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TOPICAL REVIEW — Nanophotonics

Silicon nanophotonics for on-chip light manipulation*

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The field of silicon nanophotonics has attracted considerable attention in the past decade because of its unique advantages, including complementary metal–oxide–semiconductor (CMOS) compatibility and the ability to achieve an ultra-high integration density. In particular, silicon nanophotonic integrated devices for on-chip light manipulation have been developed successfully and have played very import roles in various applications. In this paper, we review the recent progress of silicon nanophotonic devices for on-chip light manipulation, including the static type and the dynamic type. Static on-chip light manipulation focuses on polarization/mode manipulation, as well as light nanofocusing, while dynamic on-chip light manipulation focuses on optical modulation/switching. The challenges and prospects of high-performance silicon nanophotonic integrated devices for on-chip light manipulation are discussed.

Keywords: silicon, nanophotonics, polarization, mode, manipulation, nanoplasmonics, optical modulator, optical switch.

PACS: 42.25.Ja, 42.79.Hp, 42.82.–m, 42.82.Et **DOI:** 10.1088/1674-1056/27/10/104208

1. Introduction

The field of silicon nanophotonics has drawn intensive attention in recent years because of the unique advantages, including complementary metal–oxide semiconductor (CMOS) compatibility and the ability to achieve an ultra-high integration density.[1] Various passive and active silicon nanophotonic integrated devices have been developed successfully for diverse applications, including optical fiber telecommunication,[2] data communication,[3] high-performance computing systems,[4] and labs-on-chip.[5] Among the various functional elements, silicon nanophotonic integrated devices for on-chip light manipulation have played very import roles. They include two types: the static type and the dynamic type.

Regarding static on-chip light manipulation, on-chip polarization handling is very well known as one of the most important technologies for many applications, such as polarization-division multiplexed systems,[6] polarization-transparent systems,[7] and quantum photonics.[8] Recently, various on-chip polarization-handling devices have been developed successfully,[9] including polarizers, polarization beam splitters (PBSs), polarization rotators (PRs), and polarization splitter-rotators (PSRs). These devices are very beneficial for the realization of various polarization-related systems.[10] We provide a review on on-chip polarization handling in Subsection 2.1. Additionally, mode manipulation has become increasingly attractive in the past years. One of the most important types of mode-manipulation devices is mode converters, which are used to realize the desired mode conversion. Special mode converters have been developed to enhance the mode-coupling efficiency between different types of optical waveguides.[10–12] For example, inversed tapers were introduced to achieve high-efficiency fiber–chip coupling by minimizing the mode mismatch between a large single-mode fiber and a small silicon nanophotonic waveguide.[13] More recently, higher-order modes were introduced to enable mode-division multiplexing (MDM) technology, which breaks the design rule with the single-mode condition and improves the link capacity significantly. In this case, the mode (de)multiplexer enabling the mode conversion between the fundamental mode and the higher-order mode is extremely important. It is also becoming increasingly interesting to achieve light nano-focusing, which is very helpful for significantly improving the light–matter interaction on the nanoscale. In Subsection 2.2, we review on-chip mode manipulation.

For dynamic on-chip light manipulation, the representative devices include optical modulators,[14] optical switches,[15] and variable optical attenuators (VOAs).[16] These three types of optical devices can operate in a similar way by utilizing various physical effects, e.g., the electro–optic (EO) effect,[17] thermo–optic (TO) effect,[18] magneto–optic effect,[19] and acoustic–optic effect.[20] However, their requirements may differ significantly. Optical modulators are usually required to have an ultrafast modulation speed (10 GHz–100 GHz), a decent insertion loss (several deci-

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bels), and a decent extinction ratio (4 dB–10 dB).[14] In contrast, optical switches are usually required to have low loss (< 1 dB), a high extinction ratio (> 20 dB), a broad bandwidth (10 nm–100 nm), a reasonable switching speed (ranging from milliseconds to nanoseconds), and low power consumption. For VOAs, the requirements are mainly a high variable range (0–40 dB) and wavelength-insensitive operation. Here, we focus on optical modulators and optical switches, which are reviewed in Subsections 3.1 and 3.2, respectively. Nonlinear nanophotonics is also an important and content-rich topic in the field of on-chip light manipulation.[21] For example, considerable progress has been made in nonlinear photonics with two-dimensional (2D) materials (such as graphene,[22] MoS_2,[23] and black phosphorus (BP)[24,25]). Owing to the space limit, this topic is excluded from our review; further details can be found in other comprehensive review articles.[21,26]

In this paper, we review the silicon nanophotonics for on-chip static and dynamic manipulation of light. Static on-chip light manipulation focuses on polarization/mode manipulation, as well as light nanofocusing, while dynamic on-chip light manipulation focuses on optical modulation/switching. The challenges and prospects of silicon nanophotonic integrated devices for on-chip light manipulation are also discussed.

2. Silicon nanophotonics for static on-chip light manipulation

In this section, we focus on silicon nanophotonics for static on-chip light manipulation, including silicon photonic devices for on-chip polarization handling, as well as mode manipulation.

2.1. Silicon photonics for on-chip polarization handling

Polarization is one of the most important parameters for light beams; thus, polarization handling is indispensable for many applications, such as polarization-division multiplexing (PDM),[27] polarization-transparent photonic systems,[28] and coherent optical systems.[29] In the past decades, considerable efforts have been directed towards the realization of on-chip polarization-handling devices, including polarizers, PBSs, PRs, and PSRs. It is very important to achieve ultracompact on-chip polarization-handling devices with a very low loss and very high polarization extinction ratio (ERs) even in a broad wavelength band, which is a significant challenge. Fortunately, remarkable progress has been achieved in the past years.[10,30]

2.1.1. Polarizers

For the realization of polarizers, one can utilize the significant polarization dependence of the propagation loss,[31] the cut-off condition,[32] or the modal field profiles in optical waveguides. For example, silicon hybrid plasmonic waveguides (HPWGs)[33] and subwavelength gratings (SWGs)[34] have been recognized as promising waveguide structures for realizing ultra-small on-chip polarizers. For HPWGs, which consist of a low-index nanolayer (e.g., SiO_2) sandwiched by a metal cap and a high-index core region (e.g., Si), the mode field profiles have very strong polarization-dependence, which can be utilized for realizing ultracompact polarizers.[35] In 2016, a 30-μm-long transverse electric (TE)-pass polarizer based on an HPWG coupler was proposed and demonstrated with an excess loss (EL) of 0.04 dB and an ER of > 28 dB in a wavelength band of 150 nm.[36] For SWG waveguides, which consist of periodic subwavelength segments along the propagation distance,[37] the polarization dependence of the light propagation can be engineered flexibly by modifying the duty cycle of the SWG. This provides a good option for the realization of on-chip polarizers. A transverse magnetic (TM)-pass SWG polarizer was realized to support the Bloch–Floquet mode without radiation losses for TM polarization and function as a Bragg reflector for TE polarization simultaneously. For the polarizer realized in Ref. [34] , the length is ~ 18 μm, the EL is < 1 dB, and the ER is > 40 dB. These polarizers are useful for enhancing the polarization ER for various silicon photonic integrated circuits.

2.1.2. PBSs

Various waveguide structures have been proposed for the realization of on-chip PBSs, including multimode-interference (MMI) couplers,[38] Mach–Zehnder interferometers (MZIs),[39] photonic-crystal structures,[40] micro-ring resonators (MRRs),[41] mode-evolution structures,[42] arrayed-waveguide gratings (AWGs),[43] directional couplers (DCs),[44] and asymmetric DCs (ADCs).[45,46]

Because a comprehensive review was provided in Ref. [30], here, we focus on some recent progress in high-performance PBSs on silicon. According to the summary given in Ref. [10], the design with bent DCs proposed in Ref. [47] provides a very attractive option for the realization of high-performance PBSs [see Fig. 1(a)]. This design has been extended to a triple-bent-waveguide DC for realizing a compact PBS [see Fig. 1(b)],[48] for which the measured ERs are > 20 dB for the TE mode and > 15 dB for the TM mode in a broad bandwidth of 90 nm. More recently, an ultra-broadband PBS with a footprint of 6.9 μm×20 μm was demonstrated by using the design based on cascaded bent DCs reported in Ref. [49] , as shown in Fig. 1(c). The realized PBS has an ER of > 30 dB and an EL of < 0.5 dB in an ultra-broad band of > 70 nm. Furthermore, this PBS has a large fabrication tolerance of ± 40 nm, which makes the fabrication very easy.[49]

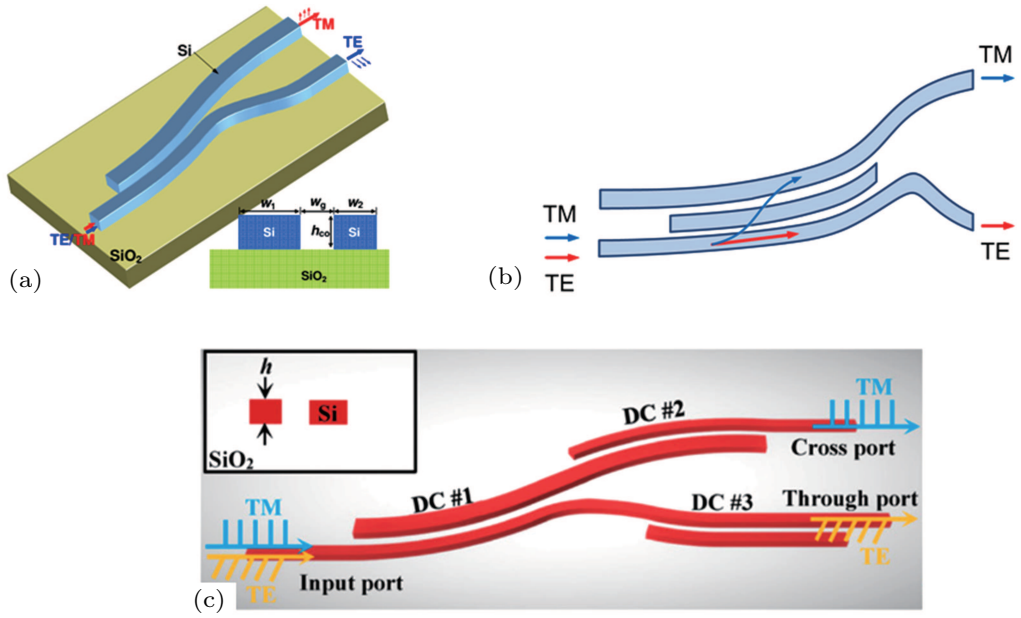


Fig. 1. (color online) Schematics of PBSs based on bent DCs: (a) single-bent DC;[47] (b) triple-bent-waveguide DC;[48] (c) cascaded bent DCs.[49]

2.1.3. PRs and PSRs

The PRs and PSRs are typically realized by utilizing hybridized-mode evolution,[50] hybridized-mode interference,[51] and hybridized-mode coupling.[52] Among these, the approach of hybridized-mode evolution [as shown in Fig. 2(a)] usually allows easy fabrication, a large fabrication tolerance, and a large bandwidth.[50] This type of PSR consists of an adiabatic taper for mode evolution and an ADC.[10] Here, the adiabatic taper is designed by choosing the core widths optimally to enable the mode hybridization. The taper should have sufficient length to be adiabatic so that efficient TM_0–TE_1 mode conversion is achieved, as proposed in Ref. [50]. The cascade ADC is designed according to the phase-matching condition, in order to efficiently convert the TE_1 mode in the wide waveguide to the TE_0 mode of the adjacent narrow waveguide. Recently, an improved PSR consisting of an adiabatic taper, an ADC, and an MMI mode filter was demonstrated.[53] The MMI mode filter is designed to have a low-loss self-image for the TE_0 mode and large-loss transmission for the TE_1 mode, which greatly improves the polarization ER for the PSR. According to these measured spectral responses at the cross- and thru-ports of the fabricated PSR, the realized PSR has excellent performances, with a low EL ($\sim$ 0.5 dB) and a high ER ($\sim$ 20 dB) in the wavelength range of 1525 nm to 1590 nm.[10] The approach utilizing hybridized-mode interference [see Fig. 2(b)] can be ultracompact (length of $\sim$ 10 μm) owing to the short hybridized mode beat length,[10,51] but the double-etching process and both the width and etch-depth of the cut corner should be well-controlled. For the approach utilizing hybridized-mode coupling [see Fig. 2(c)], a large coupling length is needed (e.g., 44 μm in Ref. [52]) because of the weak mode overlap between the TE and TM modes. Additionally, the core widths of the ADC should be well-controlled, as the effective index of the TE mode is sensitive to the narrow waveguide width.[50]

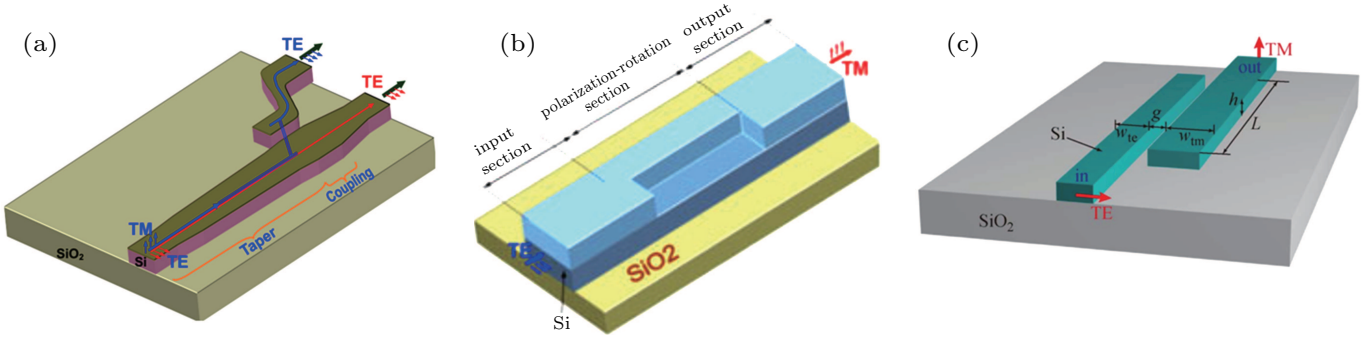


Fig. 2. (color online) (a) PSR based on hybridized-mode evolution.[50] (b) PR based on hybridized-mode interference.[51] (c) PSR based on hybridized-mode coupling.[52]

2.2. Silicon photonics for on-chip mode manipulation

As is well-recognized, mode manipulation is very important for light beams propagating along optical waveguides. A mode converter is a basic element for realizing mode manipulation in photonic integrated circuits because one often needs to achieve low-loss transmission from one optical waveguide to another having a different cross section.[11]

Generally, there are two types of mode converters. One is based on the evanescent coupling designed according to the phase-matching condition. The other is based on the mode evolution designed according to the adiabatic condition. Previously, for operation under the single-mode condition, the manipulation of the fundamental mode was mainly considered. However, in recent years, higher-order modes have been involved for many silicon photonic devices. This is becoming increasingly important for mode-division-multiplexed systems, in which multiple guided modes in a multimode optical waveguide are introduced to allow multi-channel data transmission with a high capacity. The introduction of higher-order modes is also helpful for the realization of special silicon photonic devices.[5,54] Therefore, in this paper, we discuss mode manipulation with higher-order modes.

2.2.1. Mode converters for fiber–chip coupling

Because silicon nanophotonic waveguides have ultra-high index contrast (Δ) and nanoscale cross sections, in the early years, it is a considerable challenge to achieve a high fiber–chip coupling efficiency.[55,56] People have developed excellent mode converters for improving the fiber–chip coupling efficiency by introducing inversed tapers[13] as well as grating couplers,[11,57] as shown in Fig. 3. Inversed tapers function very well with a polarization-insensitive high coupling efficiency in a broad wavelength band if a nanoscale tip at the end of the inversed taper is available.[58] In contrast, when using a mode converter based on a grating coupler, the fiber–chip coupling is polarization-sensitive and wavelength-dependent.[11] On the other hand, the grating coupler has the significant advantage of allowing wafer-scale testing, which makes the device measurement very convenient. These two approaches have been developed very successfully.[59–69]

In the case of using grating couplers, it is very important to introduce gratings with special structural designs. For example, a doubly chirped grating coupler was proposed and demonstrated with a lag effect in the inductively coupled plasma etching process.[69] It is also possible to introduce sub-wavelength structures in the grating region, for modifying the optical field distribution and thus improving the fiber–chip coupling efficiency.[63,65] In the case of using inversed tapers, a post-oxidation process can be introduced to realize nanoscale tips.[70] In this way, the tip can be as small as $\sim$ 15 nm, and the fiber–chip coupling can be improved to 0.66 dB and 0.36 dB for the TE and TM modes, respectively. Another potential approach is introducing an inversed taper based on an SWG waveguide. In this way, the mode confinement of the silicon core region is weakened. This allows a relatively large taper tip, e.g., $w_{\mathrm{tip}} = 220$ nm,[61] for achieving very high fiber–chip coupling efficiency ($\sim 92\%$).

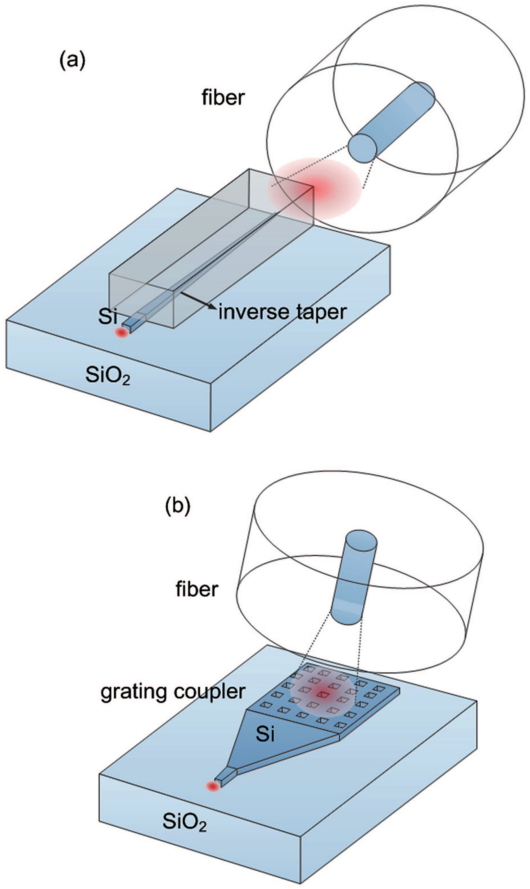


Fig. 3. (color online) Schematics of mode converters for fiber–chip coupling: (a) inversed tapers[13] and (b) grating couplers.[62]

As MDM technology has been introduced to enhance the link capacity of optical interconnects, it is becoming increasingly important to develop mode converters for fiber–chip coupling with a high mode-coupling efficiency and low mode-coupling crosstalk. In Ref. [71], a special inverse taper was proposed for realizing efficient mode conversion from six guided modes in a multimode waveguide to another six guided modes that are compatible with the LP_{01}, LP_{11a}, and LP_{11b} modes in few-mode fibers. This inverse taper allows efficient multimode fiber–chip coupling, which is very different from the case with the fundamental mode only. In contrast, the inverse taper proposed in Ref. [71] allows the connection between multimode silicon nanophotonic integrated circuits and few-mode fibers. With the inverse taper designed optimally, the mode conversion efficiency is $> 95.6\%$ and the mode ER is $< 0.5\%$ for all six modes (including the fundamental mode and the higher-order modes). This makes it possible to realize multimode silicon nanophotonic integrated circuits[72] that

can operate together with few-mode fibers. Grating couplers have also been developed for achieving coupling between a multimode waveguide and a few-mode fiber.[73,74] For example, in Ref. [74], the coupling efficiency is −10.6 dB, while the mode-dependent coupling efficiency is approximately 3.7 dB.

2.2.2. Mode converters for mode-division (de)multiplexing

It is well known that wavelength-division multiplexing (WDM) and PDM technologies have been developed successfully to achieve ultra-high-capacity optical interconnects in the past decades. For further improving the link capacity, MDM technology utilizing multiple mode channels is becoming increasingly attractive. As one of the most important elements in MDM systems, a mode (de)multiplexer is used to combine/separate the mode channels in a multimode bus waveguide so that multi-channel data transmission can be realized even when there is only one wavelength. Because the multiple guided modes are overlapped spatially, it is not easy to realize on-chip mode (de)multiplexing. Fortunately, various waveguide structures have been developed for the realization of on-chip mode (de)multiplexers, including MMI couplers,[75,76] topology structures,[77] staged couplers,[78] adiabatic mode-evolution couplers,[79–85] and ADCs.[86–90] Among these, there are two popular approaches. One is using adiabatic mode-evolution couplers, and the other is using ADCs, as shown in Fig. 4. For example, some mode (de)multiplexers with 3–4 channels were realized by using tapered mode-evolution couplers.[91–94] Some of them have low ELs and low crosstalks (< -20 dB) in a broad band.[91,94] Additionally, ADC-based mode (de)multiplexers with excellent performances, simple structural designs, and high scalability have been demonstrated.[86,87,95] In Refs. [86] and [87], the demonstrated multi-channel mode (de)multiplexer based on cascaded ADCs functioned well with a low EL of < 0.5 dB and a low crosstalk of < -20 dB in a broad wavelength band.

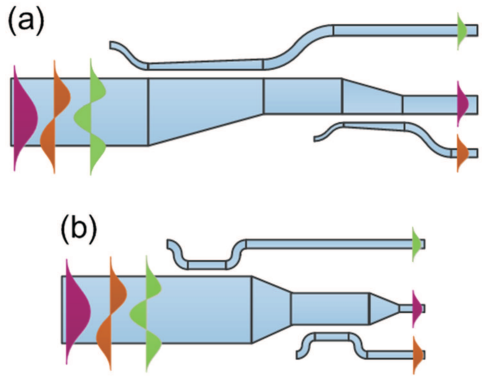


Fig. 4. (color online) Mode (de)multiplexers using[10] (a) adiabatic mode-evolution couplers[91] and (b) ADCs.[95]

More recently, on-chip mode (de)multiplexers were integrated with other functional elements to obtain multimode silicon photonic integrated circuits, including on-chip hybrid (de)multiplexers[96,97] and reconfigurable optical add/drop multiplexers (ROADMs).[98–104] For example, in Ref. [97], a 10-channel hybrid PDM–MDM (de)multiplexer combining six TE mode channels and four TM mode channels was demonstrated with the integration of PBSs and mode (de)multiplexers based on cascaded dual-core adiabatic tapers. By using a photonic integrated circuit consisting of a pair of 10-channel hybrid hybrid PDM–MDM (de)multiplexers, data transmission of 30 Gbps/channel was demonstrated experimentally. Hybrid MDM–WDM (de)multiplexers were also realized by integrating mode (de)multiplexers with wavelength-division multiplexers based on AWGs[96,105] and MRRs.[89,106] When integrating mode (de)multiplexers and optical switches based on MZIs[107] or MRRs,[108–110] ROADMs for reconfigurable MDM systems[98,100–102] as well as hybrid MDM–WDM systems can be realized.[99,103,104] Recently, an on-chip multimode optical switch for hybrid WDM–MDM systems was demonstrated by cascading two thermally tunable MRR-assisted ADCs,[103] which allowed the routing of four 10Gbps data channels. Additionally, data routing in hybrid WDM–MDM systems was realized by integrating optical switches and grating-assisted ADCs.[104]

2.2.3. Mode converters for light nanofocusing

It is always interesting to break the diffraction limit for achieving light nanofocusing as well as strong field enhancement, which is very important for many applications.[111–114] As a promising solution, the utilization of nanoplasmonic waveguides is currently very popular. Various passive and active nanoplasmonic integrated devices have been developed.[34,46,113,115] Nanoplasmonic waveguides can help reduce the device size to a scale comparable to that of state-of-the-art electronic devices.[111] This might enable photonic integrated circuits with a very high integration intensity, low power consumptions, and high speed.

Many types of nanoplasmonic waveguides have been proposed for light nanofocusing.[33,116–119] Among them, metal–insulator–metal waveguides (MIMWG)[116] and HPWGs[33,117] are the most attractive structures owing to their structural simplicity, strong light nanofocusing, and relatively low losses, as shown in Figs. 5(a) and 5(b). To further reduce the loss, a potential solution is to combine nanoplasmonic waveguides and low-loss dielectric optical waveguides, whereby nanoplasmonic waveguides can be used locally while the dielectric optical waveguide can be used to enable long-distance propagation. In this case, the mode converter for light nanofocusing plays an important role to enable low-loss mode conversion between the nanoplasmonic waveguide and the dielectric optical waveguide.

For example, in 2014, Melikyan *et al.* demonstrated an ultra-compact 65-GHz optical modulator on silicon by com-

bining a silicon nanophotonic waveguide with an MIMWG filled with nonlinear polymer.[120] For this device, a tapered structure was introduced as the photonic-to-plasmonic mode converter. In 2016, an improved photonic-to-plasmonic mode converter was demonstrated to enable low-loss (1.7 dB) mode conversion from a 400 nm × 200 nm Si nanophotonic waveguide to a 50 nm × 20 nm MIMWG.[12] For silicon HPWGs,[33] a high-efficiency mode converter between a nanoplasmonic waveguide and a dielectric optical waveguide can be realized easily by introducing simple taper structures[121] or evanescent coupling structures.[46,122]

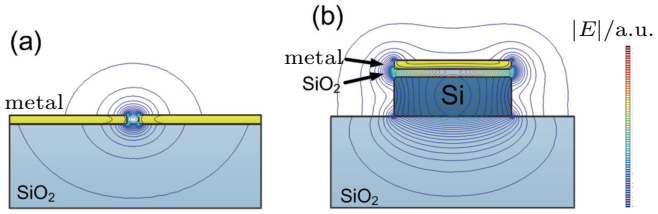


Fig. 5. (color online) Cross section and mode distribution of (a) an MIMWG[116] and (b) an HPWG.[33]

In 2004, Stockman theoretically predicted that the surface plasmon polaritons (SPPs) are slowed when propagating towards the tip of a tapered plasmonic waveguide and that strong local fields at the tip can thus be obtained.[123] Nowadays, light nanofocusing has been reported with different types of tapered plasmonic waveguides: tapered MIMWGs [Fig. 6(a)], tapered HPWGs [Fig. 6(b)], tapered metal rods [Fig. 6(c)], metal wedges, V-groove waveguides,[124] etc.[125] For example, in 2012, Choo *et al.* demonstrated light nanofocusing in a three-dimensional tapered MIMWG.[126] In two-photon luminescence measurement, an intensity enhancement of 400 and a transmittance of 74% were achieved. In 2015, Luo *et al.* reported research on light nanofocusing in a hybrid plasmonic-photonic nanotaper based on an HPWG (metal–SiO_2–Si) structure,[127] where a measured focus spot effective area of 0.013 μm^2 and a remarkable power-conversion efficiency of 92% were obtained. In practice, both the angle and length of a plasmonic taper should be carefully designed to satisfy the requirements for efficient light nanofocusing; e.g., the local field enhancement along the taper should efficiently compensate for the SPP propagation loss. The strong enhanced field caused by light nanofoucsing can be applicated in probes for near-field super-resolution imaging,[128] spectroscopy, photodetection, heat-assisted magnetic recording,[129] and lightharvesting thermophotovoltaics.[130] In addition, the slowing effect of light nanofocusing in tapered plasmonic waveguides can be used in SPP-based slow-light applications.[131]

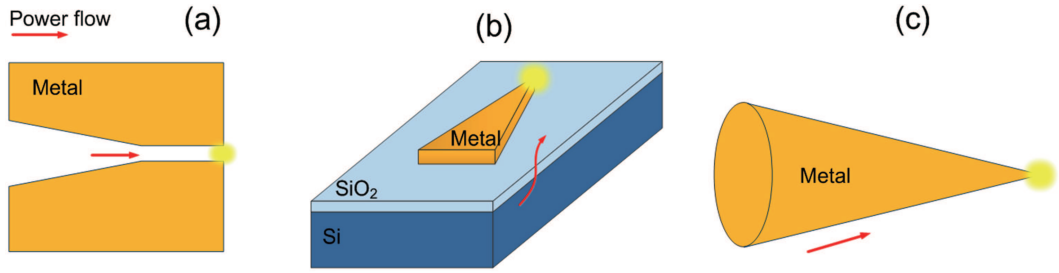


Fig. 6. (color online) Schematic diagram of typical tapered plasmonic waveguides for light nanofocusing: (a) horizontal or vertical tapered MIMWG,[126] (b) tapered HPWG,[127] and (c) conical tapered metal rod.[128]

3. Silicon nanophotonics for dynamic light manipulation

The representative devices for dynamic light manipulation include optical modulators,[14] optical switches,[15] and VOAs.[16] In principle, these three types of optical devices can be realized by modifying the real part or the imaginary part of the refractive index of the optical waveguides by utilizing various physical effects, e.g., the EO effect,[17] the TO effect,[18] the magneto–optic effect,[19] or the acoustic–optic effect.[20] In this way, it is possible to manipulate the amplitude or the phase of the light beam propagating in the waveguide by using a single optical waveguide, a two-beam interferometer, or a multi-beam interferometer. Because the materials commonly used for silicon photonics usually do not have the magneto–optic effect or acoustic–optic effect, for which special materials are required, in the present review paper, we focus on TO and EO devices. Utilizing the TO effect is one of the most popular approaches for realizing dynamic light manipulation on silicon, because silicon has a very high TO coefficient ($\sim 1.8 \times 10^{-4}$/K@$\lambda = 1.55$ μm) and high thermal conductivity.[18] As a result, many thermally switchable/tunable/variable silicon photonic devices have been developed in the past few years.[99,107,109,132–134] However, the TO effect is usually slow (milliseconds to microseconds)[134] and thus is not suitable for realizing high-speed optical modulators. Fortunately, high-speed optical modulators on silicon have been developed by utilizing the plasma-dispersion effect in silicon[14] or by introducing other functional materials.[2] In this section, we discuss the state-of-the-art devices, as well as the challenges.

3.1. Optical modulators on silicon

Currently, one of the most popular methods for realizing optical modulation on silicon is utilizing the plasma-dispersion effect in silicon. When the carrier concentration is modulated by the applied electrical field, the real and imaginary parts of the refractive index of silicon can be varied. Three main mechanisms are available: carrier injection, carrier accumulation, and carrier depletion. In Ref. [14], a comprehensive summary and review of silicon optical modulators was provided. For silicon optical modulators, the structures of MZIs and MRRs are typically used. High-performance optical modulators on silicon have been realized. For example, a silicon MZI modulator with a high speed of 128 Gbps and a modulation efficiency of 1.6 V·cm was demonstrated by introducing a substrate-removal technique.[135] When using MRRs, one can achieve optical modulators with low power consumption (e.g., $\sim$ 1 fJ/bit in Ref. [136]) because the device size is reduced. On the other hand, additional power consumption might be needed to tune the MRR so that the resonance wavelength shift due to the fabrication errors can be compensated.[2] Because the modulation efficiency of silicon modulators based on the plasma-dispersion effect is limited to $\sim$ 1 V·cm,[2] it is not easy to balance the requirements of a compact footprint, a high speed, a low driven voltage, low insertion loss (IL), a high ER, and low power consumption.

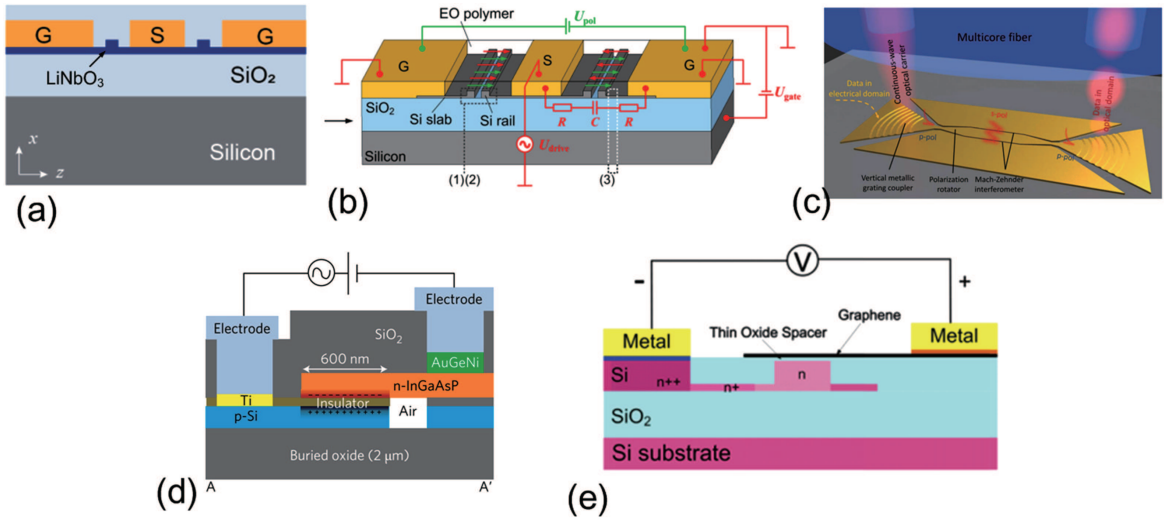


Fig. 7. (color online) Structures of hybrid silicon integrated optical modulators: (a) Si–$LiNbO_3$,[140] (b) dielectric slot waveguide-type Si-polymer modulator,[142] (c) MIMWG-type Si-polymer modulator,[120] (d) Si–III–V material,[144] and (e) Si-graphene.[149]

Considerable efforts have also been made to develop approaches for realizing high-performance optical modulators on silicon. For example, Timurdogan *et al.* recently reported the second-order nonlinear EO effects in silicon waveguides by breaking the crystalline symmetry of silicon,[137] which possibly paves a way to realize optical modulators on silicon. Another popular method for realizing optical modulation on silicon is introducing materials such as Ge,[138] EO crystals,[139,140] organic materials,[120,141,142] III–V compounds,[143–145] and 2D materials,[146] as shown in Figs. 7(a)–7(e). For example, the SiGe optical modulator using the Franz–Keldysh (FK) effect in Ge has been commercialized.[2] Other effective and popular methods for realizing optical modulators on silicon include using the Pockels effect in the EO crystal (e.g., $LiNbO_3$) or the EO polymer, which was introduced for silicon photonics. Recently, an $LiNbO_3$/silicon optical modulator with a large bandwidth of 100 GHz and a low half-wave voltage of 1.5 V was demonstrated [see Fig. 7(a)].[140] As a silicon integration compatible material with a large EO coefficient, the EO polymer has also been used in various modulators utilizing strong light confining waveguides, e.g., the dielectric slot waveguide [see Fig. 7(b)][142] and the MIMWG [see Fig. 7(c)].[120] Silicon–polymer modulators have the advantages of small footprints and low power consumption, as shown in Table 1. For introducing III–V semiconductor materials, electro-absorption modulation utilizing the quantum-confined Stark effect on silicon has yielded a large bandwidth of 74 GHz,[143] and an InGaAsP/Si metal–oxide–semiconductor phase modulator has been reported with high performances, e.g., a modulation efficiency of 0.09 V·cm–0.12 V·cm [see Fig. 7(d)] in Ref. [144] and an EO bandwidth of 25 GHz in Ref. [145]. Recently, 2D materials have drawn intensive attention for various applications, including optical modulation on silicon. For graphene, the Fermi level can be modified by changing the gate voltage when a capacitor structure is formed;[147] thus, both real and imaginary parts of the complex refractive index of graphene can be achieved. As a result, one can realize amplitude or

phase modulators by using a silicon–graphene hybrid optical waveguides, as demonstrated in Refs. [148]–[151] For the reported silicon–graphene electro-absorption modulators [see Fig. 7(e)], the bandwidth is 2.6 GHz–35 GHz,[148,149] the IL is 2 dB–4 dB, and the modulation depth is 2 dB–4 dB, which are possibly improved further by enhancing the light–matter interaction in graphene.[148,149] As an alternative, BP has attracted intensive attention in recent years, and a silicon–BP EO modulator based on the quantum-confined FK effect in BPs was also reported.[152] In particular, this type of optical modulator is promising for mid-infrared (MIR) applications. Table 1 summarizes reported silicon-integrated optical modulators. High-performance optical modulators on silicon can be achieved by introducing special optical materials.

Table 1. Recently reported silicon-integrated optical modulators.

Year	Type	Area/length	Bandwidth/speed (code type)	Power consumption	Extinction ratio/dB	Insertion loss/dB	Ref.
2018	Si	2 mm	58 GHz	–	2.7–3.6	5.4	[135]
2018	SiGe	80 μm	100 Gb/s (NRZ)	< 91 fJ/bit	6	6	[138]
2018	Si–$LiNbO_3$	20 mm	100 GHz	–	–	–	[140]
2018	Si–polymer	1.1 mm	100 Gb/s (OOK)	98 fJ/bit	6.1	8	[142]
2017	Si–polymer	36×6 μm^2	> 70 GHz	30 fJ/bit	∼ 15	–	[120]
2017	Si/III–V	250 μm	32 Gb/s	–	3.1	1	[144]
2016	Si–graphene	$\sim 50 \times 10$ μm^2	2.6 GHz–5.9 GHz	350 fJ/bit	2.5	3.8	[149]
2018	Si–graphene	300 μm	5 GHz	1 pJ/bit	35	10	[151]

3.2. Optical switches on silicon

An optical switch is a basic building block for optical cross-connects and optical add/drop systems, which enable all-optical signal routing and switching in reconfigurable photonic networks/systems.[15] For optical switches, the requirement for the switching speed varies from milliseconds to nanoseconds to satisfy the demands for different scenarios in networks, e.g., a nanosecond response is needed in optical packet switching.[15] As a result, various optical switches have been reported that utilize different physical mechanisms. For example, TO optical switches are popular for switching on the millisecond scale, microelectromechanical systems (MEMS) switches are popular for switching on the microsecond scale, and EO switches are popular for switching on the nanosecond scale. Recently, large-scale optical switch fabrics on silicon have been demonstrated by using various methods. For example, Lu *et al.* reported a non-blocking 16×16 silicon switch fabric integrated with both EO and TO tuners, which demonstrated the transmission of 50 Gb/s quadrature phase-shift keying optical signals.[153] Qiao *et al.* demonstrated a nanosecond 32×32 EO switch with a Benes structure by using the carrier depletion in silicon.[154] In 2016, Seok *et al.* presented a 64×64 digital MEMS optical switch with a low on-chip IL of 3.7 dB and a large bandwidth of 300 nm.[155] Recently, an improved 128×128 device was demonstrated.[156] In addition, multimode optical switch fabrics have been developed recently.[157,158]

For these optical switch fabrics, one of the basic elements is the 2×2 optical switch. It is very important to achieve high-performance 2×2 optical switches with low power consumption, low losses, a high ER, and a broad wavelength band. As is well-known, there are usually two types of waveguide structures for optical switches.[10] One is the MZI, and the other is the MRR. MRR-type optical switches provide a good option for realizing wavelength-selective optical switching, which is often very useful for reconfigurable systems with multiple wavelength channels.[159] For example, recently, an MRR-based wavelength-selective optical switch array was used to realize a reconfigurable optical add/drop multiplexer on silicon for hybrid WDM–MDM systems.[99] For achieving a high ER, one possible method is to use a structure of cascaded MRRs.

In contrast, MZI-based optical switches are usually broadband, which is very important for switching all wavelength channels simultaneously. The performance of an MZI switch is mainly limited by the 2×2 3-dB couplers. It is not easy to achieve a broadband power splitting ratio of 50%:50% for regular 3-dB couplers, e.g., multimode interference couplers or regular DCs. Considerable efforts have been directed towards achieving broadband 3-dB couplers by introducing special structural designs.[160,161] These smart designs significantly improve the bandwidth of the 2×2 3-dB coupler. In particular, bent DCs were introduced as a novel 2×2 sized 3-dB coupler for MZI switches in Ref. [162], and an ultrabroadband (∼ 140 nm) thermo-optical 2×2 MZS was realized in 2016.[107] One might notice that a TO switch usually has relatively large power consumption (e.g., several microwatts).[134] It is possible to reduce the power consumption by introducing air trenches for thermal isolation or special micro-heaters. For example, in Ref. [132], a silicon heater was used, and the thermal tuning efficiency (power consumption for unit resonant frequency shift) is as high as 7.25 μW/GHz. Additionally, a graphene nano-heater was introduced to improve the heating efficiency by reducing or even removing the thick SiO_2 upper-cladding layer, which is usually needed in the case of using metal micro-heaters.[133]

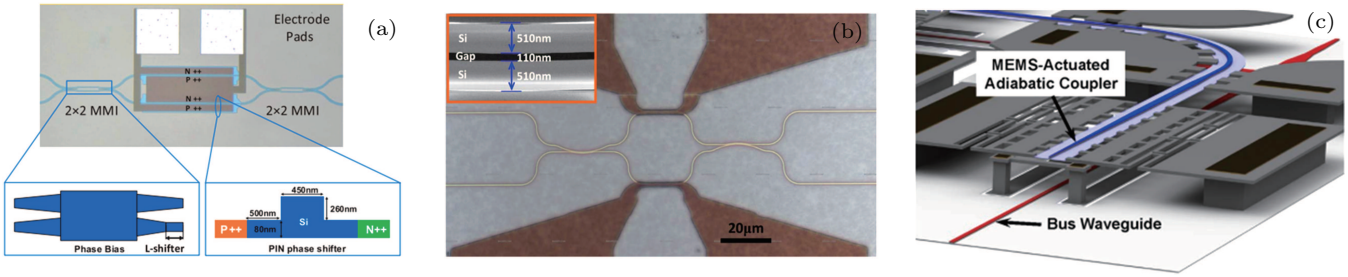


Fig. 8. (color online) Typical optical switches: (a) 2×2 EO switch,[154] (b) ultrabroadband 2×2 TO switch,[107] and (c) 2×2 MEMS switch.[155]

Table 2. Recently reported optical switches on silicon.

Year	Ports	Type	Bandwidth/nm	Rise/fall time	Extinction ratio/dB	Insertion loss/dB	Remark	Ref.
2015	2×2	EO (ITO[a])	–	–	17.6 7.2	1.3 2.4	cross bar	[163]
2016	16×16	EO	> 30	3.2/2.5 ns	> 20	6.7 14	all-cross all-bar	[153]
2017	32×32	EO	–	1.0/1.2 ns	12.9–16.5 14.4–18.5	17.9–24.8 15.1–19	all-cross all-bar	[154]
2016	2×2	TO	140	–	> 20	< 1		[107]
2018	2×2 (4 modes)	TO	40	12/9 μs	8.0–12.2	1.4 2	all-cross all-bar	[157]
2017	8×8 (TE/TM)	TO	> 35	–	> 20	30.9	–	[158]
2016	64×64	MEMS	300	900/290 ns	> 60	3.7	–	[155]

[a]This Si-ITO switch has footprint of only 4.8 μm^2 and power consumption below 0.23 fJ/bit.

4. Conclusion and perspectives

We reviewed the recent progress in silicon nanophotonic devices for static and dynamic on-chip light manipulation. The static manipulation of light includes polarization/mode manipulation and light nanofocusing, while the dynamic manipulation of light includes optical modulation/switching. For light manipulation, silicon nanophotonics play a very important role in many applications. On the other hand, high-performance silicon nanophotonic devices are still desired. It is very important to reduce the IL and improve the ER for silicon nanophotonic integrated devices used in practical applications. This depends on the improvement of the structure designs and the fabrication processes. It is also necessary to develop silicon-plus nanophotonics,[164] for which novel optical materials are introduced on silicon. This allows the realization of active photonic devices on silicon, not only for on-chip light manipulation but also for photodetection[165] and light generation.[2,166] Finally, large-scale silicon photonic integrated circuits can be realized. In this case, the structural design and the fabrication process might become complicated; thus, considerable efforts should be made in the future. Silicon-plus photonics also allow potential applications in wavelength bands other than the telecommunication band. For example, MIR silicon photonics are becoming an attractive topic owing to promising applications in optical sensing[167] and optical communications in new fibers[168] and free space.[169] Remarkable progress has been achieved[170] in both passive and active silicon photonic integrated devices. For passive silicon photonics, various smart structural designs for the near-infrared wavelength band have been extended to the MIR band, including those for on-chip light manipulation.[171] For active silicon photonic devices, MIR designs are becoming even more challenging because of the absence of the needed active materials. For example, the mature germanium material is not available for the photodetection of MIR light. It is helpful to introduce other materials (e.g., 2D materials) for MIR silicon photonics. In summary, silicon nanophotonics for on-chip light manipulation will continue to be an important research topic and will play increasingly important roles for many applications in different wavelength bands.

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