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Ultrahigh-Bandwidth WDM Signal Integrity in Silicon-on-Insulator Nanowire Waveguides

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***Abstract*: We measure signal degradation from inter-channel crosstalk of ultrahigh-bandwidth signals in silicon-on-insulator waveguides, and single-channel power penalty over a range of injection powers. The results validate the suitability of silicon-based nanowire interconnects for broadband WDM networks.**

Introduction

Photonic integrated circuits (PICs) present the possibility of implementing on-chip and chip-to-chip interconnection networks [1]. Because of the high speed and broad bandwidth of many optical technologies, the bandwidth and latency demands of high performance computing (HPC) applications could be met in an integrated optical platform. Further advantages can be realized by implementing such a system in the complementary metal-oxide-semiconductor (CMOS)-compatible silicon-on-insulator (SOI) platform [2–3], including ultra-compact footprints resulting from the high-index contrast, simple integration of electrical and optical components, and low-cost processing. Complex active and passive components have been successfully fabricated in this material system [2–3], but it is important not to overlook the performance of the photonic wires which interconnect the devices.

High-bandwidth transmission schemes have been demonstrated previously in InP-based material systems [4], but a thorough analysis of the WDM wavelength crosstalk in silicon-based platforms has not been performed. Recently, we demonstrated 300-Gb/s transmission (24 wavelength channels at 12.5 Gb/s each) through a 2-cm silicon waveguide, while maintaining an error-free signal following the waveguide; that is, bit error rates (BERs) below 10^{-12} were observed on each channel [5]. Here, we further demonstrate the suitability of silicon waveguides for carrying ultrahigh-bandwidth, wavelength-parallel data streams. We investigate the inter-channel crosstalk as evidenced by the received BER, and we measure the power penalty of single-channel signals at different injection powers. We confirm the robustness of the waveguides for propagating multi-wavelength broadband data in interconnection networks contained entirely on a single substrate, and in those that are part of a larger system where off-chip bandwidth is crucial.

Experiments and Results

The experimental setup (Fig. 1a) consists of an array of 24 distributed-feedback (DFB) continuous-wave laser sources occupying channels C22-C32, C35-C38, and C43-C51 of the ITU C-band. The laser outputs are combined onto a single fiber with a wavelength-division-multiplexer that has 100-GHz channel spacing. A $LiNbO_3$ modulator encodes a pseudo-random bit sequence (PRBS) onto all of the wavelengths simultaneously at 10 Gb/s using the non-return-to-zero (NRZ), on-off-keyed (OOK) format. Then, the signals are decorrelated by 425 ps/nm in 25 km of single-mode fiber. The light is coupled to and from the chip by tapered fibers (Fig. 1b). Following the waveguide, the signal is amplified in an erbium-doped fiber amplifier (EDFA), after which some of the power is extracted for power monitoring on an optical spectrum analyzer (OSA). One wavelength channel is selected for measurement using a tunable grating filter, which is followed by an optical attenuator and a high-speed receiver module consisting of a *p-i-n* photodiode, transimpedance amplifier, and limiting amplifier. The detected signal is monitored on a communications signal analyzer (CSA) and evaluated with a BER tester (BERT), which is synchronized to the pulse pattern generator (PPG) by a 10-GHz clock source. Polarization controllers are used throughout.

The single-mode waveguides are 5 cm in length with heights of 220 nm and widths of 520 nm (Fig. 1c). The devices were fabricated using the CMOS production line at the IBM T. J. Watson Research Center. At the chip edge, each waveguide end has an inverse-taper mode-converter covered with index-matching polymer for efficient fiber coupling [6]. The physical parameters of the waveguides have been simulated and measured in previous work [7–9].

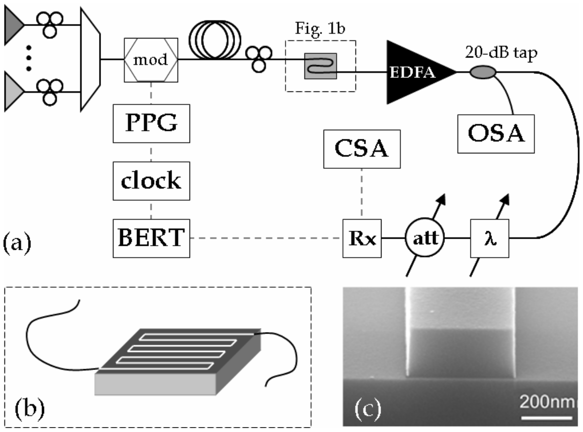

Fig. 1. (a) Diagram of the experimental setup, (b) chip layout, and (c) scanning electron microscope image of the waveguide cross-section.

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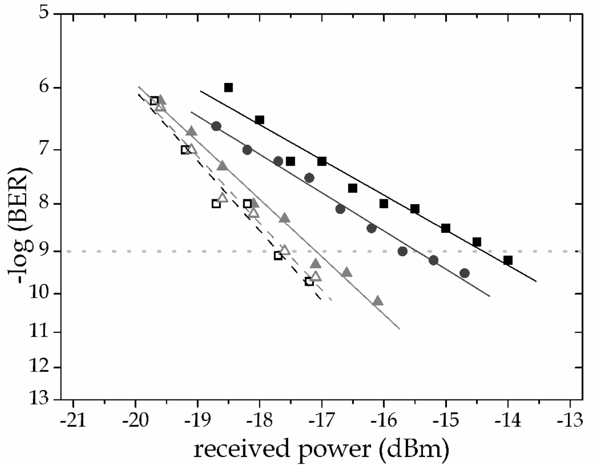

Fig. 2. BER curves showing wavelength crosstalk in a 5-cm waveguide, denoting single- (▲), 21- (●), and 24-channel (■) WDM signals. Measurements are taken going through (solid lines, filled symbols) and bypassing (dashed lines, open symbols) the waveguide.

We first experimentally characterize the crosstalk between wavelength channels in the 5-cm waveguide with a peak launch power of approximately -6 dBm per channel. BER curves (Fig. 2) are taken for a single probe wavelength (C36) at 10 Gb/s for two cases: (1) through the waveguide and (2) bypassing the waveguide, and instead passing through a variable optical attenuator, ensuring consistent power levels entering the EDFA. The observed power penalty of the waveguide is 0.6 dB. Next, 20 additional channels are enabled; the nearest channel to the probe (C32) is located at a spectral distance of greater than 3 nm from the probe wavelength. This causes a 1.5-dB shift in the sensitivity curve at a BER of 10^{-9}. Three more channels are then enabled (C35, C37, and C38), totaling 24. The added crosstalk from these channels, which are adjacent to the probe, increases the power penalty by 1.1 dB. Finally, a BER curve is again taken while bypassing the waveguide so that the overall power penalty for the 24-channel signal may be determined. The resulting power penalty is 3.3 dB. Given the length of the waveguide, which is long enough to route from any source to any destination regardless of topology in an on-chip network, and given the number of channels in the signal, the measured power penalty is quite tolerable. The reasonable overlap between the two extreme back-to-back cases (1 channel and 24 channels) in Fig. 2 indicates that the measured crosstalk is indeed occurring in the waveguide, rather than elsewhere in the setup (e.g., in the EDFA).

Previously, nonlinear phenomena such as self-phase modulation (SPM) have been observed in tightly-confined silicon waveguides using picosecond pulses near 1.5 μm in wavelength [8]. Typically the injected powers required to observe SPM have been a few tens of milliwatts with 0.4-cm waveguides. With longer waveguides, however, the input power required to observe SPM is lowered. It is therefore important to consider the power penalty induced when signals with high injection powers are launched into relatively long waveguides. Fig. 3 plots the BER curves for a single wavelength at 1550 nm with a peak power of more than 7 dBm injected into the waveguide. The resulting 0.5-dB power penalty is within the experimental error of the previous single-channel measurement (0.6 dB), which is taken with a much lower launch power (Fig. 2). This result confirms consistent power penalties over an input power dynamic range of more than 10 dB.

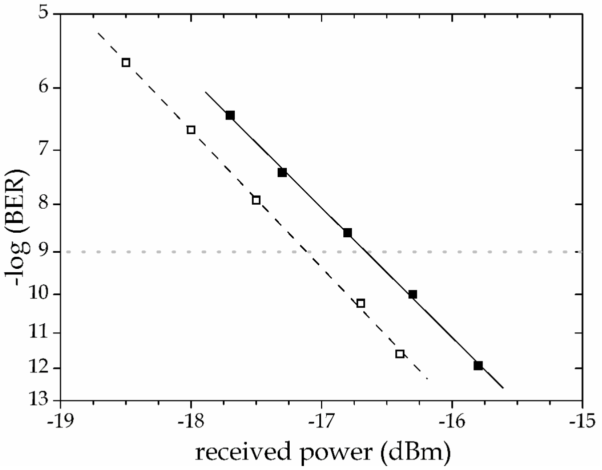

Fig. 3. BER curves for a single wavelength channel injected into the 5-cm waveguide with more than +7 dBm of peak power. Measurements are again taken through (■) and bypassing (□) the waveguide.

Conclusion

We have demonstrated the propagation of a 24-channel WDM signal through a 5-cm-long SOI waveguide, and measured a 3.3-dB power penalty resulting from the waveguide. Approximately 0.6 dB of this penalty exists with only a single channel present, with the rest attributed to inter-channel crosstalk. Moreover, the power penalty of single-channel signals is found to be steady over a large input power dynamic range for injected powers up to 7 dBm. These results further validate the use of silicon for PIC-based interconnection networks that implement waveguides as ultrahigh-bandwidth photonic wires.

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