First 80-Gb/s and 160-Gb/s Wavelength-Converted Data Stream Measurements in a Silicon Waveguide

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Abstract: Data fidelity is inspected for the first time for wavelength-converted RZ TDM 80- and 160-Gb/s data using four-wave mixing in a silicon waveguide. Open eye diagrams and error-free operation is shown for demultiplexed 10-Gb/s tributaries.

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

1. Introduction

To meet the explosive growth in bandwidth demands of optical networks, it is expected that in addition to scaling the density of wavelength-division-multiplexed channels, data rates per channel will continue to increase, soon reaching time-division-multiplexed (TDM) data rates as high as 1 Tb/s. Data manipulation and processing, including wavelength conversion and multicasting of these anticipated ultra-high-speed signals, cannot be practically accomplished by current optical network routing elements, which utilize power-hungry optical-electrical-optical interfaces that do not scale well with data rate and the number of wavelength channels. Optically-transparent routing and processing, enabled by optical parametric processing employing ultrafast four-wave mixing (FWM), is an attractive solution for realizing energy-efficient data manipulation functionalities on high-speed TDM data streams.

Such optical parametric processing systems have been demonstrated in the past using highly non-linear fiber [1], III-V material systems [2], and using silicon combined with organic materials [3]. Silicon photonic devices offer a new and exciting prospect for FWM-based processing systems, as they combine the mass-producible complementary metal-oxide-semiconductor (CMOS) compatibility with ultra-high bandwidths for optical manipulation [4,5]. System-level bit-error-rate (BER) characterization of 40-Gb/s non-return-to-zero wavelength-converted signals has been carried out for these devices [6]. We recently demonstrated the potential for wavelength conversion of high-speed return-to-zero (RZ) signals in silicon, showing minimal pulse broadening of the wavelength-converted data [7]. In this work, we evaluate the data integrity of wavelength-converted pseudo-random bit sequence (PRBS)-coded 80- and 160-Gb/s RZ signals using an optical demultiplexer. The demultiplexer is used to isolate a 10-Gb/s tributary slot out of the aggregate converted signal, which is inspected using a BER tester (BERT). We demonstrate open eye diagrams and error-free operation for the first time for high-speed RZ TDM wavelength-converted data in silicon.

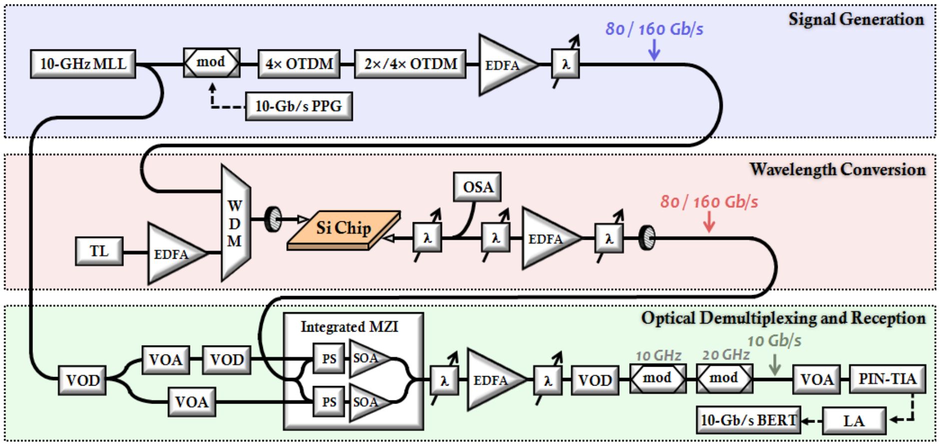

Fig. 1. Diagram of the experimental setup. Dashed lines represent electrical cable, and solid lines represent optical fiber. Highlighted areas signify signal generation, wavelength conversion, and temporal optical demultiplexing and reception functional blocks. Polarization controllers are used throughout the setup.

2. Device Structure and Experimental Setup

The silicon device used for this experiment is a silicon waveguide of 1.1-cm length with a 290-nm × 660-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 experimental setup consists of three major sections, namely signal generation, wavelength conversion, and optical demultiplexing and reception (highlighted in Fig. 1). Signal generation consists of modulating the output of a 10-GHz mode-locked-laser (MLL) at 10-Gb/s with a 2^{31}-1 PRBS pattern from a pulsed pattern generator (PPG) and then using optical time-division multiplexing (OTDM) stages to produce either an 80-Gb/s or 160-Gb/s aggregate stream. To achieve wavelength conversion, the data is amplified using an erbium-doped fiber amplifier (EDFA), a continuous-wave (CW) optical pump is produced by an amplified tunable laser (TL), and both signals are combined using a wavelength-division-multiplexer (WDM), set to TE polarization, and coupled into the silicon waveguide. The output of the waveguide is then filtered using a tunable grating filter (λ), and amplified to recover the converted signal for further processing. The final stage of optical signal processing consists of temporally demultiplexing the 80-Gb/s or 160-Gb/s streams down to the 10-Gb/s tributaries and inspecting them. The demultiplexer optically gates the data signal using a combination of an integrated semiconductor optical amplifier (SOA)-based Mach-Zehnder interferometer (IMZI) and two cascaded $LiNbO_3$ MZI modulators. The IMZI creates optical gates using a push-pull configuration where a portion of the original 10-GHz pulse train of the MLL is used to inject electrical carriers into the SOAs of the IMZI arms, shifting the phases and toggling the interference state at the output [8]. Variable optical delays (VOD) and variable optical attenuators (VOA) are used to properly configure this push-pull mechanism. The cascaded $LiNbO_3$ modulators are driven with 20- and 10-GHz clock sources to complement the gating operation of the IMZI, further suppressing the adjacent tributary bits. The demultiplexer output is received on a photodetector (PIN-TIA) with a limiting amplifier (LA) and then examined on a BERT for BER characterization. Power taps are used throughout to examine the signals using an autocorrelator and a digital communications analyzer (DCA).

3. Experiments and Results

We first show wavelength conversion of an 80-Gb/s aggregate stream in a silicon waveguide. The conversion efficiency, defined as the difference in power between the converted signal and input signal at the output of the chip, is -17.9 dB, with injected 23.8-dBm CW pump power and 14.5-dBm average signal power. Autocorrelation traces of both data input and wavelength-converted data are taken, showing no significant pulse broadening (Fig. 2b). The converted data after being demultiplexed, as seen on a DCA (Fig. 2c), shows no additional broadening when inspected on an autocorrelator (Fig. 2b). Error-free operation (defined as having BERs less than 10^{-12}) is observed for the converted 10-Gb/s tributary, and a BER curve is then taken to inspect the power penalty for the entire system, where the back-to-back case is taken on the original 10-Gb/s stream. The entire system power penalty is measured to be 11.1 dB, much of which is attributed to the multiple amplification and filtering stages in the complete experimental setup.

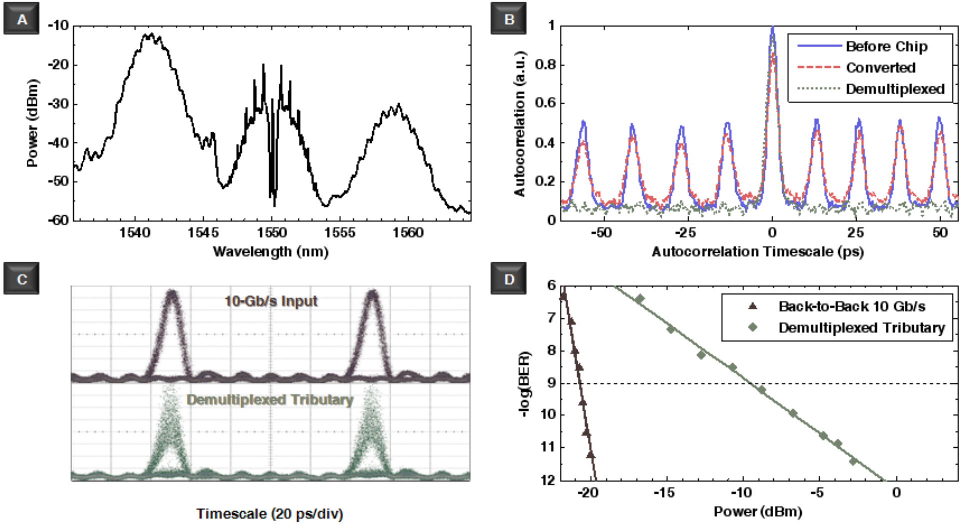

Fig. 2. (a) Output spectrum of conversion after the pump is suppressed, with 1541-nm input signal and 1559-nm converted signal. Non-degenerate FWM appears around the 1550-nm pump wavelength. (b) Autocorrelation traces taken on 160-Gb/s signals before and after wavelength-conversion, overlaid with autocorrelation trace of 10-Gb/s demultiplexed tributary. (c) Eye diagrams of 10-Gb/s input and 10-Gb/s tributary-demultiplexed signals. (d) BER curve comparing 10-Gb/s input and 10-Gb/s output, showing an overall 11.1-dB power penalty.

To validate the bandwidth scalability of this wavelength-conversion process, we convert a 160-Gb/s aggregate RZ data using the silicon chip, showing a conversion efficiency of -17.7 dB (Fig. 3a). Autocorrelation traces indicate that no significant degradation in the conversion process is incurred by the scaling of the data rate (Fig. 3b). Eye diagrams for the demultiplexed 10-Gb/s tributary stream are subsequently recorded (Fig. 3c). The large noise floor is mostly incurred by insufficient suppression of neighboring tributaries due to the performance limitations of the optical demultiplexer, rather than the wavelength conversion process itself.

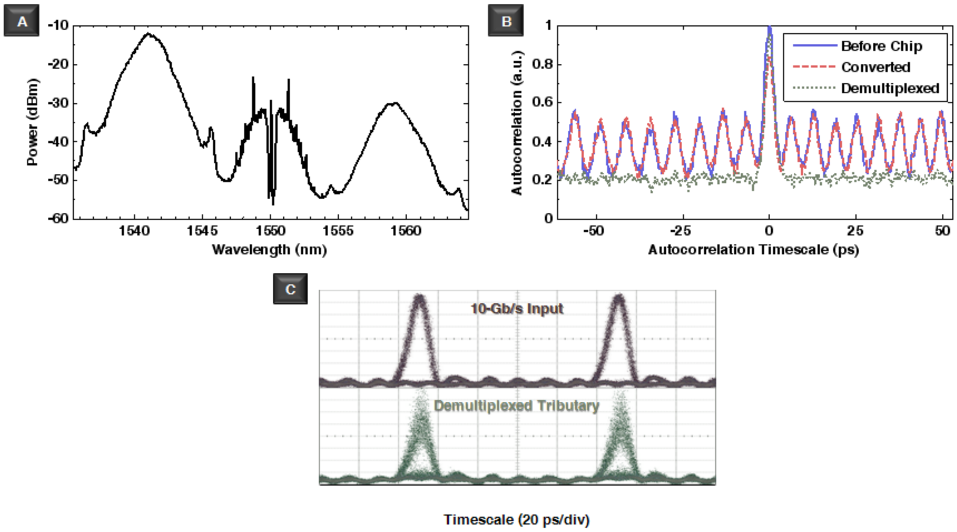

Fig. 3. (a) Output spectrum of conversion after the pump is suppressed, with 1541-nm input signal and 1559-nm converted signal. Non-degenerate FWM appears around the 1550-nm pump wavelength. (b) Autocorrelation traces taken on 160-Gb/s signals before and after wavelength-conversion overlaid with autocorrelation trace of 10-Gb/s demultiplexed tributary. (c) Eye diagrams of 10-Gb/s input and 10-Gb/s tributary-demultiplexed signals.

4. Conclusions

We have demonstrated error-free wavelength conversion of high-speed RZ data signals in a silicon waveguide for the first time, to the best of our knowledge. This demonstration emphasizes the high bandwidth and scalability offered by the CMOS-compatible silicon photonic device. Parametric optical processing technologies such as the one demonstrated in this work may potentially enable high-speed and energy-efficient all-optical data serialization, grooming, and deserialization in future core and access optical networks.

We would like to thank Dr. Benjamin G. Lee for many insightful conversations and helpful suggestions.

This work was supported in part by the DARPA MTO Parametric Optical Processes and Systems program under contract number W911NF-08-1-0058.

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