Continuous Wavelength Conversion of 40-Gb/s Data Over 100 nm Using a Dispersion-Engineered Silicon Waveguide

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***Abstract*—We demonstrate broadband continuous wavelength conversion based on four-wave mixing in silicon waveguides, operating with data rates up to 40 Gb/s, validating signal integrity using bit-error-rate measurements. The dispersion-engineered silicon waveguide provides broad phase-matching bandwidth, enabling complete wavelength-conversion coverage of the S-, C-, and L-bands of the International Telecommunication Union (ITU) grid. We experimentally show this with wavelength conversion of high-speed data exceeding 100 nm, and characterize the resulting power penalty induced by the wavelength conversion process. We then validate the bit-rate transparency of the all-optical process by scaling the data rate from 5 Gb/s up to 40 Gb/s at the 100-nm wavelength conversion configuration, showing consistent low power penalties, validating the robustness of the four-wave mixing process in the silicon platform for all-optical processing.**

***Index Terms*—Optical frequency conversion, optical Kerr effect, optical signal processing, silicon-on-insulator technology.**

I. Introduction

THE everlasting endeavor in optical communications toward achieving higher bandwidths and data rates with minimal power consumption is driving the requirement for scalable optical interfaces and means for performing energy-efficient all-optical signal processing and manipulation at high data rates. Optical-electrical-optical (OEO) interfaces composed of optoelectronic transceivers are limited by the inherent physical speeds and power consumption of electronic wiring, as well as the increasing complexity in the electronic hardware required in performing high-speed serialization and deserialization. These factors inevitably drive up the cost and power consumption of transceiver-based interfaces. The use of nonlinear effects for all-optical processing presents an attractive solution for signal manipulation in the optical domain since it circumvents OEO interfaces and mitigates the limitations of electronic circuits. A variety of material platforms capable of strong four-wave mixing (FWM) for use in all-optical processing include highly nonlinear fibers (HNLF), semiconductor optical amplifiers (SOA), chalcogenide waveguides, silicon waveguides, and silicon-organic waveguides [1]–[6]. Recent advances in these various platforms have enabled demonstrations of multiple important optical-communication functionalities including wavelength conversion [1], wavelength multicasting [2], tunable delays [3], and temporal demultiplexing [4].

Dispersion-engineered silicon waveguides have been shown to achieve record-high performances by supporting optical processing at terabit-per-second bit rates [8], and in providing continuously-tunable conversion bandwidth across hundreds of nanometers [9]. Furthermore, these complementary metal-oxide-semiconductor (CMOS)-compatible silicon waveguides present a well-refined mass-producible platform for optical nonlinear processing, requiring relatively simple fabrication and allowing for dense integration with state-of-the-art microelectronics.

In this work, we validate the conversion bandwidth of these silicon waveguides with 40-Gb/s data by scaling the conversion range from our previous demonstrations of up to 47 nm [1], to the new record of 100.2 nm, showing constant low power penalties of 1.47 dB measured at a bit-error rate (BER) of 10^{-9}. We further validate the bit-rate transparency of the wavelength converter by showing consistent low power penalties on the wavelength-converted data signal for bit rates varied from 5-Gb/s up to 40-Gb/s. With this we have achieved the broadest wavelength conversion of data in a silicon waveguide as well as validated its integrity, presenting a two-fold improvement of the power penalty over previously reported power penalties at this data rate for wavelength-conversion in silicon waveguides [1].

II. Device and Experimental Setup

In this experiment, we use a 1.1-cm long silicon waveguide with a 290-nm × 720-nm cross section, fabricated at the Cor-

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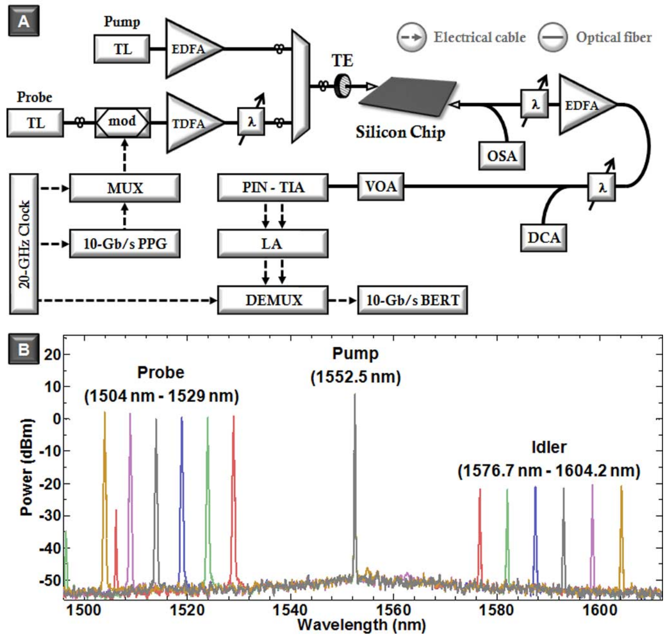

Fig. 1. (a) Experimental setup. (b) Overlaid spectra measured at the output of the chip, corresponding to wavelength conversions of 47.7 nm up to 100.2 nm. Beyond the generated idler, additional FWM products are visible at shorter wavelengths (1506.0 nm and 1496.5 nm) corresponding to a FWM process in which two probe photons interact with a single pump photon.

nell Nanofabrication Facility. The waveguide is formed on a silicon-on-insulator (SOI) platform 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 resulting in 6.4-dB fiber-to-fiber linear insertion loss. The zero-group-velocity-dispersion (ZGVD) wavelength for this waveguide was calculated to be approximately 1577 nm [10].

The experimental setup used to evaluate the wavelength conversion (Fig. 1(a)) includes a continuous-wave (CW) probe produced by a tunable laser (TL) modulated with a $2^{15} - 1$ pseudo-random-bit-sequence (PRBS) pattern which is generated by electrically multiplexing (MUX) a lower data rate PRBS pattern from a pulsed-pattern generator (PPG). A fixed CW 1552.5-nm pump is created by amplifying the output of another TL using an erbium-doped fiber amplifier (EDFA). The modulated probe in the S-band of the ITU grid is amplified using a thulium-doped fiber amplifier (TDFA), filtered using a Fabry-Perot band-pass filter (λ), and combined with the pump. The probe and pump are both set to the TE polarization using a fiber polarizer, and are injected into the silicon device. Following the device, a portion of the power is tapped for examination on an optical spectrum analyzer (OSA). The wavelength-converted data signal is recovered using additional filtering and amplification stages. It is then inspected using a digital communications analyzer (DCA), and is received using a photodetector (PIN-TIA) followed by a limiting amplifier (LA). The electrical received signal is demultiplexed (DEMUX) and then examined on a BER tester (BERT). A variable optical attenuator (VOA) is used to vary the optical power incident on the receiver. An electrically-distributed tunable clock source determines the modulated data rates, scaling between 5 Gb/s and 40 Gb/s. We perform the experiments with probe-idler detuning ranges spanning from 47.7 nm to 100.2 nm. Back-to-back eye diagrams and BER curves are recorded on the probe just before it is combined with the pump.

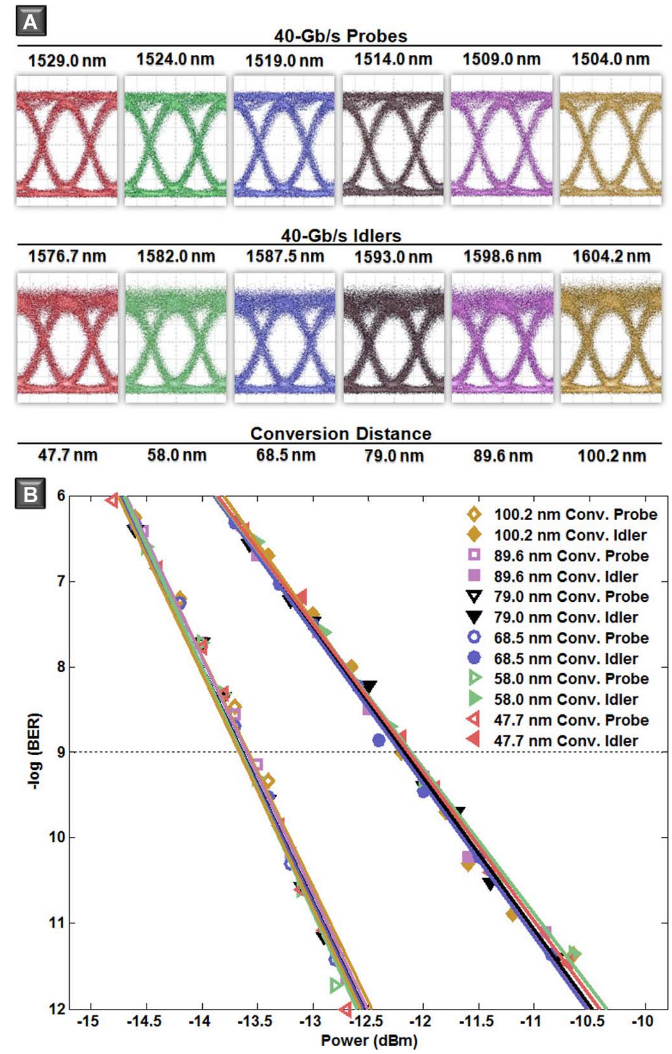

Fig. 2. (a) Eye diagrams for the back-to-back cases (probes) and wavelength-converted signals (idlers) for the listed conversion experiments. (b) BER curves measured for all the 40-Gb/s back-to-back cases (probes) and wavelength-converted signals (idlers) showing average power penalty of 1.47 dB.

III. Experiments and Results

In our first experiment, we set the data rate of the probe at 40-Gb/s and scan the probe wavelength to vary the conversion distance between 47.7 nm and 100.2 nm with 10.5-nm steps. The conversion efficiency, defined as the ratio of idler power to probe power at the chip output, remains nearly constant at -22 dB for all probe-idler separations (Fig. 1(b)), as it is well within the operational bandwidth of the waveguide. We obtain open eye diagrams for all wavelength-converted signals (Fig. 2(a)), showing minimal signal degradation. The signal integrity degradation of the wavelength conversion process is then quantified using BER curves measured for the back-to-back and wavelength-converted data signals, showing a consistent 1.47-dB power penalty (Fig. 2(b)). This power penalty includes

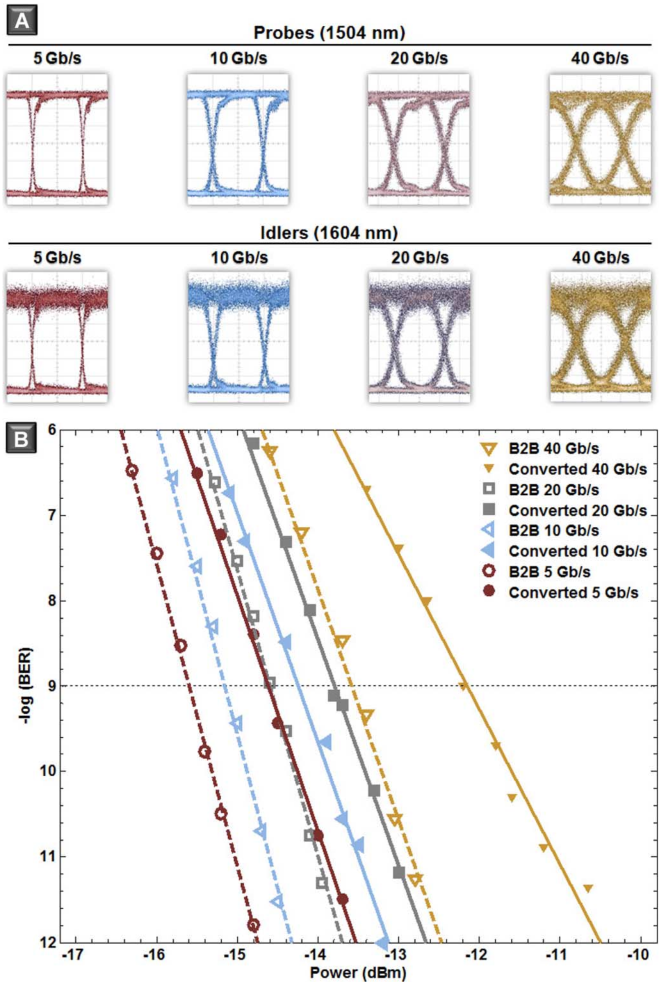

Fig. 3. (a) Eye diagrams for the back-to-back cases (probes) and wavelength-converted signals (idlers) for bit rates of 5-, 10-, 20-, and 40-Gb/s for 100.2-nm wavelength conversion. (b) BER curves for back-to-back cases (probes) and wavelength-converted signals (idlers) showing a power penalty of less than 1 dB for bit rates up to 20 Gb/s, and a 1.43-dB penalty for 40-Gb/s signals.

signal degradation induced by the post-conversion EDFA and filters. The improved power penalty compared to the previously reported 2.9-dB penalty on a similar device [1] is attributed to improvements made to the experimental setup in the data generation and reception electronics as well as optimization of the optical amplification and filtering stages.

In our second experiment, we keep the pump wavelength at 1552.5 nm, set the probe at a fixed wavelength of 1504 nm (corresponding to a 100.2-nm probe-idler detuning), and set the modulation rate to 5, 10, 20, and 40 Gb/s by changing the tunable clock source frequency while keeping the rest of the experimental setup fixed. We record open eye diagrams on the wavelength-converted signals (Fig. 3(a)), and quantify signal degradation using BER measurements (Fig. 3(b)). The calculated power penalties from these BER curves show power penalties of 0.98, 0.91, 0.80, and 1.43 dB, corresponding to the data rates of 5, 10, 20, and 40 Gb/s, respectively. The deviation in power penalties for the 5-Gb/s to 20-Gb/s rates is within experimental variation. The 0.5-dB relative increase in power penalty for the 40-Gb/s data rate is partially attributed to more pronounced sideband attenuation by the post-conversion 1.5-nm-wide filter.

IV. Conclusion

We have demonstrated broadband wavelength conversion of 40-Gb/s data in a dispersion-engineered silicon waveguide, showing constant conversion efficiencies and low power penalties as the conversion range is continuously increased to 100.2 nm, validating the feasibility of this platform for full manipulation of light in the S-, C-, and L-bands of the ITU grid. We have also demonstrated the data rate transparency of the process by varying the data rate from 5 Gb/s up to 40 Gb/s, showing nearly constant power penalties. This experiment further validates the robustness and usefulness of silicon waveguides for high-speed all-optical processing, in the conventional telecommunication bands and beyond, enabling improved bandwidth utilization and power consumption in next-generation optical communication systems.

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