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REVIEW ARTICLE

Photonic nano-device for optical signal processing

Xinwan LI (✉)[1,2], Zehua HONG[2], Xiaomeng SUN[2]

1 School of Physics Electrical Information Engineering, Ningxia University, Yinchuan 750021, China
2 State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering,
Shanghai Jiao Tong University, Shanghai 200030, China

Abstract Micro/nanostructure photonic devices offer a variety of enabling properties, including low power-consumption, cost-efficient, compact size, and reliability. These distinctive features have been exploited in a wealth of applications ranging from telecommunication and optical interconnect to photonic network on chip. In this paper, we review two main classes of micro/nanostructure photonic devices, to provide the kinds of functions for optical signal processing.

Keywords photonic nano-device, optical signal processing, micro/nano optical fiber, silicon plasmonic waveguide

1 Introduction

With the development of telecommunications and the internet, a massive amount of multi-media communications, video-streaming and file-transfers on mobile phones, handhelds, or desktop machines have been popular. And real-time interactive high-definition (HD) video with three-dimensional (3D) images will be the next hot consumer market. However, at current situation, network efficiency, power-consumption and signal processing speed are big issues. In order to achieve high speed, large capacity, flexible network services, micro/nanostructure integration optical signal processing devices are promising due to the excellent properties of low power-consumption, cost-efficient, compact size, and reliability. The functions that optical signal processing devices are expected to realize the kinds of functionalities include optical switching, optical logic manipulation, clock recovery, signal regeneration, photon calculation, pseudo-random binary sequence (PRBS) generation, etc.

The optical signal processing functions are generally achieved by nonlinear effect [1–3], such as four-wave mixing (FWM) [4,5] and cross-phase modulation (XPM) [6,7] in optical fibers, silicon on insulator (SOI) waveguides, semiconductor devices (semiconductor optical amplifier, SOA), nonlinear crystal, and micro-fiber.

SOI is considered as a promising material for all optical signal process and optical transmission due to its large nonlinear material refractive index and high refractive index contrast between silicon waveguide core and silica substrate. Large refractive index indicates that considerable nonlinear effect with low power-consumption is possible; high index contrast implies that the light field is confined in a very small size, which not only enhances the nonlinearity coefficient, but offers an excellent foundation for photonic integration devices. SOI combined with plasmonic is another approach for optical processing. He et al. [8] showed theoretical investigation that hybrid plasmonic waveguide with a metal cap on an SOI rib (or slab) had a low loss and consequently a relatively long propagation distance (on the order of several tens of λ). Lipson et al. [9] demonstrated a metal slot waveguide with deep subwavelength confinement and propagation loss that is 1 order of magnitude lower than that of previously demonstrated with comparable degrees of lateral confinement.

Compared to conventional complementary metal-oxide-semiconductor (CMOS) fabrication techniques for SOI, the fabrication of integration photonic devices based on micro/nano-fibers is another important issue. However, light propagating in micro/nano-fibers shows many excellent properties that are helpful for optical signal processing (more detail explanation shown in the next section). Enhanced nonlinearity γ is one of the excellent properties of micro/nano-fibers, which will ease the nonlinear effect. Supercontinuum generation [10], third-harmonic generation [11], slow and fast light [12] and other nonlinear effect have been observed in micro/nano-fiber, which provide the foundation for all-optical signal processing. On the other hand, many micro/nano-fiber-

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E-mail: lixinwan@sjtu.edu.cn

based functional devices have been reported. Tong et al. [13] have realized an add-drop filter using microfiber knot resonators with *Q*-factor and finesse of ~3300 and 17.3, respectively. Although the stability of the reported add-drop filter has few advantages over SOI-based devices; however, it shows special features, such as simple fabrication, easy connection to fiber systems, and compatibility with miniaturized microfiber devices. Another class of add-drop filter based on micro/nano-fiber has been reported by Pöllinger and Rauschenbeutel [14]. A bottle microresonator fabricated from a standard single-mode fiber (SMF) was demonstrated in their experiment. Due to the ultra-high *Q*-factor of ~108 with a small mode volume *V*, they observed Kerr effect at a record-low power of ~ 50 μW.

Furthermore, in current situation, high power-consumption is needed for all-optical signal processing because of varieties loss, such as scattering and coupling loss. Especially, for the SOI-based integration photonic devices, the coupling between optical fiber and silicon waveguide is a big issue. Up to date, the highest coupling efficiency of ~68% was reported by Wang et al. with the grating-assistance [15]. Highly efficient coupling between waveguides, both fiber and other waveguides, is a very important issue to be considered in optical signal processing. The highly efficient stable coupling between two conical micro/nano-fiber has been achieved by our group in the previous work [16], and coupling light from fiber to SOI-waveguide with highly efficiency is now pursuing with initial result of $>90\%$ coupling efficiency by simulation.

In the paper, we will review the widely applied functional devices based on micro/nano-fibers and SOI waveguide, including microring resonators, gratings, and SOI-plasmonic active waveguides. The main properties of light propagating in micro/nano-fibers and SOI waveguide are also illustrated. In optical signal processing, integrated and modular devices are the trend. And highly efficient coupling is an important process in integrated and modular devices. Finally, some works of our group on the grating, optical phase modulator and the solution of effectively coupling light from one waveguide to others are demonstrated.

2 Micro/nano-fiber-based photonic devices for optical signal processing

Micro/nano optical fibers (MNOFs) have attracted much attention because of their unique properties, such as large evanescent fields, high confinement, flexibility and compactness. Ten years ago, researchers realized the importance of MNOF, however, at that time fabricating a low-loss MNOF is a great challenge. They did not find an effective method to control the profile and surface roughness of MNOF that induces the high transmission loss. In 2003, Tong et al. [17] introduced a two-step drawing process to fabricate long uniform low-loss silica MNOF by a flame-heated fiber drawing. Since then, MNOF has been manufactured by a series of processes that include flame-brushing technique [18], modified flame-brushing technique [19], and direct drawing from the bulk [20]. And the material for fabricating MNOF is not limited to silica, chalcogenide glasses [19], tellurite [20], bismuthate [21] and polymers [22] were also used.

High confinement, large evanescent field, low propagation loss, and tailorable dispersion are main properties concerned by many researchers. While the diameter of an SMF decreased to micro/nanometer, the difference between core and cladding of the SMF can be ignored (they can be treated as a uniform part with an air cladding). Because of the larger refractive index difference between silica and air, the light is confined in a small size. With the radii of MNOF decreasing, the mode will become less until the confinement reaches the maximum when the *V* number is about 2 [23]. High light confinement indicates that MNOF has a very large nonlinearity. While the light beam is confined to a minimum waist diameter, according to nonlinearity

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{\mathrm{eff}}},$$

the nonlinearity of MNOF will reach the maximum, where n_2 is the material nonlinear refractive index and A_{eff} is the effective area of light beam. So the nonlinear refractive index of MNOF (fabricated from SMF) will be several times larger than that of standard single-mode fiber (SMF). If MNOF is fabricated from the material with highly nonlinear refractive index n_2, the nonlinearity γ of MNOF will be several orders of magnitude larger. Yeom et al. [10] have demonstrated As_2Se_3 fibers tapered to sub micrometer dimension yielding an effective nonlinearity of γ ~93.4 W/m, which is over 80000 times larger than SMF at wavelength of 1550 nm. High light confinement also implies that the MNOF can be bent a very small bent radii with lower bending loss. Tong et al. [17] have reported that the bending loss is less than 0.3 dB for a 90° turn with a bending radius of 5 μm in an air-clad 450-nm-diameter silica wire (for light of 633 nm wavelength). Low bending loss is very useful for integration photonic devices because the device can be fabricated with very small size, such as microring.

Large evanescent field is an extremely useful property of MNOF. While conventional optical fiber is tapered to a small diameter, a part of light power will propagate in evanescent field outside the MNOF. As a result, the light beam propagation will be affected by any environmental change. This property can be used for sensing [24], microring resonators [17], and waveguide coupling [16].

The MNOF have relatively low propagation loss due to its smooth surface. So Brambilla [25] has experimentally demonstrated a very-long ultra-low-loss taper with length > 40 mm and r~375 nm and the average loss is about 0.024 dB/mm. on the other hand, MNOF with small size will undergo mechanical and optical degradations. The degradations are more prominent as the MNOF becomes thinner and thinner [26]. Thus, some techniques are necessary to prevent MNOF from degradations such as embedding MNOF in low-index material.

The tailorable dispersion is also an interesting property of MNOF. The dispersion of a waveguide consists of material and waveguide dispersions. For MNOF, material dispersion can be ignored and waveguide dispersion is dominant, which provide a convenience to tailor the dispersion. As shown in Fig. 1, the waveguide dispersion D_w is diameter dependent. Based on this property by changing the diameter, then the light propagation property will be controlled, which can be used to optical communication and optical nonlinear [10,18].

In the following section, some typical MNOF-based photonic devices, including microring resonators, MNOF-based Bragg grating, which can be applied in signal processing, will be analyzed in detail. Together with it, high effective coupler will be given.

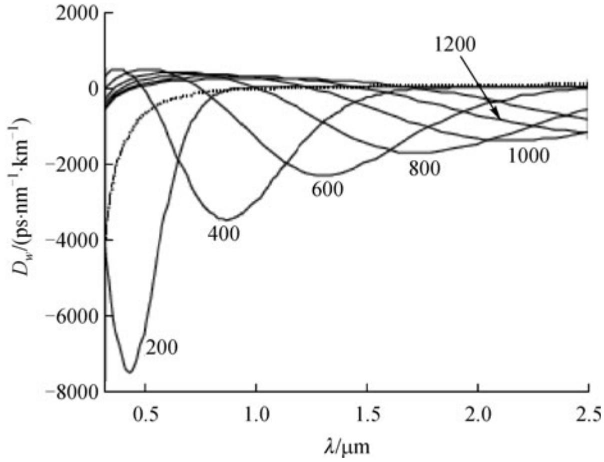


Fig. 1 Waveguide dispersion of silica MNOF with different diameters (material dispersion also shown in dotted line) [27]

2.1 Microring resonators

Resonator is an important device for optical signal processing. Two kinds of MNOF-based microring resonators (MRs) have been proposed: knot resonator and loop resonator. For these two resonators, the light modes in the adjacent section can be overlapped and coupled, creating a resonator with an extremely compact geometry. Knot resonator is the first MNOF MR with experimental demonstration [17]. Figure 2 shows a microscope image of a 0.58 mm diameter knot resonator with 2.1 μm diameter MNOF fabricated by our group. The transmission optical spectrum is shown in Fig. 3. The Q-factor of the MR is about 20000 with finesse of 10.

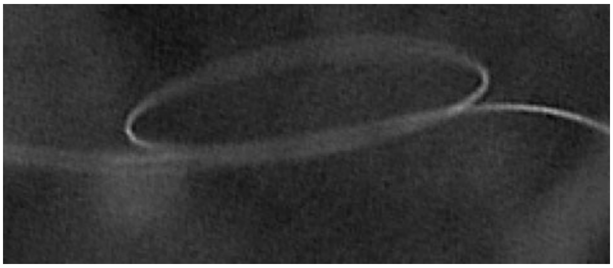


Fig. 2 Microscope image of MNOF-based microring resonator

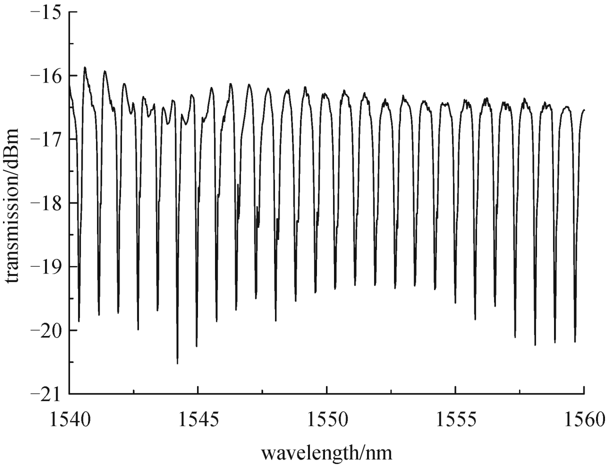


Fig. 3 Transmission spectrum of microring resonator

Compared to knot resonator, loop resonator (LR) is easier to fabricate. Figure 4 shows an LR proposed by Sumetsky [28]. The resonator has been formed in free space by creating a loop from the subwavelength diameter waist of a short biconical optical fiber taper. The fibers in coupling region were attached to each other by van der Walls and electrostatic forces. The microfiber loop resonator exhibits resonances with a Q-factor exceeding 15000 with finesse of 10.

MNOF-based photonic devices have shown many advantages, however, there is a challenge for MNOF, which is the optical and mechanical degradation that will be occurs as the MNOF is bare to environment, thus it is necessary to make protection by embedding. Lou et al. [26] have reported a technique to embed silica micro- and nanofibers in low-index material (Teflon) by using an inexpensive and straightforward fabrication process based on spin coating. Their results showed that the optical properties of completely embedded fibers do not degrade over a long time, while partially embedded fibers can preserve the large evanescent waves without undergoing considerable degradation, which represent a step forward toward the development of durable and stable devices based on MNOF. Almost at the same time, Chuo et

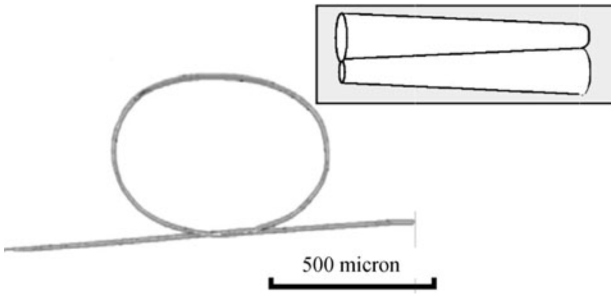


Fig. 4 SEM image of a 15-μm-diameter microring made with a 520-nm-diameter silica wire [28]

al. [29] have demonstrated a patterning technique which a microring is firstly made as a pattering groove on polydimethylsiloxane substrates, and then MNOF is placed into the groove by micromanipulation. Although the performance of the device proposed in this literature is not satisfactory, it provided a feasibility method to package the MNOF-based photonic devices.

Another issue for MNOF-based photonic devices is that the fabrication process is not compatible with the current integration circuit processing, such as CMOS, which is hampering its wide application. So the next step for MNOF-based photonic devices is to solve the problem of integration.

2.2 MNOF-based Bragg grating

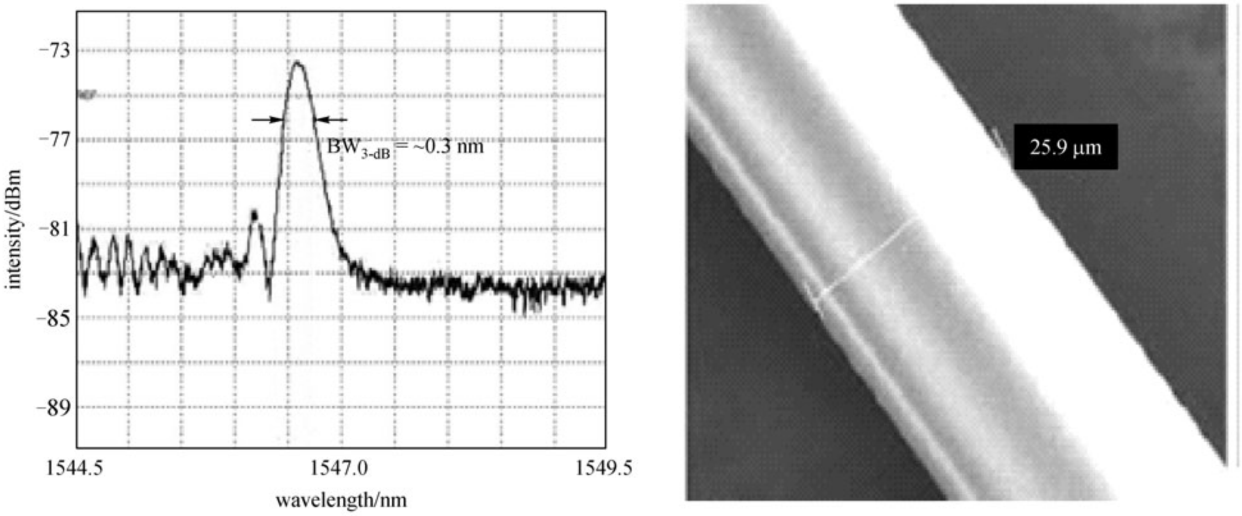
Gratings are other classes of important devices widely applied in optical signal processing. For the fiber Bragg gratings (FBGs) based on conventional single-mode fibers, the refractive index modulation depth is fixed as light energy is strongly confined in the fiber core. Therefore, the sensitivity of the conventional FBGs is limited once the grating period and length are determined due to energy distribution in core area of SMF. A possible solution is to fabricate FBGs in MNOF. As the fraction of guided light propagating outside the fiber core varies with the MNOF diameter, the index modulation depth also changes with the fiber diameter. Since a considerable fraction of light propagates outside the MNOF, it will be affected by the surrounding refractive index, which is possible to detect some change in the surrounding refractive index. A liquid concentration sensor based on MNOF gratings has been proposed [30]. The sensor is an etch-eroded fiber Fabry-Pérot interferometer with a radius of 1.5 μm and is used to measure the refractive indices of isopropyl alcohol solutions of different concentrations. Due to its narrower resonance spectral feature, the sensor has a higher sensitivity than the conventional FBG sensor and can detect an index variation of 1.4×10^{-5}.

Jin et al. [31] have presented an MNOF-based long period gratings by focused high frequency CO_2 laser pulses to periodically modify the transverse dimension of silica microfibers, which will induce a physical deformation of the MNOF and then the strong transmission dip 27 dB can be observed.

A more cost-effective method to fabricate Bragg gratings on MNOF is demonstrated in Ref. [32]. By exposing an MNOF under UV light without hydrogen load in, a 3-dB bandwidth with 0.3 nm was observed. Figure 5 shows the optical spectrum of the gratings with a diameter of 25.9 μm [32].

2.3 High effective coupler

For integration photonic devices, packaging is a key issue. Highly effective coupling between different waveguides is



(a) (b)

Fig. 5 (a) Reflection spectrum of typical MNOF-based grating; (b) typical MNOF-based grating with a diameter of 25.9 μm [32] a great issue. Many methods have been proposed, however, the coupling efficiency is low due to mode field mismatch or other reasons [33].

Using the property of large evanescent of MNOF may be an effective way to solve the coupling issue. As the evanescent field of MNOF is stronger than conventional SMF, the perturbation-based coupled mode theory is no longer applied. Recently, the coupling characteristics between two conical micro/nano-fibers have been demonstrated with numerical simulations and experiments as shown in Fig. 6 [16]. A stable coupling efficiency of $>90\%$ was observed in an experiment as shown in Fig. 7 [16]. It also provides a method for efficient light coupling between fiber and Si-based waveguide. The detail illustration for the coupling between fiber and Si-based waveguide will be shown in Sect. 3.2.

3 Silicon waveguide-based photonic devices for optical signal processing

Initially, silicon has been applied widely for infrared optics, especially at fiber optic telecommunication band; then, silicon is also the material for visible detection, for example, as the imaging element in digital cameras. The silicon material provides many benefits: in photonic, it has wide band infrared transparency; in electronic, it has low noise and high speed integrated circuits; in thermal, it has high heat conductance, and in structural, it has rugged 3D platforms and packages. All of these material properties can satisfy the need for higher speed, broader bands, and lower cost matches with the rise in internet and data transmission, which will make it possible to be a wide range of integrated electronic and photonic circuits [34].

While light propagates in silicon devices, a range of nonlinear optical phenomena will be observed including the Kerr effect, the Raman effect, two photon absorption and interactions between photons and free charge carriers. Nonlinearity is fundamental for optical signal processing, as it enables one light signal to control another, thus it permits applications such as wavelength conversion and all-optical signal routing, in addition to the passive transmission of light.

SOI-based silicon photonics has recently attracted much attention. SOI is a new way for chip-making process due to its high index contrast between the silicon core and the silica insulator, which allows strong confinement of light and enables compact devices. There are several main research areas of concentration to make silicon photonics a reality: light source [35], light guide [36], modulation [37], photo detection [38], low cost assembly, and intelligence to drive all of these.

In the following subsections, silicon-based integrated photonic methods applied in signal processing will be introduced, and coupling between optical fibers and silicon waveguides will be analyzed too.

3.1 Integrated devices for integration

On-chip optical components would offer a substantially higher bandwidth, a lower latency, and reduced power dissipation compared with electronic components [39–44]. However, typical dimensions of conventional dielectric waveguides are dictated by diffraction; therefore, the dense

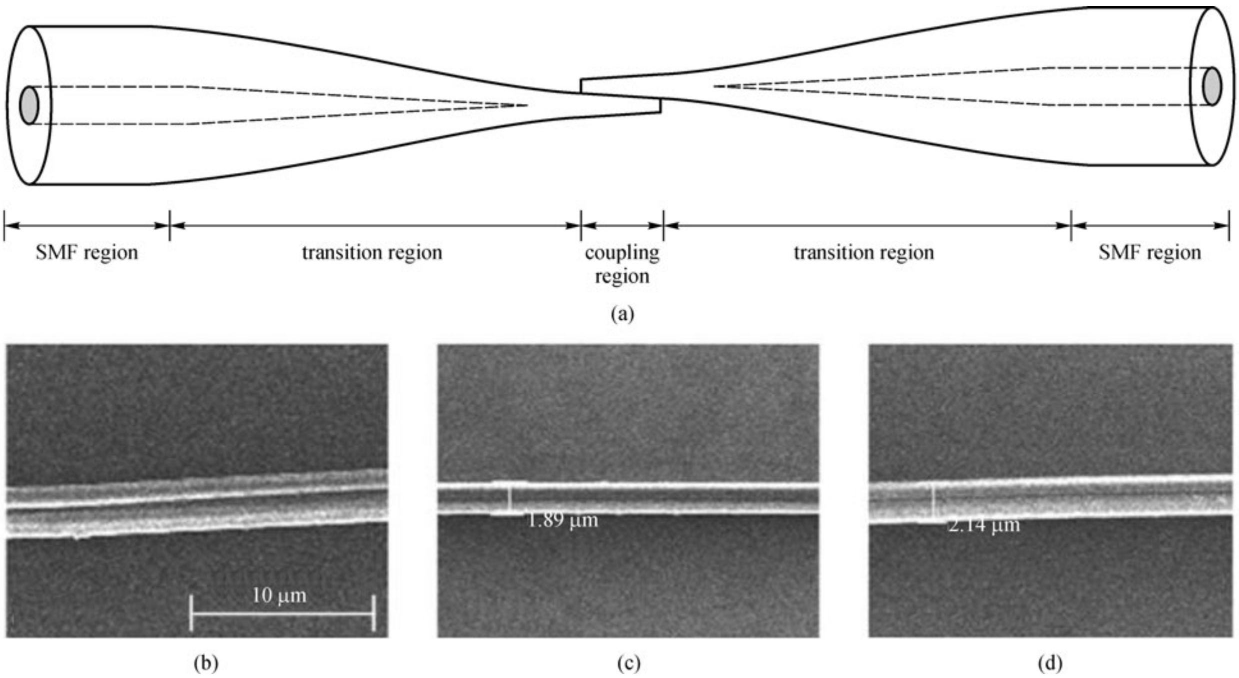


Fig. 6 Schematic diagram of conical MNOF-based coupler [16]

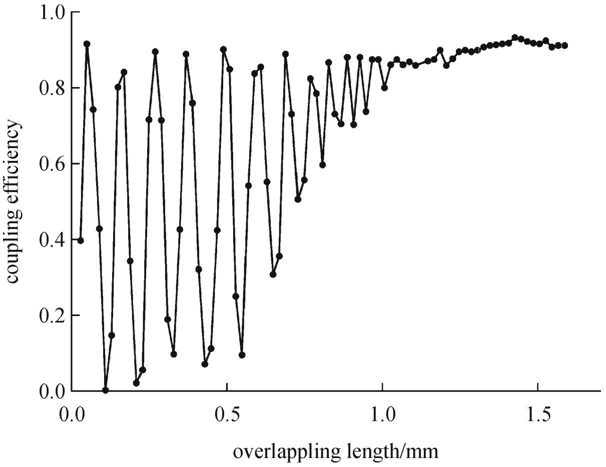


Fig. 7 Measured coupling efficiency versus overlapping length for MNOF-based couplers [16]

of on-chip integration is limited. In order to match the size between electrical and optical components, some special technologies have been proposed. These technologies allow subwavelength confinement for optical mode and have shown the tremendous potential applications in ultra-compact photonic integrated circuits. In order to break the diffraction limit to improve the integration density, surface plasmon polaritons (SPPs) [45], photonic crystal waveguides, and dielectric devices with high refractive index contrast are potential candidates for nano-scale optical elements, which have attracted the interests of researchers around the world.

SPPs, as electromagnetic (EM) excitations coupled to surface collective oscillations of free electrons in a metal, are bound to and propagate along metal-dielectric interfaces which could provide a true nano-scale waveguiding and confinement of light. SPPs have extremely short wavelengths, high optical field enhancement at the interface, and strong optical confinement down to deep subwavelength dimensions. There are various types of SPP-based plasmonic waveguides [45–59], including groove waveguides [50–52], slot waveguides [53–55], gold strip waveguides [56], hybrid plasmonic waveguides [57–59], etc. Plasmonic devices such as modulators, bends, splitters, Bragg reflectors, nano-cavities interferometers and ring resonators [59–62] have been proposed.

Photonic crystals [63] are periodic dielectric or metallo-dielectric artificially optical nanostructures that can affect the propagation of electromagnetic waves by defining allowed and forbidden photonic energy bands. It can exhibit a periodic variation in one, two, or three dimensions. In 3D photonic crystals, light at a certain wavelength band cannot propagate in any direction. While introduce defects into the periodic arrangement, the photonic crystals exhibit analogous properties with solid-state crystals, which provides a novel combination of abilities: to confine, guide, and decelerate light. Etching arrays of holes with diameters of a few hundred nanometers (or smaller) into silicon is a typical processing to fabricate photonic crystal. With the advantage of electron beam nanolithography, fabricating such photonic crystals with high precision is possible. Photonic crystals devices such as waveguide bends [64,65], branches [66], waveguide couplers [67], frequency filters [68], Mach-Zehnder interferometers [69], etc. have been proposed.

Dielectric devices with an ultra-high index-contrast can also be used to enhance and confine light in a small area, which is caused by large discontinuity of the electric field at high index-contrast interfaces. These properties may lead to all-optical switching, parametric amplification on integrated photonics, and can be used to greatly increase the sensitivity of compact optical sensing devices or to enhance the efficiency of near-field optical probes [70,71].

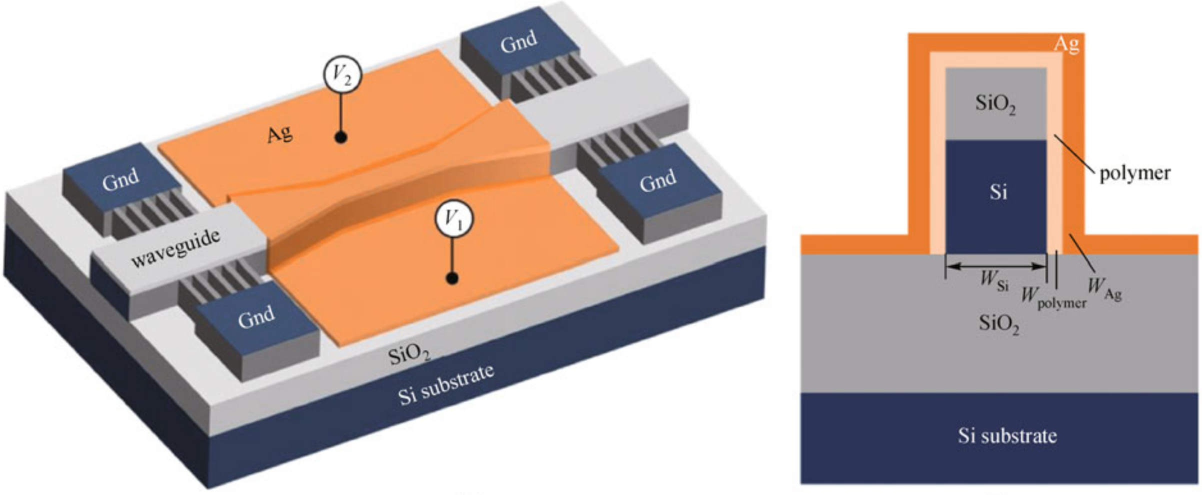
Here, we propose an optical phase modulator based on a silicon-polymer hybrid plasmonic waveguide, as shown in Fig. 8 [72]. The plasmonic waveguide is composed of silver-polymer-silicon stack layers to fully utilize the high confinement feature of the plasmonic mode and the high linear electro-optic effect of the polymer material. Due to its compact size, the modulation bandwidth is 100 GHz and the power consumption is 9 fJ/bit, with assuming the modulation frequency is 100 GHz. The proposed plasmonic waveguide based phase modulators can be found many applications in optical telecommunication and intra-chip optical interconnect.

3.2 Coupling between optical fibers and silicon waveguides

Silicon photonics is one of the leading candidate technologies in optical telecommunications, interconnects and more complex optical network-on-chip (ONoC). However, the thickness of silicon core layer is only a few hundred nanometers, while the diameter of a single-mode fiber core is about 9 mm. There is a huge mismatch between the waveguide mode and a single-mode fiber mode. If they are coupled directly, it will cause a large coupling loss and need high-precision alignment control. Moreover, the refractive index of silicon is large, which will induce large reflection when light deflects from air. So the light coupling between optical fibers and SOI waveguides is important [73–75].

In order to transform small waveguide mode into fiber-adapted mode, a converter is used. Common converter uses nanotaper structure [73], with the tapered end connecting to the silicon waveguide, and the other side gradually increasing to a considerable size as a single-mode fiber. This method needs large conversion length (usually in the millimeter level) and the coupling efficiency is not high.

An efficient coupler for compact mode conversion between a fiber and a sub micrometer waveguide was proposed and demonstrated by Cornell University [74], as shown in Fig. 9. The principle of this inverse nanotaper is that waveguide side gradually reduced to the tip of dozens



(a) (b)

Fig. 8 (a) Schematic perspective view of proposed active plasmonic waveguide; (b) cross-sectional view of active plasmonic waveguide [72]

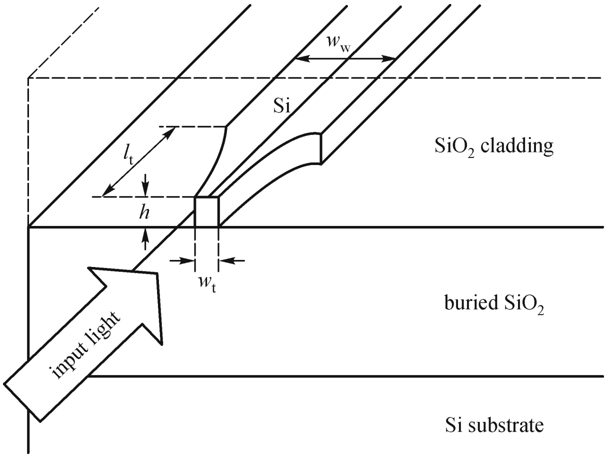


Fig. 9 Schematics of a waveguide with a nanotaper coupler [74]

of nanometer, making most of the light at the tip inside the silica cladding, which efficiently convert both the mode field profile and the effective index. Compared with the usual taper structure, it can reduce losses and size, but this method has many manufacture requirements, and it is very hard to be achieved in the lab conditions though the coupling efficiency is highest in the horizontal fiber coupling setup.

Due to the difficulties of the horizontal fiber coupling setup, researchers in Ghent University created a vertical fiber coupling setup, that was grating coupler [75], as shown in Fig. 10. Such a coupler does not require polishing of facets and allows wafer scale testing of photonic integrated circuits. The grating is only 13 μm long and 12 μm wide, which is etched into the silicon core layer and the grating grooves are invariant in the x direction. On the top of the silicon, there is an index-matching layer. The end facet of the fiber is close to the grating, and the fiber is slightly tilted. The angle between fiber axis and y axis is 8 degrees for avoiding reflection at the waveguide grating. When using SOI with a bottom reflector at the wavelength of 1550 nm, a coupling loss below 1 dB can be achieved over a 35 nm wavelength range for transverse electric (TE) mode polarization. When using regular SOI with optimized buried oxide thickness, the efficiency is 1.8 dB lower.

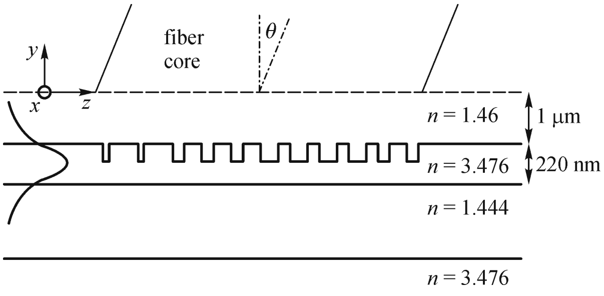


Fig. 10 SOI grating coupler problem [75]

4 Conclusion

In this paper, we have reviewed two main classes of micro/nanostructure integration photonic devices. For the micro/nano-fiber-based photonic devices, we demonstrate the development of micro/nano optical fibers. We place the emphasis on MNOF-based photonic devices that have broad range of applications in signal processing. For the silicon waveguide-based devices, we analyzed the silicon-based integrated photonic methods and coupling between optical fibers and silicon waveguides. Micro/nanostructure integration photonic devices will play very important role in areas ranging from optical communication to sensing, biology, and microelectronics.

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