240 Gb/s Mode and Wavelength Division Multiplexed Data Transmission in Si Photonics

Christine P. Chen[1✧], Jeffrey B. Driscoll[2], Brian Souhan[1,3], Richard M. Osgood, Jr.[1], Keren Bergman[1]

[1]Department of Electrical Engineering, Columbia University, 10027, NY, USA, [2]Intel Corporation, 95054, CA, USA, [3]West Point, 10996, NY, USA
Author's email address: ✧cpc2143@columbia.edu

***Abstract*— A 3-mode multiplexing and de-multiplexing silicon photonic circuit is shown to support 240 Gb/s data (3 modes x 2 wavelengths x 40 Gb/s). The key drivers for optimizing the photonic circuit performance are discussed.**

OCIS codes: (060.4510) Optical communications, (230.0230) Optical devices; (040.640) Silicon

I. Introduction

On-chip mode-division multiplexing (MDM) offers the potential to increase bandwidth density for optical interconnects. By coupling wavelength-division multiplexing (WDM) [1-3] as well as polarization-division multiplexing (PDM) [4] with on-chip MDM, data bandwidth is maximized through a single waveguide. MDM operation has been achieved through designs that have included the microring resonator [1, 5], grating coupler [6], directional coupler [3], and the asymmetric y-junction [7]. In this paper, it is shown that data bandwidth can be considerably scaled to 240 Gb/s through a system supporting 40 Gb/s *via* a single waveguide with the asymmetric y-junction structure.

Two- and three- mode operation using this device geometry have been demonstrated in [2, 8]. For this particular device, the challenge in design lies in maintaining low intra-channel crosstalk, as a result of the needed spatial resolution in fabrication of the device as the number of supported modes increases. Specific angle and multiplexer and demultiplexer waveguide widths are necessary for inducing low intermodal leakage.

Here, we demonstrate a high-bandwidth data channel stream across a 3-arm multiplexer and demultiplexer assymetric y-junction. Using 3 modes, 2 wavelengths, and 40 Gb/s data rate operation, a sufficient power penalty is obtained. We also discuss ways to alleviate the power penalty by increasing tolerance for MDM operation as the number of modal channels scale.

II. Device and Experimental Setup

The asymmetric y-junction used in this demonstration was fabricated at Brookhaven National Laboratory. Its measured dimensions are labeled in Fig. 2a. The demonstrated multiplexer/demultiplexer unit directs three channels supporting quasi-transverse magnetic modes (QTM) at two wavelengths in the C-band (Fig. 2b). Each input channel is spread over both the even and odd modes of the multimode waveguide given the angle and QTM excitation of the device. The operational wavelength selected will be incrementally limited to the areas where the crosstalk contribution of its neighboring modal channels is minimized. Previous error-free operation at lower per-channel data rate of 10 Gb/s has been shown in a device of this design [8]. With the wavelength region thusly selected for wavelength-division multiplexing functionality, we proceed with the experiment.

Two continuous-wavelength (CW) lasers are multiplexed into a single fiber before the light paths are modulated with a pulse pattern generator (PPG) putting out a non-return-to-zero (NRZ) 2^{15}-1 PRBS signal, triggered by a clock-divided 40 GHz clock source. Then, the multiplexed light paths are de-correlated by a spool of fiber before they are amplified and split into three lanes for the three modal channels. The spools of fiber per lane de-correlate the transmitted data several bits relative to

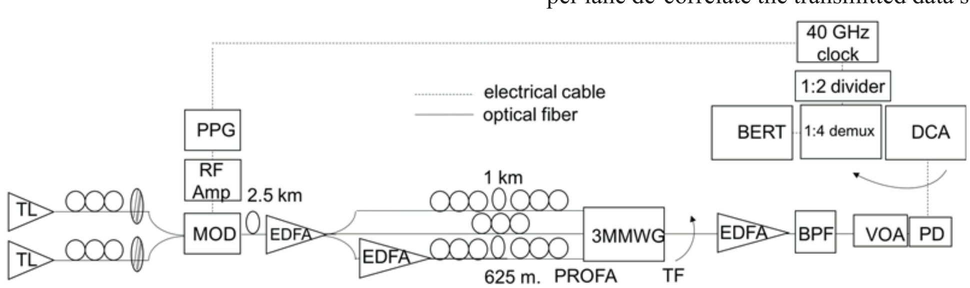

Figure 1. Experimental setup, with TL indicating tunable laser, PPG representing pulse pattern generator, MOD meaning 40 Gb/s $LiNbO_3$ modulator, EDFA as the erbium-doped fiber amplifier, DCA is digital communication analyzer, BPF as bandpass filter, and PD as the photodetector. The light path is coupled on-chip using a PROFA (pitch-reducing optical fiber array), and the channels are coupled off-chip one-by-one using a TF (tapered fiber). The ovals indicate spools of fiber for de-correlating data bits. Launch power to the MMWG is equalized, with the resulting wavelength scans shown in Fig. 2b.

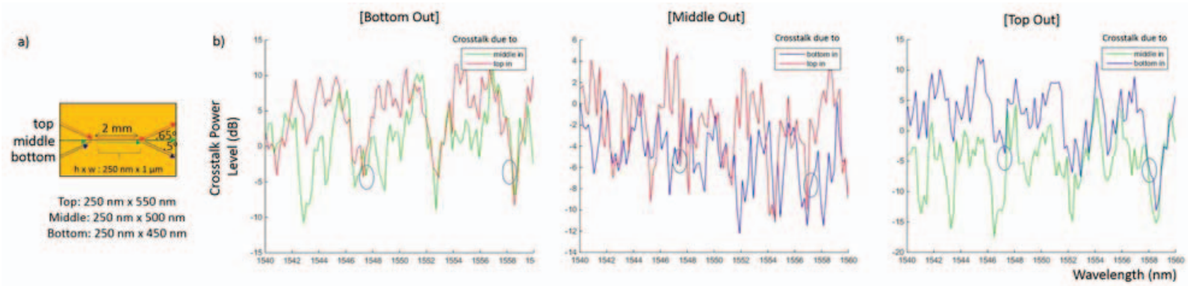

Figure 2. a) Device geometry and corresponding labelled input/output b) Spectral scan of crosstalk level from neighboring arms on through port arm. Two wavelengths at around 1547 nm and 1557 nm with equivalent power are selected, and selected wavelengths are optimized by further adjusting of polarization to maximize dips.

the neighboring pathways for launch with a 38 µm pitch-reducing optical fiber array (PROFA) onto the multimode waveguide.

Post-chip traversal, each wavelength and mode signal combination is recovered through a tapered fiber to be amplified, wavelength-filtered, and received with a photodetector for bit error tests (BERs) with a bit error rate tester (BERT) (Fig. 3b). Eye diagrams captured by a digital communication analyzer (DCA) are shown below in Fig. 3a.

III. DISCUSSION

From the bit error rate (BER) measurements at 40 Gb/s data rate per channel, variable power penalty was accrued from a combination of the device and system variation. There were two system parameters of power to account for. First, due to the imperfect power coupling on-chip, a power difference at the input to the chip can be seen. Unequal performance is likewise seen along each pathway directed to each input of the device.

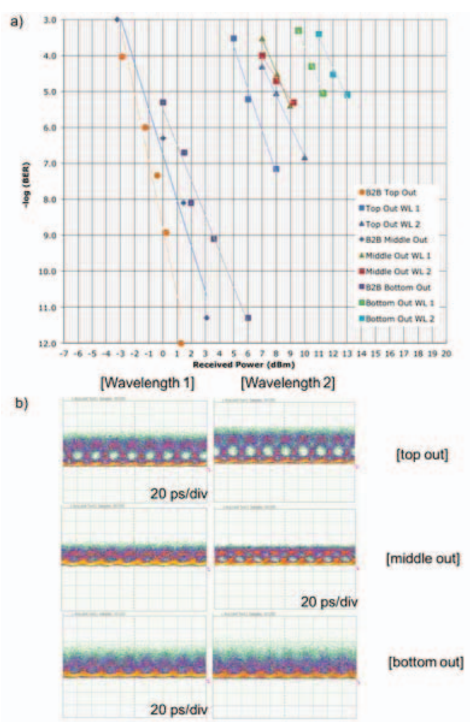

Figure 3. a) Eye diagram for three modal channels and two wavelengths b) Bit error rate measurement of 40 Gb/s signal through the system

Taking these two system parameters into account, we set the power level going on-chip to be acceptable for simultaneous MDM-WDM operation, as can be seen from the Fig. 2b scans. Operation was then at the edge of power requirements and upper bounded by receiver saturation.

Power penalty due to intra-channel crosstalk arises when there is imperfect mode confinement. In this case, for the chosen wavelengths, power penalty ranged from 7 dB at the 1e-8 BER point to considerably lower bit error rate of 1e-6 for the most impaired arm in the system, with the bottom arm seeing the highest level of intra-channel crosstalk. Low crosstalk regimes matching all three modal arms had to be selected. Compared to the multimode waveguide support two modes, there were fewer regimes with equivalently low crosstalk level. Coupled with the higher data rate, a considerably higher power penalty is accrued. To improve system performance, considerations for increasing fabrication tolerance can be investigated. Furthermore, it should also be taken into account that at higher data rates, as noise becomes a problem, forward error correction (FEC) can be employed to bring down the bit error rate. Additionally, dispersion in fiber becomes inherent at higher data rates, incurring fiber impairments [9] in the system.

In summary, we show the possibility of extending the bandwidth through an asymmetric, y-junction multimode waveguide by operating at 40 Gb/s data rate. Demonstration of 3 modes x 2 wavelengths x 40 Gb/s data rate results in 240 Gb/s aggregate bandwidth with variable performance across all channels, and further considerations can be made to equalize performance.

Acknowledgements: We acknowledge support from Intel/SRC Ph.D Fellowship and the Columbia Photonics IGERT under NSF grant DGE-1069420. The fabrication used for the device was carried out in part at the Center for Functional Nanomaterials, Brookhaven National Laboratory, which is supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. DE-AC02-98CH10886. The authors are grateful to Xiang Meng for useful discussion on the device and Qi Li for helpful discussion on experimental setup.

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