Front. Optoelectron. China 2011, 4(3): 264–269
DOI 10.1007/s12200-011-0218-x

RESEARCH ARTICLE

High-speed, compact silicon and hybrid plasmonic waveguides for signal processing

Yikai SU (✉), Gan ZHOU, Fei LI, Tao WANG

State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

© Higher Education Press and Springer-Verlag Berlin Heidelberg 2011

Abstract All-optical circuits for signal processing could be a promising solution to overcome the speed bottleneck of electronics. For the photonics industry, silicon becomes a competitive material of choice in the field of integrated optics for designing and implementing high-speed and compact photonic devices. To further increase the integration density, it is a critical challenge to manipulate light on scales much smaller than the wavelength for the dielectric waveguides due to the diffraction limitation. Surface plasmon-polaritons (SPPs), which break the diffraction limitation, are receiving increasing attentions in recent years. This paper compares the advantages and disadvantages between electronic devices and optical devices taking differentiator as an example, and proposes an optical parametric amplifier (OPA) using silicon-based hybrid plasmonic waveguide.

Keywords silicon based, surface plasmons, microring resonator, differentiator, optical parametric amplifier (OPA)

1 Introduction

Over time, a gradual transition from electrical to optical technology can be seen in the interconnect market, since the limitations of copper as an interconnect medium in term of its loss, dispersion, crosstalk, and fundamental speed are becoming increasingly obvious when the interconnect densities increase [1,2]. Optical interconnects has gained its applications from high-performance computing, date centers, down to mobile-to-server interconnects and desktop computers. Silicon photonics becomes a competitive candidate thanks to its unique combination of low fabrication costs, compact size, performance enhancements resulting from electronic-photonic integration, and compatibility with complementary metal oxide semiconductor (CMOS) technology [2,3]. To achieve miniaturization and high-speed performance of the devices, silicon microring resonators are playing a significant role in recent years, due to its ultra-compact size, periodic linear high-Q filter effect, and capability of forming strong optical field inside the ring [4–9]. Many applications have been studied, including optically tunable optical delay line [4], all-optical modulation format conversion [5,6], generation of ultra-wideband monocycle pulses [7], all-optical temporal differentiator [8], all-optical integrator [9], etc.

However, the guiding mode size of conventional dielectric waveguide is limited to the same level of the transmission wavelength, thus limiting further decreasing of the device size and therefore the integration density. To overcome the limitations, plasmonic waveguides supporting surface plasmon-polariton (SPP) mode are proposed. Due to the coupling of the electromagnetic wave and electron gas, the electromagnetic wave is localized at the interface between metal and dielectric layers, confining the mode into subwavelength region and breaking the diffraction limitation [10]. Many kinds of silicon-based plasmonic waveguides have been introduced, such as conductor-gap-dielectric (CGD) hybrid waveguide [11], wedge waveguide [12], groove waveguide [13], slot waveguide in the form of rectangular nanogaps in thin metal films [14], and hybrid plasmonic waveguide formed by a cylindrical dielectric nanowire coupled to a metal surface [15]. However, the propagation loss increases largely when the waveguide size decreases to several tens of nanometers. Step-structure hybrid plasmonic (SHP) waveguide shows unique properties [16], where nano-scale mode size and ultra-low loss can be realized simultaneously. Based on the SHP waveguide, an ultra-broadband optical parametric amplifier (OPA) was introduced [17].

In this paper, we focus on the high-speed and compact

Received March 15, 2011; accepted May 15, 2011

E-mail: yikaisu@sjtu.edu.cn

silicon devices and silicon-based plasmonic devices, including an 80-Gb/s optical differentiator using compact silicon ring resonator, and an ultra-broadband OPA with above 1 μm operational bandwidth using nano-scale SHP waveguide. To start, we compare the advantages and disadvantages between electronic devices and optical devices taking differentiator as an example.

2 Comparison between electronic and optical differentiators

After years of development, electronics has been matured in signal processing, information communication, etc. With CMOS as a successful technology for producing electronics, the densities of the electronic circuits increase significantly. However, the integration of modern electronic devices for information processing and sensing is rapidly approaching its fundamental speed and bandwidth limitations known as Moore's law. Optical technology could bring several major advantages over the electrical counterpart. It reduces the electromagnetic interference, cable length and cable weight, and may also allow increased complexity in device design through optical interconnects and optimized cooling, resulting in substantial energy savings [1]. The optical operation speed and bandwidth could be several orders of magnitude over electronics. The major problem for optical devices is the lack of integration and miniaturization, which are relatively lagging behind those achievable in modern electronics [18]. For this reason, research on optical integration has received tremendous interest in recent years.

Optical differentiator, as a basic building block for mathematical and logical operations, has received considerable attention recently due to its potential applications in ultrafast all-optical information processing and computing, optical pulse shaping and coding, ultra-wideband microwave signal generation, higher-order Hermite-Gaussian waveforms generation and processing, direct phase reconstruction of arbitrary optical signals, and high-speed analog computing. Therefore, we take differentiators to investigate the differences between electrical and optical circuits. Different optical differentiators have been proposed, such as Mach-Zehnder interferometer [19], fiber grating [20], as well as semiconductor optical amplifier (SOA) [21]. We proposed and experimentally demonstrated a temporal differentiator in optical field using a silicon microring resonator with a radius of 20 μm (Fig. 1(a)). The microring resonator operates near the critical coupling region, and can take the first order derivative of the optical field. The performance of this optical differentiator was tested using signals with typical shapes such as Gaussian, sinusoidal and square-like pulses at data rates of 10 and 5 Gb/s [8]. Furthermore, we recently demonstrated 80-Gb/s optical differentiation of picoseconds (ps) pulses. In analog computing to solve differential equation using electronic differentiator, one usually takes procedures shown in Fig. 1(b). The analog signal is sampled through an analog-to-digital (A/D) converter after filtered by a low pass filter to be a digital signal. Then the digital signal is input into a digital signal processing (DSP) chip where the digital differentiation procedure is accomplished. After processing, the digital signal is reconstructed to analog signal through a digital-to-analog

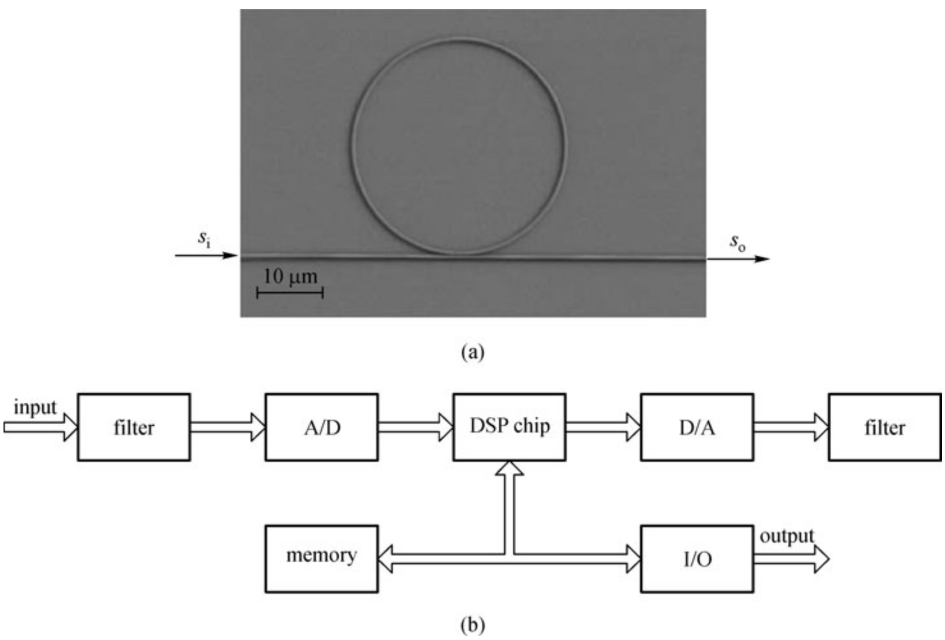

Fig. 1 Two schemes to realize optical and electronic differentiators. (a) Optical differentiator using a single silicon ring resonator; (b) realization of electronic differentiator using digital signal processing

(D/A) converter. Finally, one gets the analog differential signal after filtering.

Speed of the electronic differentiator is mainly limited by the processing speed of the A/D converter, DSP chip and D/A converter. To our knowledge, the fastest components have the following performances: A/D converter (MAX109) has a sampling speed of 2.2 GS/s, D/A converter (MAX5881) has a reconstruction speed of 4.3 GS/s, and DSP chip has 1.2 GHz clock rate. The power consumption varies from several mW to several W.

We make a comparison of these two types of differentiators with respect to complexity, line width, power, and speed as shown in Table 1. It can be seen that the electronic device can integrate many function blocks in one chip, while the optical processing device in silicon photonics is less complex with a single function on one chip. The line width of electronic device is about tens of nanometers while that of optical devices is more than 100 nm. The range of power consumption is comparable to each other, varying from several mW to several W. However, the maximum processing speed of optical devices outperforms electronic devices by 3 orders of magnitude, which can achieve several Tb/s.

Table 1 Comparison of electronic devices and optical devices

	electronic processing	optical processing in silicon photonics
complexity (number of units)	high	low
line width	10's nm	> 100 nm
power	mW–W	mW–W
speed	Gb/s	Gb/s–Tb/s

3 All-optical differentiator based on compact silicon microring resonator

In this section, we introduce an 80-Gb/s optical differentiator. Figures 2(a) and 2(b) show the scanning electron microscope (SEM) pictures of a fabricated single coupled microring resonator. A ring is evanescently coupled to a single straight waveguide. The device is fabricated on a semiconductor-on-insulator (SOI) wafer with a 250-nm-thick silicon slab on top of a 3 μm silica buffer layer, employing E-beam lithography, reactive ion etching and wet chemistry. The cross section of the silicon waveguide is 450 nm×250 nm. Wet chemistry for oxidizing 20 Å of silicon surface is carried out to reduce the surface roughness to reduce the loss. The transfer function of the microring resonator can be expressed as [8]

$$T(\omega)=\frac{s_{\mathrm{o}}}{s_{\mathrm{i}}}=\frac{\mathrm{j}(\omega-\omega_0)+\frac{1}{\tau_{\mathrm{i}}}-\frac{1}{\tau_{\mathrm{e}}}}{\mathrm{j}(\omega-\omega_0)+\frac{1}{\tau_{\mathrm{i}}}+\frac{1}{\tau_{\mathrm{e}}}}, \tag{1}$$

where ω_0 is the resonance frequency, τ is the reciprocal of photon lifetime as $1/\tau = 1/\tau_{\mathrm{i}} + 1/\tau_{\mathrm{e}}$, $1/\tau_{\mathrm{i}}$ is the power decay rate due to the intrinsic loss and $1/\tau_{\mathrm{e}}$ is the power coupling loss to the straight waveguide from the ring. Under the condition that the microring resonator works at the critical coupling region ($\tau_{\mathrm{i}} = \tau_{\mathrm{e}}$) and the frequency detuning is much less than the 3-dB bandwidth of the microring resonator, Eq. (1) can be approximated as [8]

$$T(\omega)=\frac{s_{\mathrm{o}}}{s_{\mathrm{i}}}=\mathrm{j}\tau(\omega-\omega_0). \tag{2}$$

Equation (2) is a typical function of first-order differentiator. The measured transmission spectrum of the silicon microring is shown in Fig. 2(c). The notch depth at the resonance is about 25 dB, implying that the ring resonator works close to the critical coupling condition, and the 3-dB bandwidth is 2.5 nm at the resonance frequency of 1551.7 nm.

Experiment for 80-Gb/s signal differentiator is carried out based on the measurement setup in Fig. 2(e). Figure 2(d) is the vertical coupling setup for light coupling between the fiber and the silicon waveguide, which possesses about 20-dB power loss. Inset (iii) in Fig. 2(e) shows the experimental results of 80-Gb/s signal differentiator. A 10-GHz radio frequency (RF) clock from a pulse pattern generator (PPG ANRITSE MP1763C) is amplified and used as an electrical driver of a pico-second-pulse generator (u2t tunable mode-locked semiconductor laser (TMLL) 1550), which works in active mode locking state. The output of the TMLL 1550 is pico-second pulse train with a repetition frequency of 10 GHz and a full width half maximum (FWHM) of 2.7 ps measured by a 500 GHz optical sampling oscilloscope (Alnair Lab EYE-2000C) as shown in the inset (i). The 10-GHz pico-second pulses are amplified with an erbium-doped fiber amplifier (EDFA) and input to an optical multiplexer (OMUX), where three-stages of multiplexing are employed, to generate an 80-Gb/s optical time division multiplexing (OTDM) signal, as shown in the inset (ii). After amplification, the 80-Gb/s OTDM signal is fed into the silicon microring resonator through the vertical coupling set. The signal is amplified with another EDFA after the microring resonator. Lastly, the signals are recorded using a 500-GHz optical sampling oscilloscope. Inset (iii) shows the experimental result of the differentiated 80-Gb/s OTDM signal. The shape differences between the pulses of the 80-Gb/s OTDM signal are mainly caused by the imperfect attenuations and time delays in the three propagation paths within OMUX. The phenomenon of non-return-to-zero in the middle of the two lobes of the experimental result is induced by the limited bandwidth of the 500G-oscilloscope (resolution of 1 ps). The asymmetry of the two lobes is mainly caused by the third order dispersion of the microring resonator at the resonance wavelength, and the comparable bandwidth of the ps-pulse (1.5 nm) to the operation bandwidth of the ring resonator (2.5 nm). The speed of the differentiator is mainly limited by the 3-dB bandwidth of the microring resonator. By introducing a

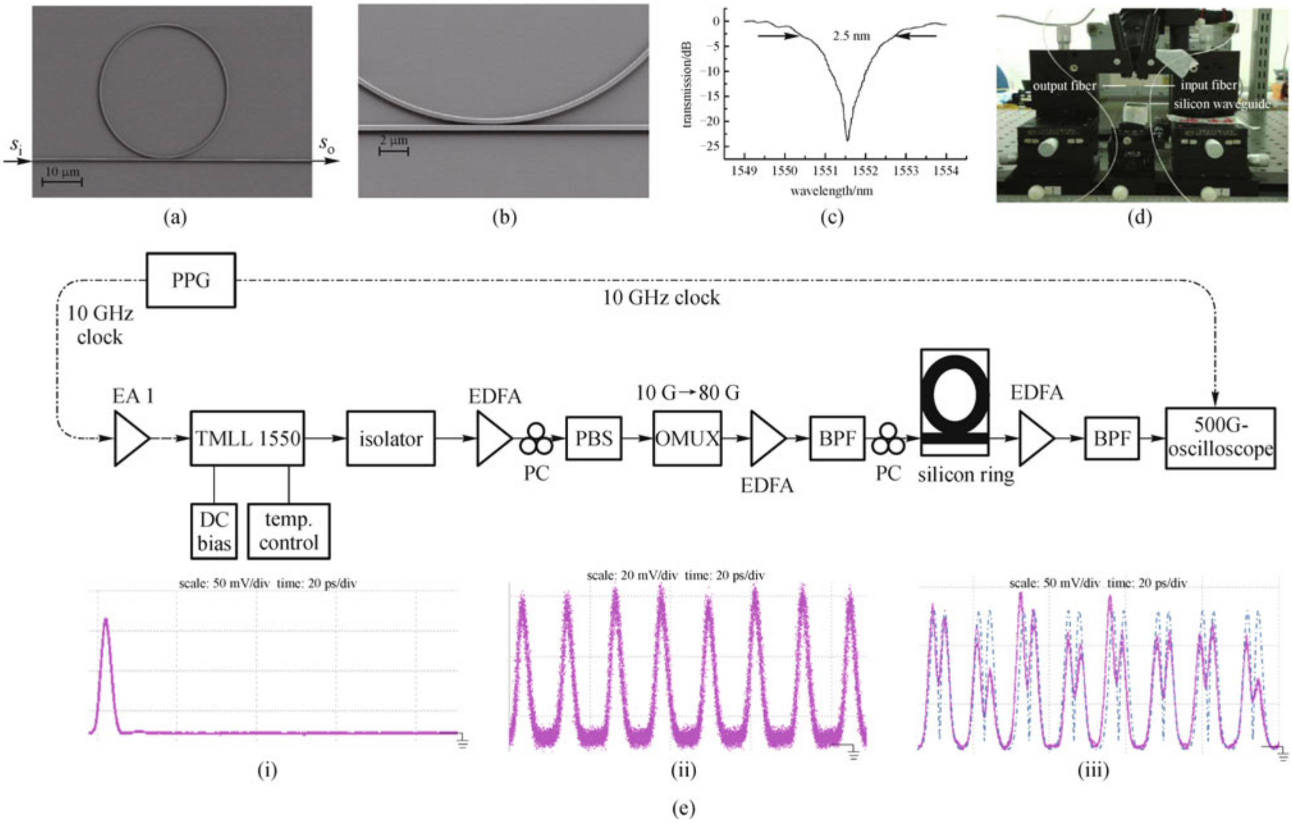

Fig. 2 80-Gb/s optical differentiator. (a,b) SEM pictures of fabrication silicon microring resonator with radius of 20 μm; (c) measured transmission spectrum of ring resonator; (d) vertical coupling setup for fiber to silicon waveguide light coupling; (e) experimental setup for 80-Gb/s signal differentiator. Inset (i) inputted 10-GHz optical ps-signal; inset (ii) generated 80-GHz OTDM signal before differentiation; inset (iii) red solid curve: the measured differential results of the 80-GHz OTDM signal; blue dotted curve: simulated curve after an ideal differentiator of 80-GHz OTDM signal

low-Q factor microring resonator operating near the critical coupling region, the differentiator can be utilized for the signal with hundreds of Gb/s date rate.

One possible important application of the silicon-based high-speed optical differentiator is the ultra-high-speed integrated all-optical analog computing, e.g., solving ordinary differential equations (ODE), as shown in Fig. 3. Using the multi-mode interferece as a subtracter and silicon ring resonator as a high-speed differentiator, an integrated silicon based analog all-optical computing for sovling first-order linear ODE can be realized.

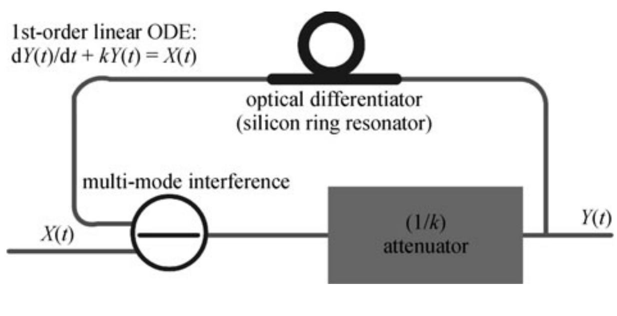

Fig. 3 Integrated analog all-optical computing scheme for real-time solving of first-order linear ODE using silicon ring resonator based ultra-fast optical differentiator

4 Ultra-broadband optical parametric amplifier employing nanoscale plasmonic waveguide

Silicon-based optical signal processing breaks the speed and bandwidth limitations of modern electronic devices. However, a major problem with using electromagnetic waves as information carrier in optical signal processing is the low level of integration and miniaturization, which is due to the diffraction limit of light in dielectric media. SPPs, which break the diffraction limitation, are capable of confining the light into subwavelength. Thus, silicon-based plasmonic devices show great promise for miniaturization and improvement of the spatial resolution of optically integrated devices [19]. For conventional silicon-based plasmonic waveguide, the propagation loss increases largely when the size of the waveguide decreases to

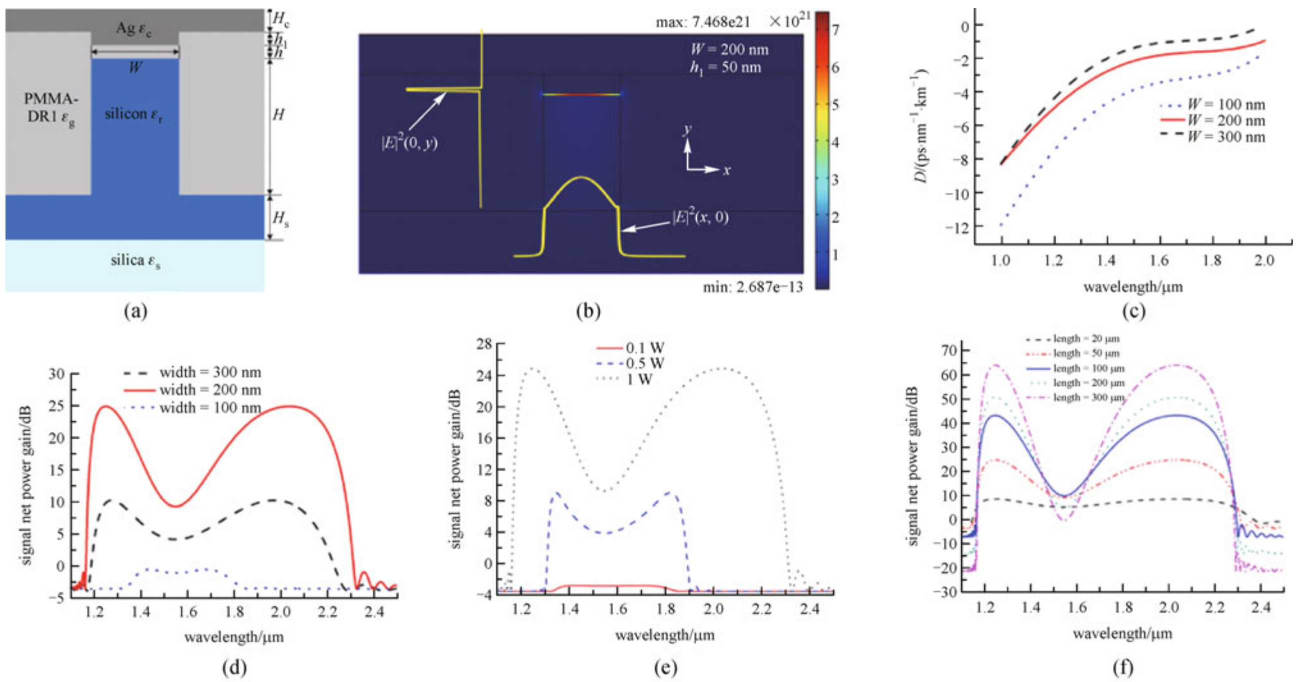

Fig. 4 (a) Schematic of SHP waveguide; (b) $|E|^2$ profiles of SHO waveguide in x-y plane, with $W = 200$ nm, $H = 300$ nm, $h = 5$ nm, $h_1 = 50$ nm, $H_c = 100$ nm, $H_s = 200$ nm; (c) calculated GVD denoted by D versus wavelength; (d) simulated curves of signal net power gain for SHP waveguide with 1-W peak pump power at 1550 nm and waveguide length of 50 μm; (e) simulated curves of signal net power gain for pump power varying from 0.1 to 1 W, with waveguide width of 200 nm and length of 50 μm; (f) simulated curves of signal net power gain for waveguide length varying from 20 to 300 μm, with pump power of 1 W and waveguide width of 200 nm

several tens of nanometers. We recently proposed an SHP waveguide as shown in Fig. 4(a) that exhibits better trade-off between the field confinement and the propagation loss. Figure 4(b) shows the mode profiles of the SHP waveguide with a waveguide width of 200 nm. The mode size of the SHP waveguide is ~ 1×10^{-3} μm. The SHP waveguide can be a competitive candidate for ultra-compact high-speed optical signal processing devices. An ultra-broadband OPA is proposed through detailed simulations based on SHP waveguide by applying highly nonlinear polymer poly (methyl methacrylate) functionalized with DR1 films (polymethyl methacrylate (PMMA)-DR1). Figure 4(c) depicts the calculated group-velocity-delay (GVD) values of the propagating mode for waveguide widths of 100, 200 and 300 nm, respectively. It is clear that the waveguides show a normal GVD from wavelength of 1000 to 2000 nm, due to the large silicon material dispersion near the wavelength of 1.55 μm. Thus, PMMA-DR1 with negative nonlinear index is introduced to satisfy the phase-matching condition. The performances of the OPA are analyzed with different waveguide widths, lengths and pump powers as shown in Figs. 4(d), 4(e) and 4(f), respectively. It is also indicated that with the length ⩾ 300 μm, the signal net gain near λ_p becomes below 0 dB, due to the large propagation loss of the long waveguide length. With a single pump power of 1 W, the optical amplifier which occupies nano-scale area (~ 1×10^{-3} μm^2) is able to provide an on/off gain over a wavelength range of above 1 μm within the communications band, thus significantly enhance the optical signal processing capabilities of all-silicon nano-photonic integrated circuits with a peak signal net gain of above 25 dB.

5 Conclusion

Silicon microring resonator shows its unique properties for high-speed signal processing such as solving ordinary differential equations. Compact 80-Gb/s all-optical temporal differentiator based on the resonator is demonstrated. In addition, plasmonic nanostructures capable of guiding light beyond the diffraction limitation are particularly useful for future design and development of highly integrated and efficient high-speed optical signal processing. SHP waveguide shows good trade-off between the propagation loss and mode size, and a 1-μm-broadband OPA with net power gain of above 25 dB is proposed by utilizing highly nonlinear polymer.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 61077052).

References

1. Koehl S. Silicon photonics could revolutionize future servers and

networks. Converge! Network Digest, 2005, http://www.converge-digest.com/blueprints/ttp03/bp1.asp?ID = 242&ctgy = Market

2. Reed G T, Mashanovich G, Gardes F Y, Thomson D J. Silicon optical modulators. Nature Photonics, 2010, 4(8): 518–526
3. Reed G T. Device physics: the optical age of silicon. Nature, 2004, 427(6975): 595–596
4. Liu F F, Li Q, Zhang Z Y, Qiu M, Su Y K. Optically tunable delay line in silicon microring resonator based on thermal nonlinear effect. IEEE Journal on Selected Topics in Quantum Electronics, 2008, 14 (3): 706–712
5. Liu F F, Li Q, Zhang Z Y, Qiu M, Su Y K. Ultra-compact mode-split silicon microring resonator for format conversion from NRZ to FSK. Proceedings of SPIE, 2008, 7135: 713537
6. Li Q, Ye T, Lu Y Y, Zhang Z Y, Qiu M, Su Y K. All optical NRZ-to-AMI conversion using linear filtering effect of silicon microring resonator. Chinese Optics Letters, 2009, 7(1): 12–14
7. Liu F F, Wang T, Zhang Z Y, Qiu M, Su Y K. On-chip photonic generation of ultra-wideband monocycle pulses. Electronics Letters, 2009, 45(24): 1247–1249
8. Liu F F, Wang T, Qiang L, Ye T, Zhang Z Y, Qiu M, Su Y K. Compact optical temporal differentiator based on silicon microring resonator. Optics Express, 2008, 16(20): 15880–15886
9. Ferrera M, Park Y, Razzari L, Little B E, Chu S T, Morandotti R, Moss D J, Azaña J. On-chip CMOS-compatible all-optical integrator. Nature Communications, 2010, 1(29): 1–5
10. Pile D F P, Ogawa T, Gramotnev D K, Okamoto T, Haraguchi M, Fukui M, Matsuo S. Theoretical and experimental investigation of strongly localized plasmons on triangular metal wedges for subwavelength waveguiding. Applied Physics Letters, 2005, 87 (6): 061106
11. Moreno E, Vidal F J G, Rodrigo S J, Moreno L M, Bozhevolnyi S I. Channel plasmon-polaritons: modal shape, dispersion, and losses. Optics Letters, 2006, 31(23): 3447–3449
12. Veronis G, Fan S H. Guided subwavelength plasmonic mode supported by a slot in a thin metal film. Optics Letters, 2005, 30(24): 3359–3361
13. Berini P. Plasmon-polariton waves guided by thin lossy metal films of finite width: bound modes of asymmetric structure. Physical Review B: Condensed Matter and Materials Physics, 2001, 63(12): 125417
14. Oulton R F, Sorger V J, Genov D A, Pile D F P, Zhang X. A hybrid plasmonic wavguide for subwavelength confinement and long range propagation. Nature Photonics, 2008, 2(8): 496–500
15. Dai D X, He S L. A silicon-based hybrid plasmonic waveguide with a metal cap for a nano-scale light confinement. Optics Express, 2009, 17(19): 16646–16653
16. Zhou G, Wang T, Su Y K. Design of Plasmon waveguide with strong field confinement and low loss for nonlinearity enhancement. Proceedings of SPIE, 2010, 7987: 79870A
17. Zhou G, Wang T, Su Y K. Wide broadband optical parametric amplifier in ultra-compact plasmonic waveguide. In: Proceedings of Asia Communications and Photonics Conference and Exhibition. 2010, SuK4
18. Gramotnev D K, Bozhevolnyi S I. Plasmonics beyond the diffraction limit. Nature Photonics, 2010, 4(2): 83–91
19. Li Z, Zhang S, Vazquez J M, Lou Y, Khoe G D, Dorren H J S, Lenstra D. Ultrafast optical differentiators based on asymmetric Mach-Zehnder interferometer. In: Proceedings of Symposium IEEE/LEOS. Benelux Chapter, 2006, 173–176
20. Slavík R, Park Y W, Kulishov M, Azaña J. Terahertz-bandwidth high-order temporal differentiators based on phase-shifted long-period fiber gratings. Optics Letters, 2009, 34(20): 3116–3118
21. Xu J, Zhang X L, Dong J J, Liu D M, Huang D X. High-speed all-optical differentiator based on a semiconductor optical amplifier and an optical filter. Optics Letters, 2007, 32(13): 1872–1874