First Demonstration of On-Chip Wavelength Multicasting

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Abstract: We demonstrate for the first time wavelength multicasting performed in a silicon photonic chip. We investigate multicast number selectivity at 40-Gb/s data rates and evaluate each configuration using BER measurements, establishing immense prospect for scalability.

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1. Introduction

Silicon has enjoyed a long-standing dominant role within the integrated electronics industry. Emerging silicon-on-insulator (SOI)-based photonic integrated circuits (PICs) compatible with the ubiquitous complementary metal-oxide-semiconductor (CMOS) platform are already bearing fruit in the form of filters, switches, modulators, as well as in prospects of complex networks-on-chip [1]. SOI-based PICs utilizing nonlinear optical processes such as four-wave mixing (FWM) have enabled such elementary all-optical functionality as wavelength conversion on chip [2]. Broadcasting and multicasting of optical messages, critical network processes associated with the selective dispersing of information across many nodes, have traditionally been performed in the electronic domain using power-hungry optical-electronic-optical (O-E-O) conversion, or within bulky fiber-based systems [3]. Here we present for the first time the use of FWM for multicasting on-chip in the silicon platform. This multicasting operation performed in the optical domain within a compact PIC, will enable the transition from the traditional power-demanding electronic domain to the significantly more scalable, compact, energy-efficient, and data-rate-transparent optical domain.

2. FWM in Silicon Waveguides

The FWM device discussed here was fabricated at the Cornell Nanofabrication Facility using electron-beam lithography followed by reactive-ion etching. The device is a 1.1-cm-long waveguide with a height of 290 nm, slab thickness of 25 nm, and width of 680 nm. Previous work with a similar device showcased FWM-based wavelength conversion in silicon waveguides with larger than 150-nm bandwidths using continuous-wave (CW) pumping [2]. In [4], we presented the first bit-error-rate characterization of silicon four-wave-mixing wavelength converters. Power penalties below 0.5 dB were demonstrated over a 20-nm wavelength range at 10 Gb/s, and 40-Gb/s measurements yielded a 2.4-dB power penalty [4]. Here, we demonstrate for the first time wavelength multicasting in silicon waveguides, investigate the selectivity of the multicast number, ranging from one-way to eight-way, and perform 40-Gb/s bit-error rate (BER) measurements for each multicasting configuration on the converted wavelength channel with the largest conversion bandwidth.

3. Experimental Setup and Multicast Number Selectivity

The experimental setup for the BER measurements (Fig. 1) incorporates eight multiplexed CW tunable laser sources (occupying channels C21 through C28 of the ITU C-band) acting as probes, and another tunable laser as the pump. The pump, operating at the 1545-nm wavelength, is externally modulated with a 40-Gb/s non-return-to-zero (NRZ) on-off-keyed (OOK) signal, encoded using a PRBS of length 2^{15}-1, generated by the pattern generator (PG). The pump signal is amplified using an erbium-doped fiber amplifier (EDFA) and then combined with the probe channels using a dense wavelength-division multiplexer (DWDM). The combined signals then pass through a fiber polarizer, selecting the TE polarization, before being coupled into the on-chip nanotapered waveguide through a tapered fiber. After exiting the chip, the signals pass through a tunable grating filter (λ), selecting the proper converted wavelength channel to evaluate, an EDFA, another tunable grating filter, and a variable optical attenuator (VOA). The selected signal is then received by a high-speed *p-i-n* photodiode and transimpedance amplifier (PIN-TIA) receiver followed

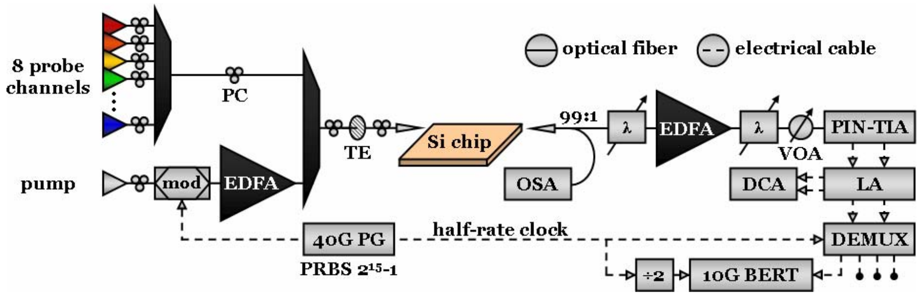

Fig. 1. Diagram of the experimental setup used for BER measurements.

by a limiting amplifier (LA). The received 40-Gb/s signal is then spatially demultiplexed using an electrical demultiplexer (DEMUX) into four 10-Gb/s signals, one of which is evaluated using a 10-Gb/s BER tester (BERT). Both the DEMUX and the BERT are synchronized to the clock output of the PG. A fraction of the power is tapped-off before the first filter for examination on an optical spectrum analyzer (OSA), and a digital communications analyzer (DCA) is used to verify the electrical signal following the LA. Polarization controllers (PCs) are also used throughout the setup. Before insertion, the average pump power is 25.1 dBm, and the probe channels are each set to 0 dBm.

The multicast number selectivity demonstration is performed by examining the wavelength spectrum at the output of the chip using the OSA (Fig. 2). An eight-way multicast is achieved by turning on all eight input probe channels (C21-C28), consequently producing eight phase-matched converted output signals (Fig. 2a). A four-way multicast is then achieved by turning off four of the input probe channels, leaving C21-C24 (Fig. 2b). Similarly, a two-way multicast is achieved by turning off two more input probe channels, leaving C21-C22 (Fig. 2c). Finally, a one-way multicast is performed when only one input probe (C21) is turned on (Fig. 2d). Similar results are obtained with arbitrary permutations of the eight input probe channels. The conversion efficiency, defined as the difference in the peak power between the input probe channels and output signals (both at the output of the chip), is -12 dB and remains constant for each multicasting configuration, indicating the possibility of further scalability.

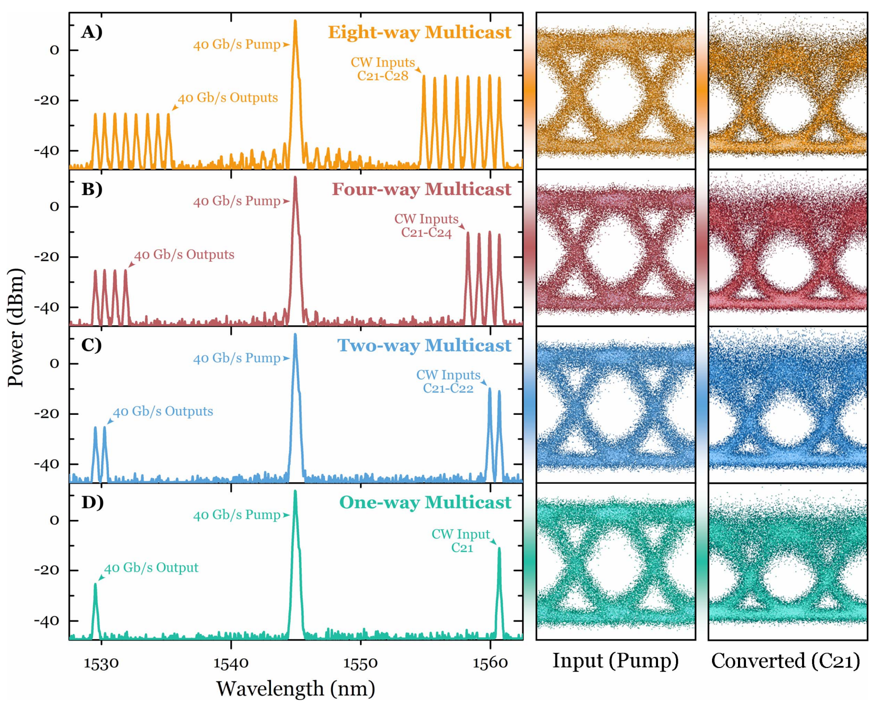

Fig. 2. Output wavelength spectra with CW input probe channels, pump signal, and converted output signals, with corresponding input (pump) and output (converted wavelength channel C21) 40-Gb/s eye diagrams for (a) eight-way, (b) four-way, (c) two-way, and (d) one-way multicast configurations.

The input eye diagram in Fig. 2 is obtained by using the DCA to examine the pump signal at the output of the chip (with all the probe channels off). The output eye diagrams are obtained by using the DCA to examine the selected converted signal (converted wavelength channel C21) with the largest conversion bandwidth at the output of the VOA for each multicasting configuration.

4. BER Characterization

BER measurements are taken at a 40-Gb/s data rate for the four selected multicast number selectivity configurations: eight-way, four-way, two-way, and one-way. For each case, error-free operation (defined as having BERs less than 10^{-12}) is observed for the converted wavelength channel C21, and a BER sensitivity curve is then taken on the same wavelength channel (Fig. 3). The four multicasting cases produce overlapping BER curves, indicating no additional power penalty associated with performing an eight-way multicast compared to a one-way multicast. This result is a clear indicator that there is still much room for further scalability.

A back-to-back case is taken for the pump signal at the output of the chip (with all the probe channels off), producing a measured 6.8 dB power penalty associated with this 40-Gb/s multicasting. Even though the waveguide used in this experiment maintained less than 8 dB of fiber-to-fiber loss, the additional power lost in the conversion efficiency strained the optical power budget of the experimental setup, placing the converted signal power on the lower end of the input power range of the preamplifier used in the experiment. Some of the observed power penalty may be attributed to OSNR degradation resulting from this effect, indicating that future work may achieve improved power penalty if a larger optical power budget, greater conversion efficiency, or reduced on-chip losses are obtained.

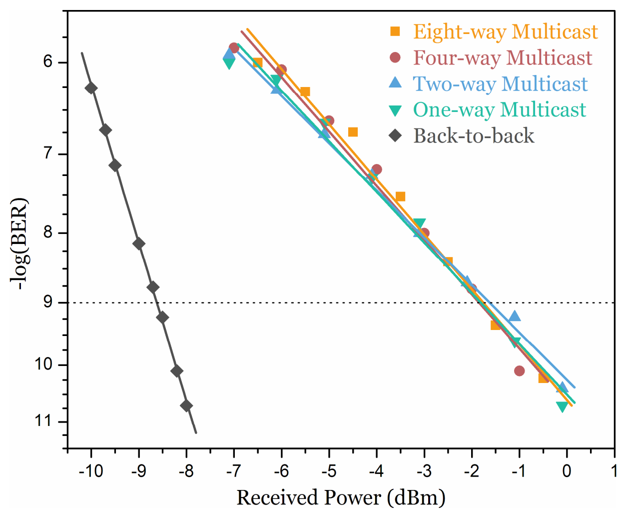

Fig. 3. BER curves recorded for eight-way (■), four-way (●), two-way (▲), and one-way (▼) multicast. Back-to-back curve (◆) is taken for the pump signal at the output of the chip with all the probe channels turned off. No additional power penalty is observed between all four multicasting configurations; equal power penalties of 6.8 dB are measured for all cases.

5. Conclusions

We demonstrate for the first time wavelength multicasting actualized in silicon waveguides. Up to eight-way multicast number selectivity is demonstrated at 40-Gb/s data rates, clean output eye diagrams are observed on the wavelength channel with the largest conversion bandwidth, and power penalties of 6.8 dB are measured for all four configurations: eight-way, four-way, two-way, and one-way multicast. The conversion efficiency remains constant at -12 dB, and no additional power penalty is measured when increasing the multicast operation from one-way to eight-way, establishing the prospect of continued scaling, both in terms of multicast number and data rate. Combined with the ubiquity of the silicon platform and CMOS compatibility of this integrated silicon photonic device, this compact, energy-efficient, and data-rate-transparent multicasting process may find its way to integrated photonic routers.

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6. References

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