Optical Crosstalk in Silicon Nanowaveguides

Yoshitomo Okawachi, Onur Kuzucu, Mark A. Foster, Reza Salem, and Alexander L. Gaeta

School of Engineering and Applied Physics, Cornell University, Ithaca, NY 14853
E-mail: a.gaeta@cornell.edu

Amy C. Turner-Foster and Michal Lipson

School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853

Aleksandr Biberman, Noam Ophir, and Keren Bergman

Department of Electrical Engineering, Columbia University, New York, NY 10027

Abstract: We characterize optical crosstalk and the associated bit-error rate degradation in silicon nanowaveguides. Our results indicate that the crosstalk decreases with increasing modulation frequency and decreases with input power, which we attribute to free-carrier absorption.

OCIS codes: (250.4745) Optical processing devices; (230.7370) Waveguides.

1. Introduction

Wavelength-division-multiplexed (WDM) communication systems have attracted significant interest in recent years, due to the large bandwidth that can be utilized for data transmission. However, a major obstacle that dealt needs to be overcome in these systems is crosstalk between the multiplexed wavelength channels. In fiber-based WDM systems, the primary source of crosstalk comes from individual components as well as nonlinear effects, including cross-phase modulation (XPM), stimulated Raman scattering (SRS), and optical Kerr effect-polarization dependent loss (OKE-PDL) [1-4]. Recent demonstrations have shown that silicon has potential to be used as a platform for integrated WDM networks [5-7]. For single-mode operation in silicon, submicron dimension nanowaveguides are required [8]. These dimensions also allow for high confinement of the optical mode, resulting in an enhancement in the nonlinearity [9]. While high nonlinearity is desirable to perform efficient parametric processes such as four-wave mixing, it also provides a coupling mechanism for inter-channel crosstalk. Since crosstalk could potentially hinder the performance of a silicon-based on-chip WDM system it is essential to understand its causes and impact on optical networks.

In this paper we investigate crosstalk in silicon nanowaveguides. We measure crosstalk and the signal bit-error rate (BER) for various data rates. Our results indicate that the crosstalk decreases as the modulation frequency increases and the total input power decreases. One contribution to crosstalk arises from a combination of two-photon absorption (TPA) and free-carrier absorption (FCA). We conclude that for multi-wavelength operation, the signal power levels must be optimized to minimize crosstalk between channels and that the utilization of amplitude invariant modulation formats such as phase-shift keying should be considered.

2. Experiment

The experimental setup for measuring crosstalk in a silicon nanowaveguide is shown in Fig. 1. The signal and pump are combined using a 3-dB coupler, amplified and coupled into a nanowaveguide. A preamplifier is inserted in the pump arm to adjust the relative power between the signal and the pump. For crosstalk measurements, both the signal and pump inputs are amplitude modulated using a clock source that drives a Mach-Zehnder modulator. The signal modulation frequency is fixed at 9.953 GHz while the pump modulation frequency is varied from 50 MHz to 9.95 GHz. The output from the nanowaveguide is amplified, filtered and sent into a photodiode and electrical spectrum analyzer (ESA) to measure power spectral density of the photocurrent [Fig. 1(a)]. Crosstalk is defined as [4]

$$\text{Crosstalk}\,(dB) = 10\log\left(\frac{\text{RF power at }\ \lambda_{signal}}{\text{RF power at }\ \lambda_{pump}}\right). \qquad (1)$$

We measure the RF power at the pump modulation frequency for both the signal and pump input wavelengths by tuning the tunable bandpass filter (TBPF). For bit-error rate (BER) measurements, both the signal and the pump are generated using a pattern generator with a pseudo-random bit sequence (PRBS) at 2^{31}-1. The data rate is fixed at 9.953 Gb/s for both the signal and the pump. The output from the nanowaveguide is amplified, filtered, and sent through a variable optical attenuator (VOA) into a 10 Gb/s lightwave receiver and a bit-error rate tester (BERT) [Fig. 1(b)]. For both measurements, the optical spectrum from the nanowaveguide output is monitored using a tap coupler.

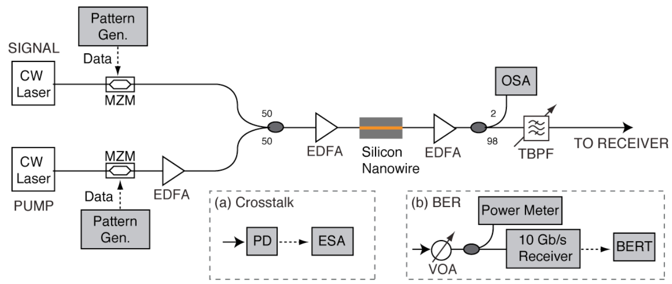

Fig. 1. Experimental setup for crosstalk measurements for a silicon nanowaveguide. Signal and pump are combined and coupled into the nanowaveguide. Output is filtered and sent to (a) for crosstalk measurements using an electrical spectrum analyzer (ESA) and (b) for bit-error rate (BER) measurements.

Figure 2(a) shows the crosstalk on the signal as a function of the pump modulation frequency. The signal and pump power inside the nanowaveguide was 3 dBm and 13 dBm, respectively. We observe a modulation frequency dependence in the crosstalk, which we attribute to the free-carrier absorption induced by two-photon absorption in the nanowaveguide. The crosstalk roll-off around 1-GHz modulation frequency is consistent with previously measured lifetimes in silicon nanowaveguides, ranging from 500 ps to 1 ns. Figure 2(b) shows crosstalk as a function of the pump power. We observe lower crosstalk and smaller variations with respect to pump power at higher pump modulation frequencies.

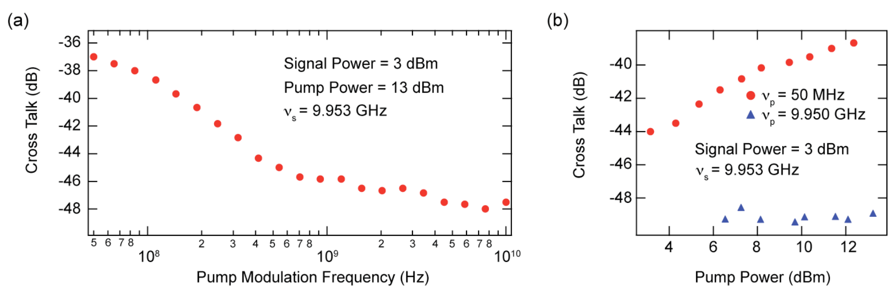

Fig. 2. Experimental results. (a) Crosstalk as a function of pump modulation frequency. (b) Crosstalk as a function of pump power.

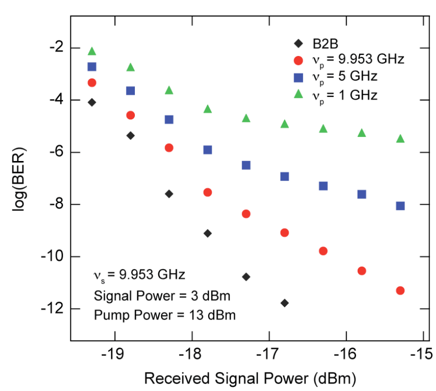

Fig. 3. Experimental results. Bit-error rate (BER) measurement for signal through nanowaveguide. Plot shows back-to-back (B2B) measurement without nanowaveguide (diamond) and three different pump modulation frequencies.

JWA21.pdf

Figure 3 shows BER measurements on the signal. As in the crosstalk measurement, the signal and the pump power in the nanowaveguide is 3 dBm and 13 dBm, respectively. The plot shows a back-to-back (B2B) measurement, where the nanowaveguide is bypassed, along with three different pump modulation frequencies. While the difference in crosstalk between a 1-GHz modulation and a 10-GHz modulation is small (~2 dB), we observe a significant power penalty.

Figure 4 shows the BER measurement for various power levels for multi-wavelength operation in the nanowaveguide. The signal (1554 nm) and the pump (1550 nm) are generated using a pattern generator with a pseudo-random bit sequence (PRBS) at 2^{31}-1 with a data rate of 9.953 Gb/s. In order to prevent correlated patterns in both inputs a timing offset of approximately 20 μs is introduced between the signal and the idler. The power levels of both modes are equalized before being coupled into the waveguide. The signal (and pump) power inside the nanowaveguide is varied from 7 dBm to 13 dBm. Two separate B2B measurements are performed, the first with the pump off and the second without the nanowaveguide. This indicates that the crosstalk is due to the interaction of the signal and the pump within the nanowaveguide. We observe BER degredation plotted in Fig. 4 as the power level is increased for both inputs.

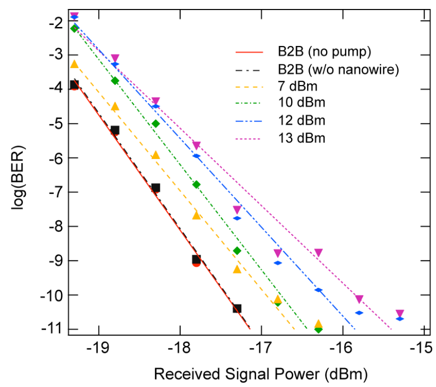

Fig. 4. Experimental results. BER measurement for various signal powers. The numbers represent the power inside the nanowaveguide. Two back-to-back measurements are performed, one with no pump and the other with the nanowaveguide removed from the setup.

3. Conclusion

We investigate crosstalk between amplitude modulated channels in a silicon nanowaveguide. Our results indicate that the crosstalk on the signal is dependent on the pump modulation frequency, which can be attributed to free-carrier absorption in the nanowaveguide. BER measurements indicate that the signal degradation is dependent on both the pump modulation frequency and the pump power. For multi-wavelength operation, the signal power levels must be optimized to minimize crosstalk between channels and using amplitude invariant modulation formats such as phase-shift keying should be considered.

References

[1] G. E. Keiser, “A review of WDM technology and applications,” Opt. Fiber Technol. **5**, 3-39 (1999).

[2] F. S. Yang, M.E. Marhic, and L. G. Kazovsky, “Nonlinear crosstalk and two countermeasures in SCM-WDM optical communication systems,” J. Lightwave Technol. **18**, 512-520 (2000).

[3] R. W. Tkach, A. R. Charaplyvy, F. Forghieri, A. H. Gnauck, and R. M. Derosier, “Four-photon mixing and high-speed WDM systems,” J. Lightwave Technol. **13**, 841-849 (1995).

[4] M. R. Phillips and D. M. Ott, “Crosstalk due to optical fiber nonlinearities in WDM CATV lightwave systems,” J. Lightwave Technol. **17**, 1782-1792 (1999).

[5] B. A. Small, B. G. Lee, K. Bergman, Q. Xu, and M. Lipson “Multiple-wavelength integrated photonic networks based on microring resonator devices,” J. Opt. Netw. **6**, 112-120 (2007).

[6] B. G. Lee, B. A. Small, Q. Xu, M. Lipson, and K. Bergman, “Characterization of a 4x4 Gb/s parallel electronic bus to WDM optical link silicon photonic translator,” IEEE Photon. Technol. Lett. **19**, 456-458 (2007).

[7] B.G. Lee, A. Biberman, A. C. Turner-Foster, M. A. Foster, M. Lipson, A. L. Gaeta, and K. Bergman, “Demonstration of broadband wavelength conversion at 40 Gb/s in silicon waveguides,” IEEE Photon. Technol. Lett. **21**, 182-184 (2009).

[8] L. Tong, J. Lou, and E. Mazur, “Single-mode guiding properties of subwavelength-diameter silica and silicon wire waveguides,” Opt. Express **12**, 1025-1035 (2004).

[9] M. A. Foster, A. C. Turner, M. Lipson, and A. L. Gaeta, “Nonlinear optics in photonic nanowaveguides,” Opt. Express **16**, 1300-1320 (2008).