Characterization of Nonlinear Optical Crosstalk in Silicon Nanowaveguides

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***Abstract*—We investigate optical crosstalk on a signal in a silicon nanowaveguide due to the presence of another signal by direct radio frequency crosstalk level measurements in a pump-probe configuration and by bit-error-rate-based characterization. We quantify this degradation as a function of the modulation frequency and power of the auxiliary signal. Our results indicate that two-photon and free-carrier absorption are primary facilitators of crosstalk in silicon nanowaveguides.**

***Index Terms*—Nanophotonics, nanowaveguides, nonlinear optical devices, nonlinear optics, optical crosstalk, optical signal processing.**

I. Introduction

As CHIP multiprocessor systems continue scaling towards increased parallelism, on- and off-chip interconnects will be required to provide much higher bisectional bandwidth to enable efficient utilization of the computing cores. While electronic interconnect technology has facilitated this increasing-parallelism trend thus far, power density and dissipation constraints will eventually limit further scalability of these interconnects [1]. Optical Networks-on-Chip (ONoC), enabled by the emergence of complementary-metal-oxide-semiconductor (CMOS)-compatible silicon photonics, have attracted significant interest as a means of achieving ultra-high bandwidth, high energy efficiency, and low power dissipation [2]. Some photonic interconnect designs have been proposed to leverage wavelength division multiplexing (WDM) to achieve power efficient optical switching of high bandwidth data [3]. Such designs are enabled by the development of silicon photonic components based on electro-optically passive or active microring resonators which are in particular suitable for WDM systems because of the microrings wavelength-localized operation [4]–[6]. Recent studies have shown that network architectures based on WDM are necessary in order for optical communications to compete with electronics [7], [8]. In addition, the silicon platform has been utilized for signal processing using nonlinear interactions based on FWM [9]–[12].

However, inter-channel crosstalk in such WDM systems, which is mediated by many different physical mechanisms, can cause severe data degradation. For single-mode operation in silicon, submicron dimension nanowaveguides are required [13]. Such nanowaveguides allow for high confinement of the optical mode, resulting in an enhancement in the nonlinearity [14], and a corresponding increase in the coupling mechanism for inter-channel crosstalk. Thus, it is essential to understand the causes and the impact of crosstalk in silicon-based WDM networks. In fiber-based WDM systems, the primary source of crosstalk comes from individual components, such as filters, multiplexers, and switches, as well as from nonlinear effects, including cross-phase modulation (XPM), four-wave mixing (FWM), stimulated Raman scattering (SRS), and optical Kerr effect-polarization dependent loss (OKE-PDL) [15]–[20]. However, no experimental work has explored the effects of cross-talk in silicon-based transmission channels. Recently, a theoretical analysis of crosstalk in silicon has been performed by Peleg, *et al.* [21].

In this letter we experimentally investigate optical crosstalk in a silicon nanowaveguide. We measure the crosstalk and the signal bit-error rate (BER) for various data rates. The frequency dependence of the crosstalk effects and the associated time constants indicate that a key contribution to crosstalk in silicon nanowaveguides arises from a combination of two-photon absorption (TPA) and TPA-induced free-carrier absorption (FCA), and that these effects appear to arise at lower power levels than other nonlinear effects such as FWM and XPM. Signal power optimization is necessary in order to minimize crosstalk and achieve error-free transmission inside the nanowaveguide.

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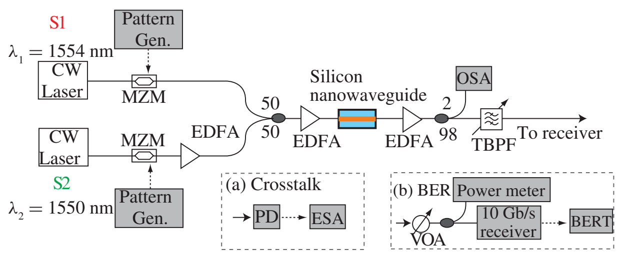

Fig. 1. Experimental setup for crosstalk measurements for a silicon nanowaveguide. Signals S1 and S2 are combined and coupled into the nanowaveguide. The output is filtered and sent to (a) for crosstalk measurements using an electrical spectrum analyzer (ESA) and (b) for bit-error rate (BER) measurements. MZM, Mach–Zehnder modulator; TBPF, tunable bandpass filter.

II. Experiment

We investigate optical crosstalk imparted on one signal (S1) propagating at an optical wavelength λ_{S1} in the presence of a second signal (S2) at an optical wavelength λ_{S2}. S1 and S2 are modulated at frequencies ν_{S1} and ν_{S2}, respectively. Crosstalk is defined as [20]

$$\text{Crosstalk (dB)} = 10 \log \frac{\text{RF power at } \lambda_{S1}}{\text{RF power at } \lambda_{S2}} \qquad (1)$$

where the RF power measurement is performed at the S2 frequency. The experimental setup for measuring crosstalk in a silicon nanowaveguide is shown in Fig. 1. Two continuous wave (cw) lasers, centered at 1554 nm and 1550 nm, are independently modulated using a Mach-Zehnder modulator to generate S1 and S2, respectively. For crosstalk measurements, both signals are generated using a clock source to drive the modulator. The modulation frequency for S1 is fixed at 9.953 GHz while the modulation frequency for S2 is varied from 50 MHz to 9.95 GHz. A preamplifier is inserted in the S2 arm to adjust the relative power between the two signals. The two signals are combined using a 3 dB coupler, amplified and sent into a silicon nanowaveguide using a lensed fiber. The embedded nanowaveguide is fabricated as described previously [22], and is 17.25-mm long with a cross-section of 300 nm by 600 nm. Although the nanowaveguide is not strictly single mode at telecommunication wavelengths, inverse tapers at the chips facets are used which minimize the excitation of higher-order modes, and is highly suitable for FWM processes due to the resulting group-velocity dispersion profile [22]. The propagation loss of the nanowaveguide is 1.1 dB/cm. The output from the nanowaveguide is amplified, filtered and sent into a photodiode, and the electrical signal is collected using an electrical spectrum analyzer (ESA) [Fig. 1(a)]. We measure the RF power at the S2 modulation frequency for both signal input wavelengths by tuning the tunable bandpass filter (TBPF). The output spectrum from the nanowaveguide is monitored using a tap coupler.

Figure 2(a) shows crosstalk on S1 as a function of the S2 modulation frequency. The average power of S1 and S2 inside the nanowaveguide is 3 dBm and 13 dBm, respectively. We observe that the crosstalk is dependent on the S2 modulation frequency, which indicates that free-carrier generation is the physical mechanism facilitating the inter-signal crosstalk. The optical spectrum does not exhibit effects due to FWM or other

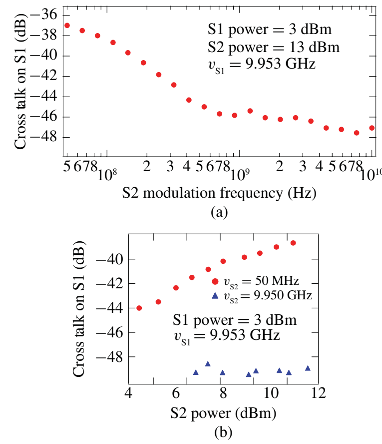

Fig. 2. Experimental results. (a) Crosstalk as a function of S2 modulation frequency. (b) Crosstalk as a function of S2 power for S2 modulation frequencies of 50 MHz and 9.95 GHz. The S1 modulation frequency is fixed at 9.953 GHz.

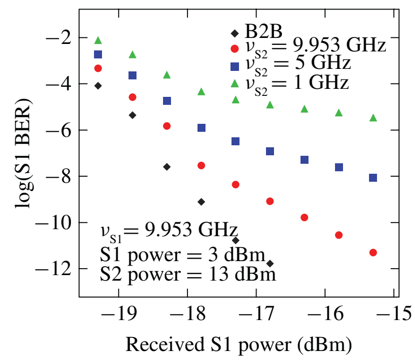

Fig. 3. Experimental measurements of bit error rate (BER) for S1 through the nanowaveguide for S2 modulation frequencies of 1, 5, and 9.953 GHz, and a back-to-back (B2B) measurement without the nanowaveguide (diamond).

$\chi^{(3)}$ nonlinearities. Figure 2(b) shows crosstalk as a function of S2 power. We observe lower crosstalk and smaller variations with respect to power at higher S2 modulation frequencies. The crosstalk roll-off at 1 GHz is consistent with previously measured free-carrier lifetimes of 1 ns for waveguides with similar dimensions [23]. We attribute the crosstalk beyond this roll-off point primarily to TPA.

Next, we investigate the bit-error-rate (BER) of S1 in the presence of S2. In the experiment, S1 is generated using a pattern generator with a 2^{31}-1 pseudo-random bit sequence (PRBS) data at 9.953 Gb/s. S2 is generated using a clock source. The output from the nanowaveguide is amplified, filtered, and sent through a variable optical attenuator (VOA) into a 10-Gb/s lightwave receiver (Agilent 83434A) and a BER tester (BERT) [Fig. 1(b)]. Figure 3 shows BER measurements on S1. As in the crosstalk measurement, S1 and S2 powers in the nanowaveguide are 3 dBm and 13 dBm, respectively. The plot shows a back-to-back (B2B) measurement, where the nanowaveguide is bypassed, along with three different S2 modulation frequencies. While the difference in crosstalk between a 1-GHz modulation and a 10-GHz modulation, as shown in Fig. 2(a), is small (2 dB), we observe a significant improvement in BER as the modulation frequency is increased, which is consistent with the free-carrier lifetime in the medium. At lower S2 modulation frequencies, the

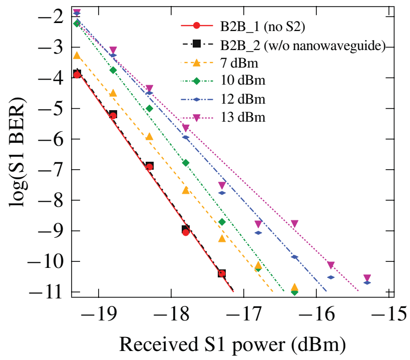

Fig. 4. Experimental measurement of the BER for various S2 powers. The numbers represent the power inside the nanowaveguide and S1 and S2 have equal powers. Two B2B measurements are performed, one without S2 and the other without the nanowaveguide.

free-carrier density follows the S2 modulation, resulting in distortions in both the amplitude and shape of S1. At higher modulation frequencies, the medium response cannot follow the S2 modulation, resulting in a free-carrier density with a dominant DC component. Thus, at these frequencies, S1 primarily experiences a constant attenuation in amplitude due to FCA while the shape generally remains unchanged.

Figure 4 shows the BER measurement for various power levels for multi-wavelength operation in the nanowaveguide. Both S1 (1554 nm) and S2 (1550 nm) are generated using a pattern generator with PRBS data at 2^{31}-1 and a data rate of 9.953 Gb/s. We introduce a 20 μs timing offset between the two signals in order to prevent correlated patterns. The two signal powers are adjusted such that S1 and S2 have the same average power inside the nanowaveguide. The average power of S1 and S2 inside the nanowaveguide are each independently varied from 7 dBm to 13 dBm. Two separate B2B measurements are performed, the first with S2 off and the second without the nanowaveguide. The B2B results confirm that the signal degradation is indeed due to the interactions between the two signals. We observe an increase in power penalty as high as 2 dB, indicating that the combined signal powers inside the waveguide must be optimized ($<$ 7 dBm for a power penalty $<$ 0.5 dB) in order to minimize the power penalty due to crosstalk.

III. Conclusion

We investigate optical crosstalk in a silicon nanowaveguide. Our results indicate that the crosstalk on the signal is dependent on both the power and modulation frequency of the second signal, which is attributed to free-carrier absorption in the nanowaveguide. BER measurements indicate that the signal degradation is dependent on both the modulation frequency and the power of the second signal. For multi-wavelength operation, the signal power levels must be optimized to minimize crosstalk between channels. Alternatively, the free-carrier lifetime can be reduced by utilizing a reversed biased p-i-n structure to remove free-carriers [24]. In addition, amplitude invariant modulation formats, such as phase-shift keying, should be considered to overcome the effects of free-carrier absorption.

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