions. Recently, we demonstrated a silicon photonic comb filter, which was wavelength and bandwidth tunable [59]. Fig. 16a shows the schematic of the proposed silicon photonic comb filter. It is basically a Fabry-Perot (FP) cavity structure. The mirrors of the cavity are two Sagnac-loop mirrors (SLMs). Two MZIs are added into the cavity, which are shown in Fig. 16b. Fig. 16c depicts the microscope image of the comb filter. Three TiN micro-heaters are used to tune the phase shifts of the waveguide. The waveguide with a cross section dimension of 500 nm width and 220 nm thickness is coated with a SiO2 layer. The lengths of the heaters are all 100 μm.

Both the center wavelength and the operation bandwidth of the filter can be tuned by adjusting the phase shifters. To tune the center wavelength of the silicon photonic comb filter, the cavity length is changed by adjusting Heater 2 in Fig. 16b. Fig. 17a shows the transmission spectra of the comb filter when changing the voltage of Heater 2. It can be seen that the center wavelength of the comb filter changes from 1,550.41 to 1,550.57 nm when the power of Heater 2 increases from 0 to 11 mW. Fig. 17b shows the measured center wavelength shift when adjusting heating power of Heater 2. The Fitting curve is also shown in Fig. 17b. The tuning efficiency is estimated to be ~0.017 nm/mW from Fig. 17b. The bandwidth of the fabricated silicon-based photonic comb filter can be also tuned. Here, three micro-heaters need to be all employed. Fig. 17c shows the measured spectra for bandwidth tuning by simultaneously changing the power of Heater 1, Heater 2 and Heater 3. Heater 1 and Heater 3 are used to change the reflection coefficients of the Sagnac mirror. Heater 1 and Heater 3 are adjusted symmetrically to keep balanced reflection coefficients. Heater 2 is used to maintain the center wavelength. Fig. 17d depicts the bandwidth and extinction ratio as a function of the power applied to Heater 1 and Heater 3. The bandwidth of the comb filter is tuned from 4.37 to 27.6 GHz, and the ER of the filter is decreased from 15.24 to 3.52 dB.

4.3. Polarization/wavelength (de)multiplexing

Another commonly used linear photonic processing function is (de)multiplexing, which is very essential in optical multiplexing communication systems. One can realize ultra-compact (de)multiplexing on silicon platform. Here we show a silicon photonic polarization and wavelength demultiplexer based on a silicon 2D grating coupler and two microrings [69]. The 2D grating coupler is used to perform the polarization multiplexing. After the 2D grating coupler, the x-polarization (X-Pol.) and y-polarization (Y-Pol.) of the signal can be coupled into two waveguides, respectively. After that, two wavelength demultiplexing is realized based on two silicon microrings with different resonant wavelength. Thus, on-chip polarization and wavelength demultiplexer is realized. Fig. 18 shows the fabricated silicon photonic device for on-chip simultaneous polarization and wavelength demultiplexing. The 2D grating has an etching pattern of a single cylinder. The etching depth is 70 nm, and the cylinder radius is 200 nm, with a pitch of 612 nm.

We use OFDM/OQAM 64/128-QAM signals to examine the system performance of the polarization/wavelength (de)multiplexing. The measured BER curves are shown in Fig. 19. Two kinds of signals are adopted in the experiment, i.e. 35.8 Gbit/s OFDM/OQAM 64-QAM and 41.8 Gbit/s OFDM/OQAM 128-QAM. The measured OSNR penalties at a BER of $2 \times 10^{-3}$ (EFEC threshold) are less than 4 dB for 35.8-Gbit/s OFDM/OQAM 64-QAM and 6.8 dB for 41.8-Gbit/s OFDM/OQAM 128-QAM.

4.4. Mode (de)multiplexing

In mode-division multiplexing (MDM) communication systems, low-crosstalk mode (de)multiplexer is a key component. Here we propose and demonstrate an on-chip silicon photonic two-mode (de)multiplexing [71]. It is based on a tapered grating-assisted directional coupler. The schematic of the mode (de)multiplexer is shown in Fig. 20. Two TE0 modes are launched into the waveguides, simultaneously, as depicted in Input 1 and Input 2 of Fig. 20. Through a grating-assisted directional coupler, the upper narrow waveguide is coupled with a bus waveguide. In the bus waveguide, TE2 mode is excited owing to the mode conversion. TE2 carries the information of TE0 mode launched from Input 1. After the region of grating-assisted directional coupler, TE0 mode

![Fig. 16. (Color online) Concept, fabrication and test of the silicon photonic comb filter. (a) Schematic illustration of a comb filter. (b) Details of the comb filter structure. (c) Measured microscope image of the device. (d) Experimental platform for testing the fabricated silicon comb filter. SLM: Sagnac-loop mirror. MMI: multimode interferometer. MZI: Mach-Zehnder interferometer. Reprinted with permission from Ref. [59], Copyright 2017 The Optical Society.](image-url)
Fig. 17. (Color online) Experimental results for the silicon photonic comb filter. Measured transmission spectra for (a) center wavelength and (c) bandwidth tuning. (b) Center wavelength shift versus heating power $P$ (Heater 2). (d) Bandwidth and extinction ratio versus heating power $P$ (Heater 1, Heater 3). Reprinted with permission from Ref. [59], Copyright 2017 The Optical Society.

Fig. 18. (Color online) Fabricated silicon photonic device for on-chip simultaneous polarization and wavelength demultiplexing. (a) Microscope image and (b)–(e) SEM images of silicon photonic device. (b) 2D grating coupler. (c) Some of holes in the 2D grating coupler. (d) Coupling region between the bus waveguide and bending waveguide of microring resonator. (e) 1D grating coupler for easy fiber coupling [69].

Fig. 19. (Color online) Measured BER curves of the polarization and wavelength demultiplexer. (a) OFDM/OQAM 64-QAM. (b) OFDM/OQAM 128-QAM [69].
and TE₂ mode propagate simultaneously along the multimode waveguide. Hence, the mode multiplexer is achieved by adopting the grating-assisted directional coupler. Similarly, the demultiplexer can be also achieved by another grating-assisted directional coupler with the same parameters.

Fig. 21a–c shows the measured SEM images of the grating coupler for optical I/O, grating-assisted directional coupler, and the zoom-in grating structure of the device.

Data transmission through the fabricated two-mode (de)multiplexer using 23.89-Gbit/s OFDM/OQAM 256-QAM signals is demonstrated. The BER curves are shown in Fig. 22. The measured OSNR penalties are $\sim$1.9 and $\sim$1.8 dB for Input 1 (I₁) to Output 1 (O₁) and Input 2 (I₂) to Output 2 (O₂), respectively.

4.5. Wavelength conversion and signal regeneration

4.5.1. Wavelength conversion of high-order OFDM m-QAM signal

Wavelength conversion is also very fundamental and important photonic signal processing function. Wavelength conversion is regarded as the building block enabling other advanced and complicated photonic signal processing functions. We demonstrate wavelength conversions of high-order OFDM m-QAM signal based on degenerate four-wave mixing (FWM) process in a silicon waveguide [105]. Fig. 23 shows the principle of wavelength conversion of high-order OFDM m-QAM signal in a silicon waveguide. One pump and one data carrying signal are simultaneously launched into the silicon waveguide. Pump photons are annihilated to create signal photons and newly converted idler photons.
in the waveguide. Thus, the data of the input signal is converted to the idler, which means the wavelength conversion from the signal to the idler is realized.

Fig. 24a and b shows the measured spectra of the input signal and pump, respectively. A typical optical OFDM m-QAM spectrum can be seen from the spectrum of the signal light (Fig. 24a). Fig. 24c shows the spectrum after wavelength conversion. The FWM conversion efficiency is defined as the power ratio between the idler and the signal, which is estimated to be about $-33 \, \text{dB}$.

Fig. 25a–d shows the measured BER performance for wavelength conversions of OFDM m-QAM signals. As shown in Fig. 25a, for OFDM 16-QAM, the observed OSNR penalty is $-3 \, \text{dB}$ at 7% FEC threshold. The received OSNR penalty is $-4 \, \text{dB}$ at 7% FEC threshold for OFDM 32-QAM wavelength conversion, as shown in Fig. 25b. The received OSNR penalties are $-3.5$ and $-4.5 \, \text{dB}$ at 20% FEC threshold for OFDM 64-QAM and OFDM 128-QAM wavelength conversions, respectively, as shown in Fig. 25c and d.

4.5.2. Wavelength conversion of WDM 16-QAM signal
WDM wavelength conversion operation is also of great importance in photonic signal processing with multiple wavelength channels. We also demonstrate wavelength conversion of WDM 16-QAM signal using a silicon waveguide [111]. Fig. 26 depicts the schematic illustration of WDM 16-QAM wavelength conversion using a silicon waveguide. A continuous wave (CW) pump and a four-channel WDM 16-QAM signal are simultaneously fed into the silicon waveguide through a grating coupler. Owing to the FWM process, the idler takes the information carried by the input WDM 16-QAM signal at the output port.

The wavelengths of the WDM signal used in the experiment are set to be 1,552.5, 1,552.1, 1,551.7 and 1,551.3 nm, respectively. The pump wavelength is 1,549.3 nm. Fig. 27 shows the degenerate FWM-based wavelength conversion spectrum. According to the frequency relationship of FWM, the wavelengths of the idler are 1,546.1, 1,546.5, 1,546.9 and 1,547.3 nm, respectively.
Fig. 28a shows the measured conversion efficiency as a function of the pump power when the pump wavelength is \( \lambda_{\text{pump}} = 1.549.3 \) nm. It can be seen that when the pump power increases, the conversion efficiency increases. The wavelengths of the idler can also be tuned easily by adjusting the wavelength of the pump. The conversion efficiency versus the wavelength of pump, with a fixed 16.7 dBm pump power, is shown in Fig. 28b.

Fig. 29 shows the measured BER as a function of the received OSNR. The OSNR penalties are \( \approx 1.8 \) dB at EFEC threshold for wavelength conversion of WDM 16-QAM signal when the wavelengths of the converted idler are 1,546.1 and 1,546.5 nm. The OSNR penalties are \( \approx 2.7 \) dB for converted idler wavelengths at 1,546.9 and 1,547.3 nm.

4.5.3. Wavelength conversion of PAM-4 signal and its application in signal regeneration

Based on degenerate FWM of the silicon waveguide, we also demonstrate on-chip PAM-4 wavelength conversion and signal regeneration [112]. The input lights of the waveguide include a CW pump and a signal (S). During the propagation through the waveguide, idler 1 and idler 2 are generated by degenerate FWM processes with their powers expressed as \( P_{i1} \approx \gamma L^2 P_p P_s^2 \) (idler 1) and \( P_{i2} \approx \gamma L^2 P_p P_s^2 \) (idler 2), respectively, under the non-depletion approximation. It can be seen that \( P_{i1} \propto P_s \) (idler 1) and \( P_{i2} \propto P_s^2 \) (idler 2). In general, there are two cases considering different forms of the input signal. In Case 1, with a standard PAM-4 signal input, idler 1 has linear relationship with the input signal. In contrast, idler 2 becomes a distorted signal. Thus, the data information carried by the input signal S is converted to idler 1 in this case. In Case 2, the input PAM-4 signal is distorted, which has nonuniform power intervals. In a specific situation, the distorted signal can be regenerated in the converted idler 2 following the nonlinear relationship \( P_{i2} \approx \gamma L^2 P_p P_s^2 \).

We experimentally measure the power relationship between idlers and signal to verify the basic principle of the proposed wavelength conversion and signal regeneration. The measured idler power as a function of the signal power is shown in Fig. 31. The signal wavelength is 1550.1 nm, and the pump wavelength is 1553.4 nm.
nm. It can be seen that the idler 1 has linear dependence on the signal, while the idler 2 has quadratic dependence on the signal. In addition, we do not observe significant saturation in the experiment.

The measured eye diagrams and BER curves are shown in Fig. 32. In Case 1, a standard PAM-4 signal is adopted as the input signal. It can be seen from the eye diagrams in Fig. 32a, that idler 1 is uniform, while idler 2 becomes degraded. The corresponding BER curves are shown in Fig. 32b. In Case 2, the input signal is a distorted PAM-4 signal. After propagation through the waveguide, the idler 2 with uniform power interval is generated, as shown in Fig. 32c. The BER performance of the converted idler 2 is greatly improved compared to the input signal, as shown in Fig. 32d, indicating successful implementation of signal regeneration.

4.6. Optical logic and computing

4.6.1. Optical binary half-adder and half-subtractor

Optical nonlinearities in silicon waveguides can be also used for optical logic and computing applications. We first propose a scheme to realize 160-Gbit/s optical binary half-adder and half-subtractor simultaneously, which is based on a single slot waveguide [253]. Silicon-nanocrystal (Si-nc) is considered as the material of the slot region.

The gate-level conceptual diagram and the truth table of half-adder and half-subtractor are shown in Fig. 33. For two binary inputs (A, B), there are two binary outputs for half-adder operation, which are Sum (A ⊕ B = A · B + A · B) and Carry (A · B). The half-subtractor provides two binary outputs of Difference (A ⊕ B) and Borrow (A · B or A · B). It is known that the Sum of half-adder and the Difference of half-subtractor take the same output, that is logical XOR function (A ⊕ B). The output Carry of half-adder is the logical AND function (A · B), while the output Borrow for A-B is logical A · B function. Similarly, the output Borrow for B-A of half-subtractor is logical A · B function.

The operation principle relies on twin degenerate four-wave mixing (TDFWM) processes, as shown in Fig. 34a. For two input signals (signal A at λsa, signal B at λsb), two idlers (idler 1 at λ1, idler 2 at λ2) are generated by TDFWM processes. It is possible to deplete both signals by controlling the power of signals appropriately. Owing to the depletion effect, output signals at λsa and λsb from the slot waveguide correspond to logical A ⊕ B and A · B, respectively. Moreover, both idlers at λ1 and λ2 correspond to logical AND and XOR, which is the Carry output of half-adder. In addition, the combination of A-B and A-B produces logical XOR. Thus, single slot waveguide based simultaneous half-adder and half-subtractor can be realized.

Fig. 35 depicts the simulated temporal waveforms and eye diagrams for 160-Gbit/s half-adder and half-subtractor.
show the data streams of signal A, signal B, Borrow A-B, Borrow B-A, Sum/Difference, Carry 1 and Carry 2, respectively. The calculated temporal waveforms shown in Fig. 35a–g indicate that single slot waveguide based half-adder and half-subtractor can be successfully realized. The eye diagrams corresponding to Fig. 35a–g are shown in Fig. 35h–n.

4.6.2. Optical quaternary addition/subtraction

Beyond binary optical logic operation, nonlinear silicon waveguides can be also considered to perform high-base optical computing functions. We then propose and demonstrate two-input (A, B) optical quaternary hybrid doubling/subtraction (2A-B, 2B-A), which is based on a silicon waveguide [254]. Fig. 36 shows the concept and principle of the proposed optical quaternary hybrid doubling/subtraction based on silicon waveguide. The four phase levels ($\frac{\pi}{4}$, $\frac{3\pi}{4}$, $\frac{5\pi}{4}$, $\frac{7\pi}{4}$) of the QPSK signal can be considered to represent quaternary numbers, i.e. 0, 1, 2, 3. Two input quaternary numbers (A, B) are injected into a silicon waveguide. Two output idlers are obtained due to the degenerate FWM process in the silicon waveguide. Since the phase relationship between the idlers and the input signal can be written as $\phi_1 = 2\phi_A - \phi_B$ and $\phi_2 = 2\phi_B - \phi_A$, the phase levels of the two output idlers represent two quaternary numbers, i.e. 2A-B and 2B-A.

Fig. 37 shows the measured symbol sequences for two-input optical quaternary hybrid doubling/subtraction. The symbol sequences of A and B are (3 1 0 0 0 2 0 2 0 0 0 1 0 3 3) and (0 2 1 0 2 1 3 2 2 1 1 0 0 3), respectively. The output symbol sequences 2A-B and 2B-A indicate the successful implementation of the quaternary hybrid doubling/subtraction function.

The measured BER performance as a function of the received OSNR and typical QPSK constellations are shown in Fig. 38a and b. The measured OSNR penalty is ~7 dB at a BER of $2 \times 10^{-3}$ for
Fig. 32. (Color online) Measured eye diagrams and BER curves. (a) and (c) Eye diagrams. (b) and (d) BER curves. (a) and (b) Case 1. (c) and (d) Case 2. Reprinted with permission from Ref. [112], Copyright 2016 The Optical Society.

Fig. 33. Diagram and truth table of half-adder and half-subtractor. Reprinted with permission from Ref. [253], Copyright 2013 IEEE.

Fig. 34. (Color online) Concept and principle. (a) Illustration of TDFWM and (b) principle of single slot waveguide based simultaneous half-adder and half-subtractor. Reprinted with permission from Ref. [253], Copyright 2013 IEEE.
Fig. 35. (Color online) Simulated temporal waveforms and eye diagrams. (a)–(g) Temporal waveforms and (h)–(n) eye diagrams for single Si-nc slot waveguide based 160-Gbit/s half-adder and half-subtractor. Reprinted with permission from Ref. [253], Copyright 2013 IEEE.

Fig. 36. (Color online) Concept and principle of two-input optical quaternary hybrid doubling/subtraction based on degenerate FWM in a silicon waveguide [254].

Fig. 37. (Color online) Measured symbol sequences for two-input optical quaternary addition/subtraction (2A-B, 2B-A) [254].
quaternary 2A-B and 2B-A. The obtained results shown in Figs. 37 and 38 confirm the successful implementation of computing operation 2A-B and 2B-A using QPSK signal, FWM processing, and coherent detection.

4.6.3. Optical octal addition/subtraction

Beyond quaternary operation, we also experimentally demonstrate on-chip optical octal addition/subtraction [109]. Instead of using QPSK signals in quaternary computing, 8PSK signals with eight phase levels, representing octal numbers, are employed in the experiment. Instead of exploiting degenerate FWM, non-degenerate FWM is used in the experiment. As illustrated in Fig. 39, two input 8PSK signals and a CW pump are launched into the silicon waveguide. After propagation through the silicon waveguide, three idlers can be generated by three non-degenerate FWM processes. According to the linear phase relationships between three output idlers and two input signals, the converted idler 1, idler 2 and idler 3 take octal addition/subtraction results of A + B, A – B and B – A, respectively. The measured BER curves for 5-Gbaud octal addition/subtraction are shown in Fig. 40a. The OSNR penalties at a BER of $3.8 \times 10^{-3}$ for A + B, A – B and B – A are about 4.3, 4.2 and 4.6 dB, respectively. The corresponding constellations are also shown in Fig. 40b.

4.6.4. Optical hexadecimal addition/subtraction

We also simulate hexadecimal optical addition/subtraction using the aforementioned silicon-organic hybrid slot waveguide [255]. 16PSK signals with 16 phase levels, representing...
hexadecimal numbers, are employed. We use PTS as the high non-linear material in the slot region. The simulation results for three-input 40-Gbaud hexadecimal addition/subtraction are shown in Fig. 41. The constellations are also shown in Fig. 42 with estimated error-vector magnitude (EVM) under an OSNR of 28 dB of input signals. The obtained results shown in Figs. 41 and 42 indicate the successful realization of three-input optical hexadecimal addition/subtraction with favorable performance.

Fig. 41. (Color online) Simulated symbol sequences for three-input 40-Gbaud (160-Gbit/s) hexadecimal addition/subtraction. Reprinted with permission from Ref. [255]. Copyright 2014 Nature Publishing Group.

Fig. 42. (Color online) Simulated constellations for three-input hexadecimal addition/subtraction. Reprinted with permission from Ref. [255]. Copyright 2014 Nature Publishing Group.
5. On-chip silicon+ photonic signaling and processing

Remarkably, silicon photonics can be also integrated with other material platforms to provide extended and enhanced abilities of on-chip silicon+ photonic signaling and processing applications. In recent years, there have been increasing research efforts towards hybrid silicon + x platforms. For instance, silicon + III-V [256], silicon + LiNbO3 [257,258], silicon + organic material [259], silicon + metal (plasmonic) [260,261], silicon + 2D material (graphene, black phosphorus, etc.) [262–267] have been widely studied to implement optical modulators with impressive performance for signaling, as briefly summarized in Fig. 43.

In addition to photonic signaling, silicon+ photonic processing has also been widely investigated. Among various hybrid material platforms, graphene has recently attracted increasing interest. It features many interesting optical, electrical and mechanical properties [268,269]. Many amazing optical properties of graphene have been discovered, such as strong nonlinearity, tunable optical absorption, self-luminescence, saturable absorption, and so forth [270–272]. Especially, optical nonlinearities of graphene have been widely studied in various configurations, such as graphene-silicon photonic crystal waveguide [273], graphene coated fiber ferrules [274], and graphene coated microfiber [275]. Recently, various optical signal processing functions have been presented using graphene-based devices, such as perfect absorption [276], phase shifter [277], polarizer [278], wavelength conversion [279–281], and optical computing [282,283]. Very recently, by introducing graphene into silicon photonic devices, the nonlinearities of these devices can be further improved, which is favorable for efficient on-chip nonlinear signal processing [284–286]. Here we introduce our recent progress in on-chip graphene-silicon photonic signal processing.

We fabricate a graphene-silicon microring resonator (GSMR). The width and height of the ridge waveguide are 450 and 200 nm, respectively. Fig. 44a plots the measured Raman spectrum of the sample. As illustrated in Fig. 44b, the Fermi level is lower than half the photon energy, thus there are no electrons existing for the interband transition which is associated with the light absorption. The measured SEM image of the fabricated GSMR is shown in Fig. 44c. We then evaluate the conversion efficiency of FWM process in the GSMR as a function of the input pump power, as shown in Fig. 45. Vertical coupling method is used to couple the light into the GSMR. Average 5.3-dB conversion efficiency enhancement is observed in the GSMR.

We further characterize the wavelength conversion performance of QPSK signal using the fabricated GSMR [285]. We...
measure the BER curves for back-to-back signals and up/down converted idlers, as shown in Fig. 46. The conversion efficiencies are $-38.3$ and $-40.2$ dB for idlers at $1538.64$ nm (up conversion) and $1558.15$ nm (down conversion), respectively. The OSNR penalties are less than $1.4$ dB at a BER of $1 \times 10^{-3}$ (7% FEC threshold) for both idlers.

Additionally, the fabricated GSMR can be also used to demonstrate selective wavelength conversion of WDM signals [286]. Fig. 47 illustrates the concept of the proposed selective wavelength conversion of WDM 16-QAM signal using a GSMR. A CW pump and four channel WDM 16-QAM signal are launched into the GSMR. At the output of the silicon waveguide, the data information carried by the input WDM 16-QAM signal is converted to the idler. The resonant dip of the GSMR is aligned to one of the WDM signal, and only the selected channel can be converted, enabling channel-selective wavelength conversion. Moreover, by properly changing the pump wavelength and tuning the resonant

![Fig. 45. (Color online) Conversion efficiency versus input pump power. Reprinted with permission from Ref. [284], Copyright 2015 The Optical Society.](image1)

![Fig. 46. (Color online) Measured BER versus received OSNR for up and down wavelength conversion of QPSK signal using the fabricated GSMR. Insets show constellations of QPSK. Reprinted with permission from Ref. [285], Copyright 2016 The Optical Society.](image2)

![Fig. 47. (Color online) Concept and principle of selective wavelength conversion of WDM 16-QAM in a GSMR. Reprinted with permission from Ref. [286], Copyright 2017 The Optical Society.](image3)
wavelength of the GSMR, the desired channel of the WDM signal can be selected.

The channel spacing of the four channel WDM signal is first set to be 100 GHz, i.e., 0.8 nm. The measured spectra after the GSMR are shown in Fig. 48. The wavelengths of the input four channel WDM signal are 1,556.6, 1,557.4, 1,558.2 and 1,559.0 nm, respectively. When the pump wavelength is set to be 1,546.8 nm, the idler at 1,537.1 nm is observed, corresponding to the initial signal at 1,556.6 nm. The temperature of the chip is about 17 °C. Then we change the pump light to 1,557.6 nm and tune the temperature accordingly, the idler at 1,537.1 nm disappears but the idler at 1,537.9 nm appears. By adjusting the pump wavelength and the temperature, the data information carried by the desired channel of the WDM 16-QAM signal can be selected and converted. We also demonstrate the channel-selective wavelength conversion with variable channel spacing of 200, 50 and 25 GHz, respectively. Similar channel-selective wavelength conversion spectra are observed which are not shown here. Note that the crosstalk, defined by the power ratio of the desired idler to the largest undesired idler, increases when reducing the channel spacing, leading to slight performance degradation of wavelength conversion with small channel spacing.

We further characterize the performance of the channel-selective wavelength conversion of WDM 16-QAM signal. Shown in Fig. 49 are measured BER curves with variable channel spacing of 200, 100, 50 and 25 GHz, respectively. The OSNR penalties are all less than 1 dB for 200, 100 and 50 GHz channel spacing. The OSNR penalties for 25 GHz channel spacing are around 1.2 dB. The measured constellations of 16-QAM signal and converted idlers are also shown in Fig. 49. The obtained results in Figs. 48 and 49 indicate impressive performance of the channel-selective wavelength conversion of flexible grid WDM signal using the GSMR.

6. Discussion

Owing to the fast development in the last decade, the research of silicon photonics now covers a large area. Fig. 50 shows a tree plot of the research field of silicon photonics in on-chip photonic
signaling and processing, which is mainly discussed in this review article. The future trends of on-chip silicon photonic signaling and processing are the large-scale integration of the whole communication system on a chip and the hybrid integration of silicon photonics and silicon nanoelectronics on a chip [25,287]. Beyond photonic signaling and processing, numerous other novel applications of photonics, including supercontinuum generation [288–290], real-time optical measurements [291–293], optomechanics [38,294], sensors [44], time lens [295], optical neural network [296,297], microwave photonics [299], quantum optics [300–302], and mid-infrared photonics [49,50,303–305] come into being. Small footprint, low cost, and high efficiency are highly desired in these applications. Silicon photonics provides a promising alternative platform for these applications. Some of prototype chips have already been demonstrated. For example, octave-spanning supercontinuum generation at telecommunication wavelengths has been demonstrated recently using a specifically designed silicon waveguide [289]. Very recently, silicon photonics has been introduced to develop large scale neural network for deep learning [298]. Such nanophotonic chip is able to give equivalent learning performance while potentially achieve three orders of magnitude faster speed than conventional electronic counterparts. Also, silicon photonics has been considered to be a powerful platform for broadband mid-infrared photonics [304,305]. Additionally, some more interesting applications, such as optical coherence tomography [306,307], ultrafast optical ranging [308], spatial mode or structured light manipulation [309–311], optical phased array and LiDAR [320–324] have also been widely studied. In future, it is believed that silicon photonics will facilitate more and more emerging advanced applications in a compact way with superior performance.

7. Conclusion

In summary, we comprehensively review recent research efforts towards on-chip photonic signaling and processing with advanced multi-level modulation signals on silicon platform. The review includes four parts: lasers, modulators and detectors; on-chip silicon photonic signaling (transmission/interconnects); on-chip silicon photonic processing; on-chip silicon+ photonic signaling and processing.

(1) Lasers, modulators and detectors: we first briefly introduce the development of silicon-based lasers, modulators, and detectors. Both the milestones in the history and state-of-the-art devices are introduced. Among these three key devices, silicon modulators and detectors are relatively mature. The performance of silicon modulators and detectors is comparable to the discrete optimized components based on other platforms. For silicon-based lasers, III-V-based hybrid silicon lasers currently show the highest potential for industrialization. However, this method is not a monolithic integration approach. III–V QD lasers, monolithically grown on silicon, could be more promising in the future.

(2) On-chip silicon photonic signaling (transmission/interconnects): we present recent progress in high-speed on-chip photonic signaling in silicon microring resonator (strip waveguide structure), silicon slot waveguide, hybrid SPP slot waveguide, and SWGS waveguide. Up to 512-QAM high-order advanced multi-level modulation signal transmissions through a silicon microring resonator are demonstrated. Up to 1.8-Tbit/s on-chip broadband signal transmissions (161 WDM channels each carrying 11.2-Gbit/s OFDM 16-QAM signal) through silicon slot waveguide and hybrid SPP slot waveguide are demonstrated. 2-μm on-chip signal transmissions through SWGS waveguides are demonstrated. The obtained results of on-chip photonic signaling indicate the successful implementation of chip-scale optical interconnects on silicon platform with favorable performance.

(3) On-chip silicon photonic processing: after a brief summary of various on-chip silicon photonic processing functions (wavelength conversion, buffer, regeneration, (de)multiplexing, logic, computing, monitoring, format conversion, demodulation, multicasting, switching), we introduce silicon-based photonic switches. Large-scale TO, EO and MEMS silicon photonic switches up to 64 × 64 are reviewed. We then present recent progress in on-chip filtering (comb filter), polarization/wavelength (de)multiplexing, mode (de)multiplexing, wavelength conversion, signal regeneration, binary optical logic (half-adder and half-subtractor), and high-base optical computing (quaternary, octal and hexadecimal addition/subtraction) functions on silicon platform. Silicon strip waveguide, directional coupler, 2D grating coupler, and microring resonator are employed and advanced multi-level modulation signals are adopted. The obtained results of on-chip photonic processing indicate...
the successful implementation of linear and nonlinear optical signal processing applications in a compact way with impressive performance. (4) On-chip silicon+ photonic signaling and processing: we further introduce the extended silicon+ photonics by integrating silicon photonics with other material platforms to provide enhanced abilities and superior performance. Various silicon+ x platforms are discussed, including silicon + III-V, silicon + LiNbO3, silicon + organic material, silicon + metal (plasmonic), silicon + 2D material (graphene, black phosphorus). We then present recent progress in on-chip graphene-silicon photonic signal processing, i.e. GSMR-enabled channel-selective wavelength conversion of flexible grid WDM signal.

With future improvement, the large-scale integration of the whole communication system on a chip and the hybrid integration of silicon photonics and silicon nanoelectronics on a chip are the trends of on-chip silicon photonic signaling and processing. It is believed silicon photonics will continue to develop rapidly, enabling more and more emerging advanced applications even far beyond silicon photonic signaling and processing, such as metrology, sensing, imaging, microscopy, artificial intelligence, nonlinear optics, mid-infrared photonics, microwave photonics and quantum optics.

Conflict of interest

The authors declare that they have no conflict of interest.

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