CWI5.pdf

Broadband Continuous Wavelength Conversion of 10-Gb/s Data in Silicon Waveguides Spanning S-, C-, and L-Bands

Noam Ophir[1], Aleksandr Biberman[1], Kevin J. Luke[1], Amy C. Turner-Foster[2], Mark A. Foster[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, Ithaca, NY 14853, USA
ophir@ee.columbia.edu

Abstract: We demonstrate broadband continuous wavelength conversion of 10-Gb/s data across 100 nm using four-wave mixing in dispersion-engineered silicon waveguides. Error-free operation and constant 2-dB power penalties are experimentally obtained for all examined probe-idler separations.

OCIS codes: (130.7405) Wavelength conversion devices; (190.4380) Nonlinear optics, four-wave mixing.

1. Introduction

Ever-increasing bandwidth demands in optical communication networks are placing a greater emphasis on all-optical processing systems capable of replacing optically-opaque electrical counterparts that employ power-hungry transceivers. Network-level all-optical parametric systems utilizing wavelength conversion, wavelength multicasting, and temporal demultiplexing empower this new networking domain with enhanced performance, energy efficiency, and long-term scalability. Such enabling devices leveraging four-wave mixing (FWM) for all-optical parametric processing have been demonstrated in highly-nonlinear fiber (HNLF) [1], III-V semiconductors [2], chalcogenides [3], silicon [4], as well as silicon-organic hybrid systems [5].

Recent advances in complementary metal-oxide-semiconductor (CMOS)-compatible silicon photonic devices have enabled the emergence of small-footprint low-cost silicon waveguides for FWM applications, capable of being dispersion engineered to maximize performance [6]. Since the effective bandwidth of the nonlinear interaction is largely determined by the phase-matching conditions over the interaction length, short length dispersion-engineered silicon waveguides can enable ultra-broadband parametric systems, with demonstrated wavelength conversion bandwidths exceeding 800 nm [7]. We have previously demonstrated wavelength conversion of 40-Gb/s data across 47.7 nm [8]. In this work, we demonstrate wavelength conversion of high-speed data in silicon waveguides continuously across 100 nm, validating the capacity of these silicon waveguides for ultra-broadband parametric systems. We wavelength convert 10-Gb/s data over varying probe-idler separations, and experimentally evaluate the performance of this functionality using bit-error-rate (BER) characterization and power penalty performance metrics. We demonstrate error-free (defined as having BERs less than 10^{-12}) operation of wavelength conversion, and a constant 2-dB power penalty with increasing probe-idler separations from 50 to 100 nm.

2. Experiments and results

The device discussed here is a silicon waveguide of 1.1-cm length and a 290-nm × 720-nm cross section, fabricated at the Cornell Nanofabrication Facility using electron-beam lithography followed by reactive-ion etching. Each end of the waveguide has an inverse-taper mode converter for efficient coupling to tapered fibers. The zero-group-velocity-dispersion (ZGVD) wavelength for this waveguide was calculated to be approximately 1577 nm [6].

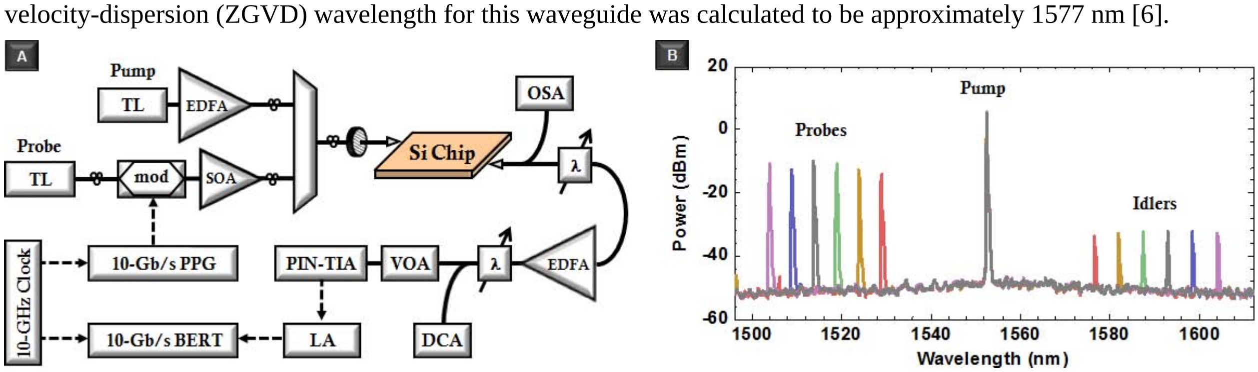

Fig. 1. (a) Diagram of experimental setup used for wavelength conversion. (b) Overlaid spectra of wavelength conversion configurations recorded directly after the chip. Conversion efficiencies remain constant at about -21 dB for all probe-idler separations. Probe wavelengths are set to 1529, 1524, 1519, 1514, 1509, and 1504 nm, corresponding to probe-idler separations of 47, 58, 68, 79, 89, and 100 nm, respectively.

CWI5.pdf

The experimental setup used to evaluate the wavelength conversion (Fig. 1a) includes a continuous-wave (CW) probe produced by a tunable laser (TL) modulated with a 10-Gb/s 2^{15}-1 pseudo-random bit sequence (PRBS) pattern from a pulsed-pattern generator (PPG). A CW 1552.5-nm pump is created by amplifying the output of a TL using an erbium-doped fiber amplifier (EDFA). The modulated probe signal is amplified using a semiconductor optical amplifier (SOA) and combined with the pump. The probe and pump are both set to TE polarization and injected into the device. Following the device, a portion of the power is examined on an optical spectrum analyzer (OSA). The converted data signal is recovered using filtering (λ) and amplification stages. It is then inspected using a digital communications analyzer (DCA), received using a photodetector (PIN-TIA) followed by a limiting amplifier (LA), and examined on a BER tester (BERT). A variable optical attenuator (VOA) is used to vary the optical power incident on the receiver. We perform the experiments with probe-idler detuning ranges spanning 47 to 100 nm. Open eye diagrams are observed (Fig. 2a) for the converted data signal. Moreover, error-free operation is observed for all configurations, BER curves are experimentally obtained, and the resulting power penalties are measured to be 2±0.35 dB (Fig. 2b). Back-to-back eye diagrams and BER curves are recorded directly after of the modulator.

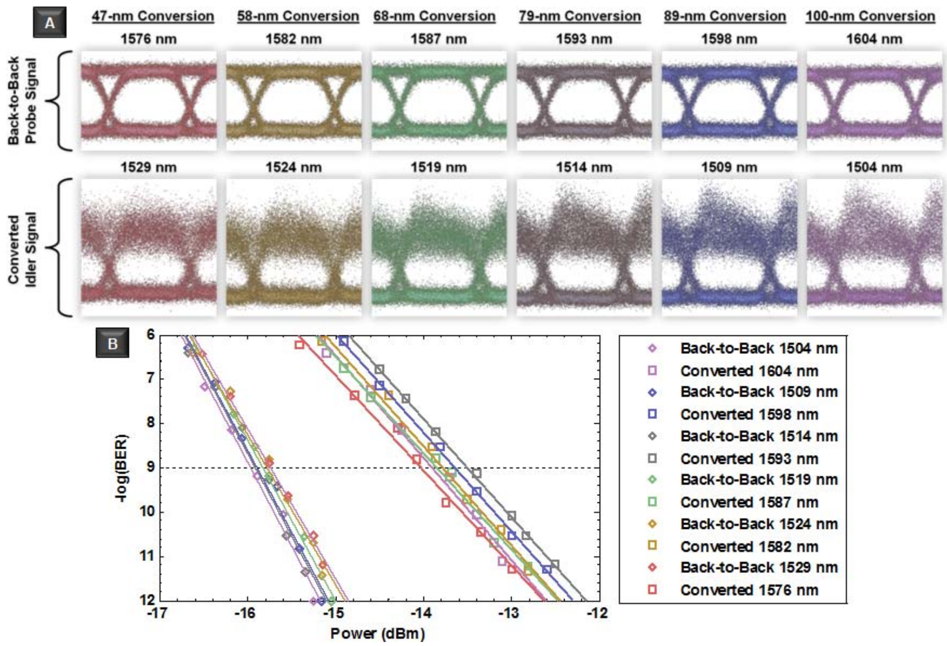

Fig. 2. (a) 10-Gb/s eye diagrams of back-to-back signals above corresponding wavelength-converted signals. Open eye diagrams are observed for all probe-idler separations. (b) 10-Gb/s BER curves of all wavelength-converted and back-to-back signals with constant 2-dB power penalties.

3. Conclusion

We have demonstrated a record 100-nm continuous wavelength conversion of 10-Gb/s data using FWM in silicon waveguides. We observed no additional signal degradation from varying probe-idler separations from 50 to 100 nm. The results affirm the utilizable continuous conversion bandwidths spanning the full S-, C-, and L-bands of the ITU grid, potentially enabling full-scale ultrahigh-bandwidth optically-transparent and energy-efficient systems in wavelength-routed networks, developed in the fully-integrated CMOS-compatible platform.

4. References

[1] A. O. Wiberg *et al.*, "Multicast parametric synchronous sampling of 320-Gb/s return-to-zero signal," *IEEE Photon. Technol. Lett.* **21** (21) 1612-1614 (2009).

[2] C. Porzi, A. Bogoni, L. Poti, G. Contestabile, "Polarization and wavelength-independent time-division demultiplexing based on copolarized-pumps FWM in an SOA," *IEEE Photon. Technol. Lett.* **17** (3) 633–635 (2005).

[3] M. Galili *et al.*, "Breakthrough switching speed with an all-optical chalcogenide glass chip: 640 Gbit/s demultiplexing," *Opt. Express* **17** (4) 2182-2187 (2009).

[4] A. Biberman *et al.*, "First demonstration of on-chip wavelength multicasting," in *OFC 2009*, OTuI3 (2009).

[5] C. Koos *et al.* "Silicon-organic hybrid (SOH) devices for optical signal processing," in *FiO 2008*, paper FMG6 (2008).

[6] A. C. Turner, C. Manolatou, B. S. Schmidt, M. Lipson, M. A. Foster, J. E. Sharping, A. L. Gaeta, "Tailored anomalous group-velocity dispersion in silicon channel waveguides," *Opt. Express* **14** (10) 4357–4362 (2006).

[7] A. C. Turner-Foster, M. A. Foster, R. Salem, A. L. Gaeta, M. Lipson, "Frequency conversion in silicon waveguides over two-thirds of an octave," in *CLEO 2009*, CFR4 (2009).

[8] B. G. Lee *et al.*, "Demonstration of broadband wavelength conversion at 40 Gb/s in silicon waveguides," *IEEE Photon. Technol. Lett.* **21** (3) 182-184 (2009).