105 nm Wavelength Conversion of 40-Gb/s DPSK in a Dispersion-Engineered Silicon Waveguide

Qi Li[1], Lin Xu[1], Michael Menard[2], Ryan K. W. Lau[3], Michal Lipson[2], Alexander L. Gaeta[3] and Keren Bergman[1]

1: Department of Electrical Engineering, Columbia University, 500 W. 120th Street, New York, NY 10027, USA
2: School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853, USA
3: School of Applied and Engineering Physics, Cornell University, 159 Clark Hall, Ithaca, NY 14853, USA
ql2163@columbia.edu

Abstract: We demonstrate wavelength conversion of 40-Gb/s DPSK signals across a 105-nm range in a dispersion-engineered silicon waveguide with 1.83-dB average power penalty, further confirming broadband and format-transparent parametric-processing potential in silicon.
OCIS codes: (060.5060) Phase modulation; (190.4380) Nonlinear optics, four-wave mixing.

1. Introduction

All-optical signal processing technologies are expected to be an essential part of future optical networks as data rates continue to increase [1]. Traditional signal manipulation based on optical-electrical-optical (OEO) transceivers at network interface points and switches is ultimately limited by the speed, hardware complexity, scalability and power consumption of the electrical processing circuit, requiring power-hungry serialization and deserialization circuits in network interfaces and therefore does not scale gracefully with signaling rate. Circumventing the OEO conversion, all-optical processing presents an attractive alternative solution for certain network-required functionalities such as wavelength conversion. Silicon waveguides in particular, through dispersion engineering [2] allow extremely broad and uniform operation across many wavelength bands which is essential for operating over the increasing waveband utilization. In addition, compatibility with the complementary metal-oxide-semiconductor (CMOS) processes provides the potential for low-cost mass production and dense integration with microelectronics.

Phase-shift keying (PSK) format is widely used in today's optical communication systems because of the superior spectral efficiency of coherent communications. Many long-haul Tb/s transmission experiments utilizing phase-encoded modulation format are already using as many as 640 WDM channels spanning C+L band [3-4]. And opening new transmission windows such as S-band can further increase transmission capacity for future optical communication systems [5]. Therefore a wavelength conversion scheme of DPSK signals spanning S-, C-, and L-band is highly desirable. However, previous DPSK conversion demonstrations have focused on different aspects such as high speed or large conversion efficiency [6-9]. In this work, we demonstrate wavelength conversion of 40-Gb/s DPSK signals with conversion range up to 105 nm while maintaining nearly constant conversion efficiency and showing average power penalty of 1.83 dB for varied conversion ranges, validating broadband and format transparency of four-wave-mixing in the silicon platform. To the best of our knowledge this is the data-validated DPSK conversion with the largest probe-idler separation in the silicon waveguide platform.

2. Device and Experiment

The 1.1-cm long silicon nanowaveguide, fabricated at the Cornell Nanofabrication Facility, has a 300-nm × 710-nm cross section. Device dimensions were optimized for quasi-TE operation and the zero-group-velocity-dispersion (ZGVD) wavelength of this waveguide was calculated to be approximately 1546nm [10]. Fiber-to-fiber insertion loss is measured as ~ 8.9 dB at low input power; additional 1.5 dB loss results from two-photon absorption (TPA) and TPA-induced free carrier absorption when a 19-dBm total optical power is used.

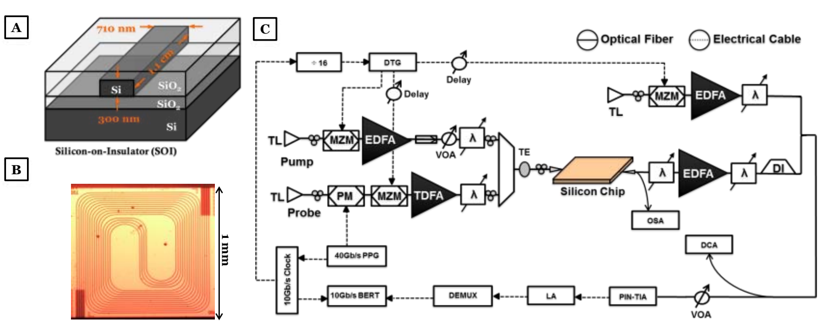

Fig. 1. (a) Cross-section view of the silicon waveguide; (b) Microscope image of silicon waveguide; and (c) experimental setup.

The experiment setup (Fig.1) includes a CW probe modulated by a phase modulator (PM) and driven with a 40-Gb/s non-return-to-zero (NRZ) 2^{15}-1 pseudo-random-bit-sequence pattern (PRBS), which is also used to trigger the data timing generator (DTG) and bit-error-rate tester (BERT). Because of the relatively low conversion efficiency of the available device, the probe and pump signals are packetized in order to increase the peak power while maintaining a low average power. The probe signal is gated using a LiNbO3 Mach-Zehnder Modulator (MZM) driven by the DTG which outputs 192-ns period with 25% duty cycle. The S-band probe signal is amplified using a thulium-doped fiber amplifier (TDFA), filtered and combined with the pump. The pump signal is created by gating the CW light from another TL with a MZM using the same period and duty cycle with electrical delay to ensure the packets of the probe and pump signals overlap in time domain exactly. The packetized pump signal is amplified using an erbium-doped fiber amplifier (EDFA), goes through an isolator, variable optical attenuator (VOA) and band-pass filter before being combined with the probe using a C + S/L band WDM. Following the silicon chip, the L-band idler is filtered out, amplified using an L-band EDFA and demodulated using a 40-Gb/s delay line interferometer (DI). In order to avoid the strong voltage bias of directly receiving the packetized idler with an AC-coupled photodetector, an auxiliary light channel is inserted between the data packets to maintain a near constant power profile before the receiver, a technique used in previous experiment [11, 12]. The auxiliary channel is electrically delayed with the DTG so that it is inserted between the idler data packets. This auxiliary channel is amplified, filtered and combined with the demodulated idler data packets. The combined signal is attenuated, detected and demultiplexd before being examined on a BERT. Back-to-back measurement is performed bypassing the TDFA, Fabry-Perot filter and silicon chip while keeping the same injected power to the L-band EDFA with the presence of auxiliary channel.

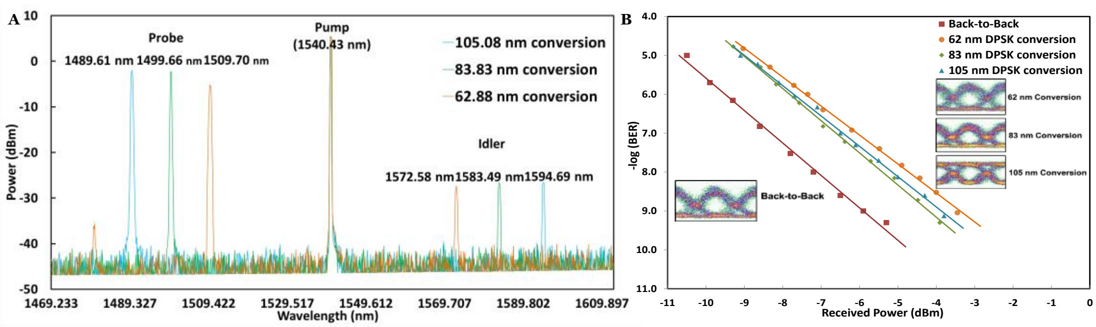

Fig. 2. (a) Overlaid spectra measured at the output of the silicon waveguide. Additional visible signal at 1480 nm is due to FWM process of two probe photons interact with one pump photon. (b) BER curves measured showing power penalties of 2.1 dB (62 nm conversion), 1.6 dB (83 nm conversion) and 1.8 dB (105 nm conversion). Inset: respective demodulated eye diagrams.

In order to validate the wavelength converter's broadband operation of DPSK format, the pump wavelength is fixed at 1540.43 nm while the probe wavelength is tuned between 1548.61 nm and 1509.70 nm with ~ 20 nm steps to vary the conversion distance (Fig. 2). The conversion efficiency remains nearly constant at ~ -24.7 dB for all the probe-idler operations. The lower optical power of the probe at 1509.70 nm is attributed to the gain spectrum of the TDFA. Average power penalty is measured to be 1.83 dB. The additional increase in power penalty for the 62-nm conversion is due to the fact that the generated idler has a lower power entering the L-band EDFA.

3. Conclusion

We have presented wavelength conversion of 40-Gb/s DPSK signal in the silicon platform at up to 105-nm probe-idler detuning, further validating the broadband and format transparency of silicon-based all-optical processing for future optical communication systems utilizing phase-encoded modulation format.

This work was supported in part by the DARPA MTO Parametric Optical Processes and Systems Program under Contract W911NF-08-1-0058, in part by NSF through CIAN ERC under grant #EEC-0812072 and by NSF and Semiconductor Research Corporation under Grant ECCS-0903406 SRC Task 2001.

4. References

[1] M. J. O'Mahoney *et al.*, "Future optical networks," J. Lightw. Technol., vol. 24, no. 12, pp. 4684–4696, Dec. 2006.
[2] A. C. Turner *et al.,* "Tailored anomalous group-velocity dispersion in silicon channel waveguides." Opt. Express 14.10 (2006): 4357-4362.
[3] B. Zhu *et al.*, "6.4-Tb/s (160 x 42.7 Gb/s) transmission with 0.8 bit/s/Hz spectral efficiency over 32 x 100 km of fiber using CSRZ-DPSK format." OFC, 2003.
[4] X. Zhou *et al.,* "64-Tb/s (640× 107-Gb/s) PDM-36QAM transmission over 320km using both pre-and post-transmission digital equalization." OFC, 2010.
[5] H. J. Thiele *et al.*, "40-Gb/s S-band WDM transmission over installed fiber links using erbium-based fiber amplifiers." OFC, 2005.
[6] H. Hu *et al.*, "Ultra-high-speed wavelength conversion in a silicon photonic chip." Optics Express 19.21 (2011).
[7] Y. Kuo *et al.* "Demonstration of wavelength conversion at 40 Gb/s data rate in silicon waveguides." Opt. Express 14.24 (2006): 11721-11726.
[8] F. Li *et al.*, "All-optical wavelength conversion for 10 Gb/s DPSK signals in a silicon ring resonator." Optics Express 19.23 (2011).
[9] X. Wu *et al.*,"Simultaneous two-channel wavelength conversion of 40-Gbit/s DPSK WDM signals without additional pumps." CLEO, 2010.
[10] M. A. Foster *et al.*, "Broad-band optical parametric gain on a silicon photonic chip," Nature 441(7096), 960–963 (2006).
[11] L. Xu *et al.*, "40-Gb/s DPSK Data Transmission Through a Silicon Microring Switch," PTL, IEEE, vol.24, no.6, pp.473-475, 2012.
[12] X. Zhu *et al.*, "4× 44 Gb/s Packet-Level Switching in a Second-Order Microring Switch." IEEE PTL 24.17 (2012): 1555.