Development trends in silicon photonics

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Silicon photonics has become one of the major technologies in this very information age. It has been intensively pursued by researchers and entrepreneurs all over the world in recent years. Achieving the large scale silicon photonic integration, particularly monolithic integration, is the final goal so that high density data communication will become much cheaper, more reliable, and less energy consuming. Comparing with the developed countries, China may need to invest more to develop top down nanoscale integration capability (more on processing technology) to sustain the development in silicon photonics and to elevate its own industry structure.

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1. Introduction

Since the early work by Soref and Petermann[1−4], the silicon photonics has been in the rapid development track since it potentially allows optical devices to be made much cheaper, more reliable, and less energy consuming by using complementary metal oxide semiconductor (CMOS) fabrication technology and through integration with microelectronic circuits. To make the silicon photonics chip a reality, "siliconizing" photonic devices or making them compatible with silicon microelectronic technology and integrating high performance photonics and electronics devices into a single chip are two main challenges.

With the extensive efforts from the researchers all over the world, many high performance photonic devices have been siliconized and varieties of microsystems based on silicon photonics are also under development. Large scale monolithic integrations of photonic and electronic devices has also been carried out.

This paper, as a sequel of the first such paper published in the Electronics Letters[5], will review recent developments in silicon photonics inside and outside of China, and speculate its future trends.

2. Development outside of China

By leveraging on the well established Si-CMOS fabrication technologies and facilities, researchers outside of China, particularly those in US, Europe, Japan, have successfully demonstrated high performance silicon photonic components and microsystems. Some of the representatives are outlined below.

2.1 Silicon photonic components

2.1.1 Light sources

As an indispensable part of the silicon photonic circuits, a fully CMOS compatible silicon based on chip light source is still the most challenging requirement. Currently, the extensively explored and most promising candidates are: 1) erbium doped silicon based light source, 2) hybrid laser on silicon, 3) Germanium (Ge) laser on silicon, and 4) surface plasmon-polariton (SPP) laser.

a) Erbium doped light source

Erbium doped silicon rich silicon oxide (Er:SiO_x) has become a promising method for its advantage of erbium's luminescence around 1.55 μm and quantum confinement in silicon nanocluster (nc-Si). Being formed inside SiO_2 layers, nc-Si can suppress the non-radiative transition, act as the sensitizers transferring the energy to Er ions to achieve electroluminescence and greatly improve the carrier injection and transportation. The main obstacle is the emitting efficiency. One of the solutions is to suppress the free carrier absorption (FCA). An Er-doped SiO_2/nc-Si multilayers structure was studied for this purpose both theoretically and experimentally[6]. In another study, the FCA from nc-Si was strongly suppressed 9 times for transverse magnetic (TM) polarization through the unique photon confinement effects in the Er-doped SiO_2/nc-Si horizontal multi-slot waveguide structure[7], which may greatly reduce the loss and increase the emission efficiency.

b) Hybrid lasers

Recently, a GaAs/Si direct fusion bonding technique was presented with ideal bandgap combination free from lattice-match restrictions. Based on this technique, a 1.3-μm InAs/GaAs quantum dot laser on Si substrates was demonstrated with the ever lowest threshold current density of 205 A/cm^2[8].

c) Ge lasers

As a competitive candidate for on chip laser, a milestone work of Ge has been achieved by the first demonstration of the electrically pumped Ge laser[9]. However, the extremely high current density threshold of 280 kA/cm^2 and relatively low power efficiency impeded its application. A recent theoretical analysis predicted that over 200x threshold reductions and enhancement in slope efficiency can be achieved by tensile strain, as shown in Fig. 1. Compared with the N-type doping reaching its fundamental limit, large tensile strain ($> 1\%$) could be

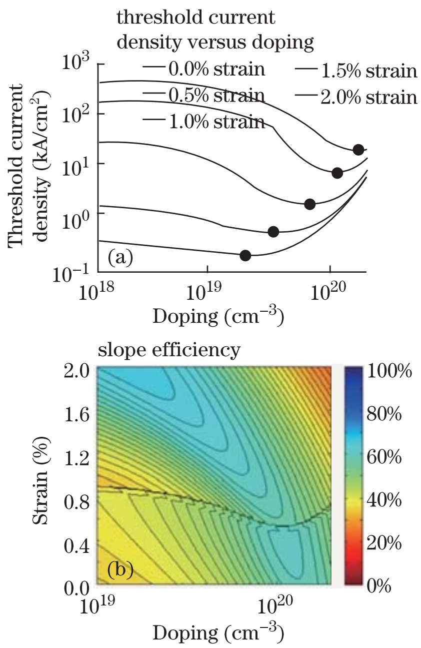

Fig. 1. (Color online) (a) Threshold current versus doping for various strain values, showing that an optimal doping value (black dot) always exists. (b) Slope efficiency of a Ge laser as a function of biaxial tensile strain and doping at optical cavity loss=1 500 cm^{-1}.

a more viable path to obtain a practical germanium-on-silicon laser[10].

d) SPP sources

To break through the diffraction limit, surface plasmon polariton has been sought to take the advantage of having many metal-dielectric interfaces on silicon integrated circuit (IC) chips. Recently, a deep sub-wavelength waveguide embedded (WEB) plasmon laser was demonstrated, directing more than 70% of its radiation into waveguide and dramatically enhancing radiation efficiency about 20 times to 35%[11]. What's more, an array of five multicolored WEB laser was successfully multiplexed onto a single semiconductor nanobelt waveguide, indicating the great potential application of plasmon lasers in optoelectronic integration.

It can be seen from above that although an ideal light source or laser has not been obtained, more attention has been paid to the compatibility with the silicon platform and how to integrate a potential light source on chip.

2.1.2 Modulators

Silicon optical modulator is regarded as one of the most important component for silicon photonic circuits. It has been extensively investigated to improve modulation rate, reduce power consumption, and apply advanced modulation formats. Modulation rates of 40 Gb/s or higher have been widely demonstrated in 2012, such as 50 Gb/s with the basic reverse-biased PN junction[12], 40 Gb/s with PIPIN junction[13], 50 Gb/s with forward-biased PIN junction[14] and so on. Microring is an efficient approach for low power modulator because of its compact size, for example 33 fJ/bit[15] at 20 Gb/s reported by IBM in 2011. Furthermore, advanced modulation formats is also a key technology for silicon modulator to increase the capacity of optical communication networks. In 2012, Bell Labs reported the first demonstrations of quadrature phase-shift keying (QPSK) modulation using silicon microring modulator[16] and silicon Mach-Zehnder (MZ) modulators working at 20 and 50 Gb/s, respectively[17], as shown in Fig. 2.

2.1.3 Photodetectors

Owing to the advantage of the high responsivity in the 1.55-μm wavelength range and the compatibility with the CMOS process, Ge photodetectors (PDs) on Silicon have become widely recognized over the past ten years[18]. To make it more compatible with CMOS technology, two schemes are winning in coupling light to the Ge PD region. They are the evanescently coupling and the butt-coupling methods[19]. For the evanescently coupled Ge PDs, the operation speed has reached more than 45 GHz[20]. The Ge PD is rather compact, which is 1.3×4 (μm), with a best-in-class dark current of 3 nA. The butt-coupled Ge PD can operate at 40 Gb/s under zero bias, and its 3-dB bandwidth was estimated up to 120 GHz[21], as shown in Fig. 3.

2.2 Silicon Photonic Microsystems

To further reduce the cost and the power consumption,

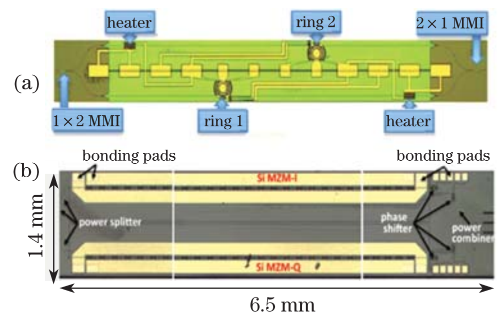

Fig. 2. Microscopy optical images of (a) the fabricated QPSK microring and (b) MZ modulators.

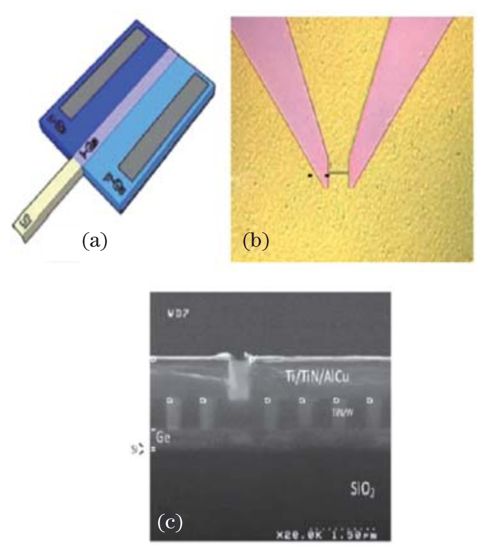

Fig. 3. (a) Schematic view of the PIN Ge PD; (b) top-view optical microscopy and cross-sectional scanning electron microscope (SEM) images of the Ge PD; (c) SEM cross-section of the Ge PD.

and to obtain a higher system reliability, monolithically system integration is the best choice. Great efforts and excellent demonstrations have been reported by Intel, IBM, Luxtera, Bell Labs and other research groups.

From IBM, an ultra-compact 10-wavelength wavelength-division multiplexing (WDM) receiver was demonstrated with 250 Gb/s data receiving capability on a footprint of 0.96 mm^2. In this receiver, optical devices with one echelle grating and 10 Ge PDs were wire-bonded to a CMOS transimpedance amplifier-limiting amplifier (TIA-LA) which was fabricated using 90-nm technology[22].

Luxtera demonstrated an integrated 4×25 Gb/s parallel optical transceiver, where laser source was epoxy-bonded onto the chip and the light was coupled in through grating then split to four channels. The modulators and photodetectors were monolithic integrated with driver and TIA on the same chip using the 0.13-μm CMOS silicon-on-insulator (SOI) process[23].

Bell Labs presented the first 112-Gb/s dual polarization QPSK modulator based on a silicon photonic technology, seen Fig. 4. By combining polarized beam combiner (PBC) with polarization rotator (PR), a polarization-diversity circuit with a 1.5-dB insertion loss and >30-dB polarization extinction ratios over a 60-nm spectral range was used to implement the dual-polarization modulation[24]. For receiving, Bell Labs also presented first 112-Gb/s packaged monolithic coherent receiver in silicon in 2011. It was a dual-polarization, dual-quadrature coherent receiver, where two polarization bean splitting gratings, two thermal phase shifters, eight polarization clean-up filters, four multimode interference (MMI) couplers and eight Ge PDs were monolithically integrated and wire-bonded to two dual-TIA chips[25].

In summary, many milestones have been reached on the research of silicon photonic components and systems. The figures of merit of the devices have reached historically highest levels. The first electrically pumped Ge multimode laser on silicon was realized. The modulation rate is as high as 50 Gb/s, and the Ge PD exhibits a 3-dB bandwidth of 45 GHz. The performances of the modulators and PDs are comparable with the commercialized ones that are made of III-V or other materials.

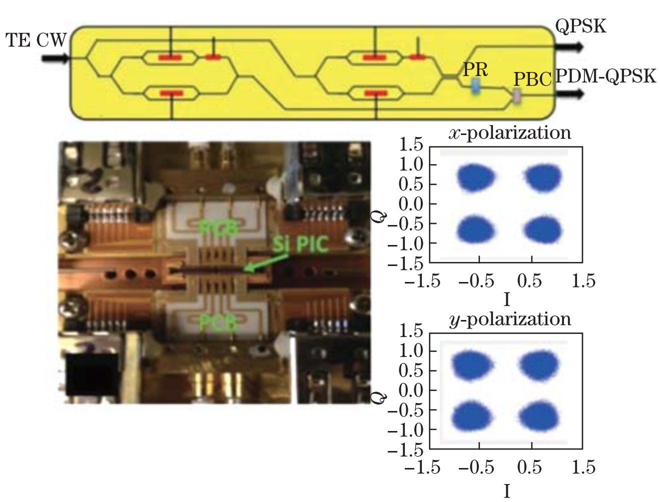

Fig. 4. Monolithic silicon PDM-QPSK modulator.

By integrating these high performance devices on a single chip, a 250-Gb/s WDM receiver and 112-Gb/s QPSK transceiver and coherent receiver have been realized, which are ready to be used in optical communications and interconnections.

3. Development inside of China

China, as the world second largest economic entity, has been increasing its investment towards further and deeper innovations in silicon photonics in the last few years. There are many research groups who devote themselves to silicon photonics, including Z. Zhou's group from Peking University (PKU), J. Chen's group from Shanghai Jiaotong University (SJTU), H. Tsang's group from Chinese University of Hong Kong (CUHK), L. Yang's group from the Institute of Semiconductors (CAS), Y. Su's group from Shanghai Jiaotong University (SJTU), the T. Chu's group from Institute of Semiconductors (CAS), S. He's group from Zhejiang University (ZJU) and so on. Their efforts and achievements are outlined below.

3.1 Silicon photonic components

3.1.1 Microring resonators and devices

Silicon microring resonators have the advantages of compact scale, high quality factor, and therefore, find application in many areas such as sensing, signal processing, and interconnections.

Microring resonator has the high sensing sensitivity by the strong interaction between light field and analyte. Zhou's group proposed a multi-resonance shift sensing theory, which introduced the Vernier calipers mechanism to the optical sensing[26]. Instead of conventional phase-induced sensing theory, a coupling-induced sensing mechanism was proposed. The analyte affects the coupling coefficient in microring resonator and leads to a rapid change in intensity, which resulted in the improved 10 times sensitivity without relying on the quality factor[27]. Because microring resonator is very sensitive for the thermal influence, an athermal sensing theory for the silicon microring resonator was investigated based on the interferometer consisted of a reference ring and a sensing ring. The sensor can keep serving at high sensitivity of 10^{-7} refractive index unit (RIU) for $\pm 5°$ temperature range to overcome the thermal influence[28]. Chen's group recently demonstrated a novel self-coupled optical waveguide (SCOW) resonator to fully utilize the counter-propagating modes to flexibly tailor its resonance transmission spectrum[29]. Due to its potential applications in future optical interconnections, on-chip optical delay line is very attractive. Su's group studied the system performances of optical delay lines based on the silicon microring resonator for different digital modulation formats and obtained a maximal delay of ~ 120 ps[30]. Furthermore, a tunable photonic radio frequency (RF) phase shifter using thermal nonlinear effect in a ring resonator and a phase-shift tuning range of 0–4.6 rad for 40-GHz RF signals were demonstrated[31].

3.1.2 Grating based devices

Grating can be used as a building block for couplers, beam splitters, polarization beam splitters (PBS), filters and so on. Tsang's group demonstrated a grating coupler with a coupling loss as low as 1.2 dB by using apodized gratings[32]. They showed that the effective medium theory may be applied in the design of sub-wavelength structured grating couplers to enable polarization independence and broader wavelength coverage in the sub-wavelength grating couplers[33,34].

Zhou's group proposed a coupler based on binary blazed grating (BBG) which had a high coupling efficiency of 65% for transverse electric (TE) mode[35]. A broadband polarization insensitive reflector was realized both theoretically and experimentally with up to 96% reflectivity over a wavelength rang of 1.2~1.7 μm[36,37]. A special narrow filer with tunable wavelength and one with tunable bandwidth were also designed[38,39]. The resonant wavelength of this grating filter shifts from 1 558.5 to 1 531.5 nm when the angle of incidence ranges from 42° to 48°, which can function as an ultra-narrow filter with the full width at half maximum (FWHM) of 0.6 nm. When the angle of incidence is changed to 10°, it turns into a broadband filter with a bandwidth over 90 nm, as shown in Fig. 5.

3.1.3 Light manipulating devices

From He's group, ultra small on-chip polarization handling devices have been realized for silicon photonics, including the polarization beam splitters and polarization rotators[40]. What's more, they also realized ultra-compact SOI-nanowire arrayed-waveguide grating (AWG) (de)multiplexer/routers with several novel layouts[41,42], as shown in Fig. 6.

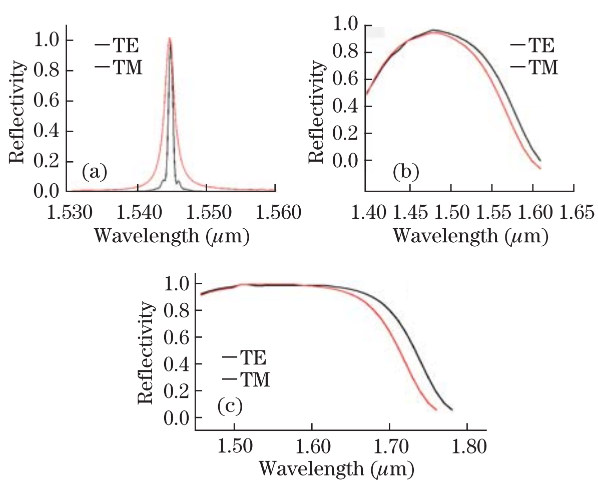

Fig. 5. (Color online) Spectral reflectivity of the grating filter for different polarization states when (a) $\theta = 45°$; (b) $\theta = 22°$; (c) $\theta = 10°$.

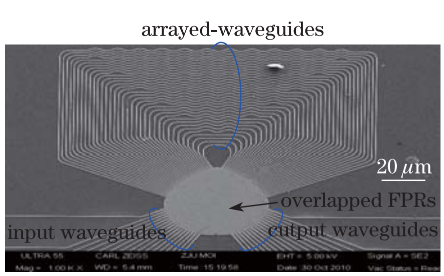

Fig. 6. SEM picture of an SOI-nanowire AWG router with microbends.

Yang's group also demonstrated microring-resonator-based four-port and five-port optical routers for photonic networks-on-chip (NoC)[43,44]. They also proposed a universal method to construct scalable N-port non-blocking optical router for photonic NoC[45]. In addition, they also demonstrated a four-channel reconfigurable optical add-drop multiplexer based on microring resonators[46]. All of the referred light manipulating devices can be readily integrated into a silicon photonic microchip.

3.1.4 Erbium doped light source

Zhou's group recently studied photoluminescence and electroluminescence of Erbium Yttrium and Ytterbium Co-doped Er silicates, which are a potential candidate material for monolithic integrated light emitters or optical waveguide amplifiers. They fabricated three kinds of waveguide structure, the strip-loaded, slot and hybrid ErYb/Y silicates waveguides, and the optical amplification was observed in these waveguide structures[47,48], as shown in Fig. 7. 1.53-μm electroluminescence in ErYb silicates was also realized using hot carriers' impact excitations of Er ions. The current conduction behavior, electroluminescence (EL) emissions, and impact excitation cross sections were studied[49,50].

3.1.5 Modulators

The carrier-depletion mechanism in reversed PN junction is a cost-effective mechanism to realize high modulation speed for silicon optical modulators, while this structure produces rather low modulation efficiency due to a poor overlap of free-carrier region and waveguide mode. Chu's group dealt this problem by engineering the junction's profile. They firstly proposed and analyzed an interleaved PN junction with both high modulation efficiency and high speed[51]. In 2012, they realized a traveling-wave silicon Mach-Zehnder interferometer (MZI) modulator with the similar doping profiles and obtained a dynamic extinction ratio of 7.2 dB at 44 Gb/s[52]. Recently, they proposed a zigzag PN junction designed for the reductions of the junction capacitance, as shown in Fig. 8. Based on this novel junction, a 44-Gb/s silicon microring modulator with over 50-GHz electrical bandwidth was experimentally demonstrated[53].

By optimizing the doping profile as well as the coplanar waveguide electrodes, Yang's group demonstrated a 2-mm-long carrier-depletion optical modulator which can work at a speed of 40 Gb/s under a differential voltage of 0.36 V with no reverse bias. The modulator had the smallest power consumption of 49 fJ/bit[54]. The low driving voltage and low power consumption made the modulator possible to be directly driven by a CMOS digital integrated circuit at next-generation 22-nm technology node[55].

3.2 Silicon photonic microsystems

Recently, Zhou's group has been focusing on the research of Si based integrated 100-Gb/s coherent optical transmitter and receiver supported by the national 863 program. The key devices have been demonstrated. They realized a multimode interference polarization splitter with over 20-dB polarization extinction ratio[56]. A below 2.2° phase deviation optical 90° hybrids based on

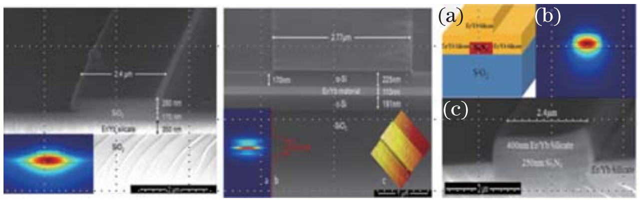

Fig. 7. SEM images of three kinds of waveguide.

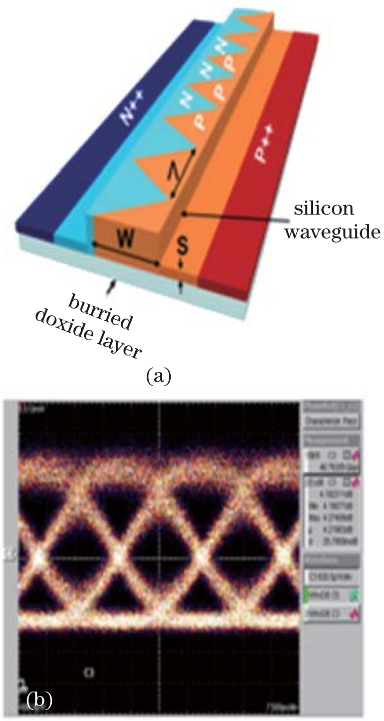

Fig. 8. (a) Schematic image of the zigzag PN junction; (b) 44-Gb/s optical eye-diagram of the silicon microring modulator with the zigzag PN junction.

silicon-on-insulator 4 × 4 MMI couplers were fabricated using E-Beam technology[57]. They also demonstrated an error-free 80-km transmission using a silicon carrier-depletion MZ modulator at 10 Gb/s and the power penalty is as low as 1.15 dB[58]. Ge waveguide PD exhibited a 3-dB bandwidth of 20 GHz at the wavelength of 1.55 μm and showed good eye opening at 28 Gb/s date rate. Now the work to integrate these devices monolithically to obtain high performance transmitter and receiver is underway.

As a whole, numerous progress has been made in silicon photonics components in China, such as the miroring resonator, grating based devices, light manipulating devices, modulators and so on. Among them, the outstanding performance of the silicon modulators is very prominent. The silicon MZI modulator can reach a high speed of 44 Gb/s, and the silicon microring modulator can demonstrate a 50-GHz electrical bandwidth, which is comparable with the highest speed reported in the world. This indicates that the gap in silicon photonic components development inside and outside of China is reduced. However, due to the limitations of fabrication infrastructure, semiconductor processing technologies, and other factors, few achievements are made in the area of monolithically integration of silicon photonic microsystems.

4. Conclusion

In this paper, we reviewed recent major developments in silicon photonics in the world, including silicon photonic components and microsystems that may be used for communications, interconnections, sensing, and other applications. The developments inside and outside of China are listed separately and compared. It shows that more active components and more tightly integrated systems have been pursued outside of China, while less active components (particularly the light sources and PDs) and microsystems are supported inside of China. It is understood that the large scale monolithic integration of photonic and electronic devices is still a big challenge to researchers and developers, but it is so far the best way to reduce cost, size, and energy consumption of the communication and computing equipments and infrastructures. The entrepreneurs know this very well and they are becoming the major driving force for the development of the silicon photonics. Since China does not have a strong semiconductor processing capability, more investments in this area, from basic theory to practical application, are truly necessary, should a sustainable development in silicon photonics is sought to elevate China's industry structure.

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References

1. R. Soref and J. Lorenzo, IEEE J. Quantum Electron. **22,** 873 (1986).
2. R. A. Soref and B. R. Bennett, in *Proceedings of SPIE Integr. Opt. Circuit Eng.* 32 (1986).
3. B. Schuppert, J. Schmidtchen, and K. Petermann, Electron. Lett. **25,** 1500 (1989).
4. R. A. Soref, J. Schmidtchen, and K. Petermann, IEEE J. Quantum Electron. **27,** 1971 (1991).
5. Z. Zhou, Electron. Lett. **45,** 588 (2009).
6. H. Krzyżanowska, K. S. Ni, Y. Fu, and P. M. Fauchet, Mater. Sci. Eng. B **177,** 1547 (2012).
7. Y. Fu, "Light emission and slot waveguide effect in Er-doped SiO_2/Si nanocrystalline multilayer structures", PhD. Thesis (University of Rochester, 2012).
8. K. Tanabe, K. Watanabe, and Y. Arakawa, Sci. Rep. **2,** 1 (2012).
9. R. E. Camacho-Aguilera, Y. Cai, N. Patel, J. T. Bessette, M. Romagnoli, L. C. Kimerling, and J. Michel, Opt. Ex-

press **20,** 11316 (2012).

10. B. Dutt, D. S. Sukhdeo, D. Nam, B. M. Vulovic, Z. Yuan, and K. C. Saraswat, IEEE Photon. J. **4,** 2002 (2012).
11. R. Ma, X. Yin, R. F. Oulton, V. J. Sorger, and X. Zhang, Nano Lett. **12,** 10 (2012).
12. D. J. Thomson, F. Y. Gardes, J. Fedeli, S. Zlatanovic, Y. Hu, B. P. P. Kuo, E. Myslivets, N. Alic, S. Radic, G. Z. Mashanovich, and G. T. Reed, IEEE Photon. Technol. Lett. **24,** 234 (2012).
13. M. Ziebell, M. M. Delphine, G. Rasigade, J. M. Fédéli, P. Crozat, E. Cassan, D. Bouville, and L. Vivien, Opt. Express **20,** 10591 (2012).
14. S. Akiyama, T. Baba, M. Imai, T. Akagawa, M. Noguchi, E. Saito, Y. Noguchi, N. Hirayama, T. Horikawa, and T. Usuki, in *Proceedings of IEEE 9th International Conference on Group IV Photonics (GFP)* **ThC2,** 192 (2012).
15. J. C. Rosenberg, W. M. J. Green, S. Assefa, C. L. Schow, A. V. Rylyakov, D. M. Gill1, B. G. Lee, C. Jahnes, T. Barwicz, S. M. Shank, and Y. A. Vlasov, in *Proceedings of IEEE Photonics Conference (PHO)* (2011).
16. P. Dong, C. Xie, L. Chen, N. K. Fontaine, and Y. Chen, Opt. Lett. **37,** 1178 (2012).
17. P. Dong, L. Chen, C. Xie, L. L. Buhl, and Y. Chen, Opt. Express **20,** 21181 (2012).
18. M. Takenaka, K. Morii, M. Sugiyama, Y. Nakano, and S. Takagi, Opt. Express **20,** 8718 (2012).
19. J. Michel, J. Liu, and L. C. Kimerling, Nat. Photon. **4,** 527 (2010).
20. C. T. DeRose, D. C. Trotter, W. A. Zortman, A. L. Starbuck, M. Fisher, M. R. Watts, and P. S. Davids, Opt. Express **19,** 24897 (2011).
21. L. Vivien, A. Polzer, D. Marris-Morini, J. Osmond, J. M. Hartmann, P. Crozat, E. Cassan, C. Kopp, H. Zimmermann, and J. M. Fédéli, Opt. Express **20,** 1096 (2011).
22. H. Pan, S. Assefa, F. Horst, C. L. Schow, A.V. Rylyakov, W. M. J. Green, M. H. Khater, S. Kamlapurka, C. Reinholm, E. Kiewra, S. M. Shank, C. W. Baks, B. J. Offrein, and Y. A. Vlasov, in *Proceedings of the 9th IEEE International Conference on Group IV Photonics* 162 (2012).
23. T. Pinguet, P. M. De Dobbelaere, D. Foltz, S. Gloeckner, S. Hovey, Y. Liang, M. Mack, G. Masini, A. Mekis, M. Peterson, T. Pinguet, S. Sahni, J. Schramm, M. Sharp, L. Verslegers, B. P.Welch, K. Yokoyama, and S. Yu, in *Proceedings of the 9th IEEE International Conference on Group IV Photonics* 189 (2012).
24. P. Dong, C. Xie, L. Chen, L. L. Buhl, and Y. Chen, in *Proceedings of ECOC* Th.3.B.1 (2012).
25. C. R. Doerr, L. L. Buhl, Y. Baeyens, R. Aroca, S. Chandrasekhar, X. Liu, L. Chen, and Y. -K. Chen, IEEE Photon. Technol. Lett. **23,** 762 (2011).
26. H. Yi, D. S. Citrin, Y. Chen, and Z. Zhou, Appl. Phys. Lett. **95,** 191112 (2009).
27. H. Yi, D. S. Citrin, and Z. Zhou, J. Opt. Soc. Am. B **28,** 1611 (2011).
28. H. Yi, D. S. Citrin, and Z. Zhou, IEEE J. Quantum Electron. **47,** 354 (2011).
29. L. Zhou, T. Ye, and J. Chen, Opt. Lett. **36,** 13 (2011).
30. Q. Li, F. Liu, Z. Zhang, M. Qiu, and Y. Su, J. Lightwave Technol. **26,** 3744 (2008).
31. Q. Chang, Q. Li, Z. Zhang, M. Qiu, T. Ye, and Y. Su, IEEE Photon. Technol. Lett. **21,** 60 (2009).
32. X. Chen, C. Li, C. K. Y. Fung, S. M. G. Lo, and H. K. Tsang, IEEE Photon. Technol. Lett. **22,** 1156 (2010).
33. X. Chen and H. K. Tsang, Opt. Lett. **36,** 796 (2011).
34. X. Chen, K. Xu, Z. Cheng, C. K. Y. Fung, and H. K. Tsang, Opt. Lett. **37,** 3483 (2012).
35. J. Yang, Z. Zhou, H. Jia, X. Zhang, and S. Qin, Opt. Lett. **36,** 2614 (2011).
36. H. Wu, J. Hou, W. Mo, D. Gao, and Z. Zhou, IEEE Photon. Technol. Lett. **22,** 203 (2010).
37. H. Wu, J. Hou, W. Mo, D. Gao, and Z. Zhou, Appl. Phys. B **99,** 519 (2010).
38. D. Wu, X. Sui, J. Yang, and Z. Zhou, Front. Optoelectron. **5,** 78 (2012).
39. D. Wu, L. Yu, H. Yi, and Z. Zhou, Proc. SPIE **8564,** 856415 (2012).
40. D. Dai, L. Liu, S. Gao, D. Xu, and S. He, Laser Photon. Rev. **1,** 23 (2012).
41. X. Fu and D. Dai, Electron. Lett. **47,** 266 (2011).
42. D. Dai, X. Fu, Y. Shi, and S. He, Opt. Lett. **35,** 2594 (2010).
43. R. Ji, L. Yang, L. Zhang, Y. Tian, J. Ding, H. Chen, Y. Lu, P. Zhou, and W. Zhu, Opt. Express **19,** 18945 (2011).
44. R. Ji, L. Yang, L. Zhang, Y. Tian, J. Ding, H. Chen, Y. Lu, P. Zhou, and W. Zhu, Opt. Express **19,** 20258 (2011).
45. R. Min, R. Ji, L. Yang, L. Zhang, Y. Tian, J. Ding, H. Chen, Y. Lu, P. Zhou, W. Zhu, in *Proceedings of Conference on Lasers and Electro-Optics (CLEO)* **JW4A.14,** 1 (2012).
46. M. Geng, L. Jia, L. Zhang, L. Yang, P. Chen, T. Wang, and Y. Liu, Opt. Express **17,** 5502 (2009).
47. R. Guo, X. Wang, K. Zang, B. Wang, and L. Wang, Appl. Phys. Lett. **99,** 161115 (2011).
48. R. Guo, B. Wang, X. Wang, L. Wang, L. Jiang, and Z. Zhou, Opt. Lett. **37,** 1427 (2012).
49. B.Wang, X. Wang, M. J. A. de Dood, R. Guo, L. Wang, M. Vanhoutte, J. Michel, L. C. Kimerling, and Z. Zhou, J. Phys. D: Appl. Phys. **45,** 165101 (2012).
50. B. Wang, R. Guo, X. Wang, L. Wang, L. Hong, B. Yin, L. F. Gao, and Z. Zhou, Opt. Mater. **34,** 1371 (2012).
51. Z. Li, D. Xu, W. R. McKinnon, S. Janz, J. H. Schmid, P. Cheben, and J. Yu, Opt. Express **17,** 15947 (2009).
52. H. Xu, X. Xiao, X. Li, Y. Hu, Z. Li, T. Chu, Y. Yu, and J. Yu, Opt. Express **20,** 15093 (2012).
53. X. Xiao, X. Li, H. Xu, Y. Hu, K. Xiong, Z. Li, T. Chu, J. Yu, and Y. Yu, IEEE Photon. Technol. Lett. **24,** 1712 (2012).
54. J. Ding, H. Chen, L. Yang, L. Zhang, R. Ji, Y. Tian, W. Zhu, Y. Lu, P. Zhou, and R. Min, in *Proceedings of IEEE 9th International Conference on Group IV Photonics (GFP)* **ThP23,** 305 (2012).
55. M. J. Kobrinsky, B. A. Block, J. F. Zheng, B. C. Barnett, E. Mohammed, M. Reshotko, F. Roberston, S. List, I. Young, and K. Cadien, Intel Technol. J. **8,** 129 (2004).
56. Z. Tu, Y. Huang, H. Yi, X. Wang, Y. Li, L. Li, and W. W. Hu, in *Proceedings of Asia Communications and Photonics Conference* **8307,** 1 (2011).
57. T. Hong, W. Yang, H. Yi, X. Wang, Y. Li, Z. Wang, and Z. Zhou, Proc. SPIE **8255,** 82551Z (2012).
58. H. Yi, Q. Long, W. Tan, L. Li, X. Wang, and Z. Zhou, Opt. Express **20,** 27562 (2012).