Harnessing the Properties of Optical Channel Diversity in a Multi-mode Silicon Nanophotonic Waveguide for High-Speed Data

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Abstract—Vastly growing data traffic demands across system interconnects have driven the need for increased bandwidth densities. Using a single silicon photonic link waveguide, mode-division and wavelength-division -multiplexing are performed simultaneously to garner an aggregate bandwidth of 60 Gb/s for error-free (BER $<10^{-12}$) operation.

Keywords—silicon photonics, space division multipexing, wavelength division multiplexing, multi-mode

1 Introduction

As high-performance computing systems continue to increase in functionality and speed, sustained growth in data rates is beginning to reach a saturation point due to the bandwidth bottleneck of current microelectronic systems. With its enhanced bandwidth capacity, silicon photonics offers a possible avenue toward increasing a system's aggregate bandwidth. As such, integration of silicon photonics onto microelectronic platforms will require smooth embedding of optoelectronic devices and the use of compatible system-on-chips to minimize power dissipation [1,2].

In order to maximize the bandwidth capacity of integrated optics, the employment of multi-mode systems is an emerging area which offers an orthogonal dimension to scaling data rates considerably for a given spatial density [3]. Transmission of multiple channels in these systems occurs on a single path by combining signals on independent modes using a mode-multiplexer. These modes can then be received separately at the output via a mode-demultiplexer. This technique is also completely compatible with wavelength-division-multiplexing (WDM), allowing WDM and mode-division-multiplexing (MDM) to be used simultaneously to further scale the aggregate bandwidth of a single link. This paper discusses a demonstration of high-speed data transmission by using a unique, multi-mode device engineered on a nanophotonic waveguide through a MDM transmission scheme. An aggregate bandwidth of 60 Gb/s transmission is realized by using 2 modal channels and 3 wavelength channels at 10 Gb/s with power penalties < 1 dB at the receiver.

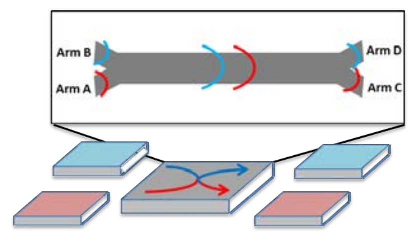

Fig. 1. Data transmitted on QTM mode, going from Arm A to Arm C and from Arm B to Arm D.

Experimentally, at each wavelength, laser light modulated at the two input ports are multiplexed into a single waveguide path to traverse the length of a multimode waveguide (MM-WG) and then demultiplexed to output dual sets of data. It is shown that crosstalk between channels is minimal through measurements performed on the demultiplexed ports of the MM-WG, a result of engineering the waveguide's geometry and effective index.

Performance of this device is measured by output coupling to a multi-core fiber and an-

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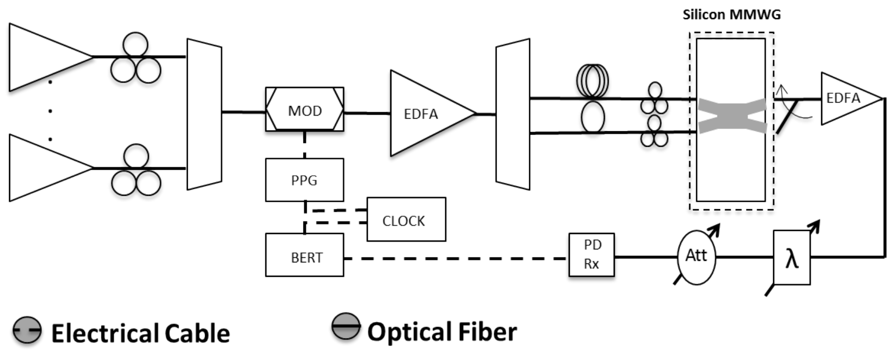

Fig. 2. Experimental Setup: Three wavelengths are muxed-demuxed at each arm of the multi-mode device. BER measurements and eye diagrams are taken at the output to the MMWG.

alyzed by measuring the power penalty and crosstalk between the two arms of the MM-WG demultiplexer. This experiment illustrates the performance benefit of channel-diversity afforded through optical MDM transmission across orthogonal channels in a single path, resulting in an increased dimensionality of the transmission data rate.

2 DEVICE

The experiment is composed of integrating a multimode device into a whole optical system. The mode multiplexer is realized via an asymmetric Y-junction device described in [4]. The Y-junction is designed with a branch angle of 3 degrees. Its dimensions of height by width of each arm are 250 nm by 450 nm for arm A, 250 nm by 550 nm for arm B, and 250 nm by 1 um for the multimode link.

For this angle and dimension, the device is inside the mode-sorting regime for quasi-transverse-magnetic (QTM) mode excitation [4,5], allowing each mode of the multimode link to be addressed by the multiplexer. Furthermore, by the property of time-reversal symmetry, residual crosstalk in the demultiplexer can be coherently suppressed at wavelengths where the relative phase difference between the even and the odd modes is equal to an integer multiple of 2π [4]. Using this approach, compact devices can achieve even crosstalk < -30 dB in the demultiplexer.

3 EXPERIMENTAL SETUP

Three wavelengths are combined to one fiber by using a wavelength-division-multiplexer and separate laser diodes. All signals are modulated with a 2^{31}-1 PRBS, 10 Gb/s data using a pulse-pattern-generator. The signals are amplified with an erbium-doped fiber amplifier (EDFA) before going through a 1.5 km spool of standard single mode fiber (SSMF) to decorrelate wavelength channels by 25 ps/nm. Two tributaries are formed with a 50/50 inline splitter. One arm has a delay of several bits from an additional 100 m of SSMF to decorrelate the two arms before entering the Si waveguide, with polarization controllers maintaining QTM.

A 38-micrometer pitch reducing optical fiber array (PROFA) is used to simultaneously couple both channels onto the chip. Approximately 10 dBm of input power is measured in each channel before the PROFA, and the entire device experiences an insertion loss of 28 dB, mostly due to mode mismatch between the 10 μm spot size of the PROFA and the tapered waveguide mode converter. A lensed tapered fiber is used at the output to select a single MDM channel for analysis. A tunable filter, EDFA, and another tunable filter are used to suppress ASE noise and isolate a single wavelength channel. The optical signal is passed through a variable optical attenuator (VOA) before it is converted to an electrical one by passing it through a transimpedance amplifier and a limiting amplifier (TIA-LA).

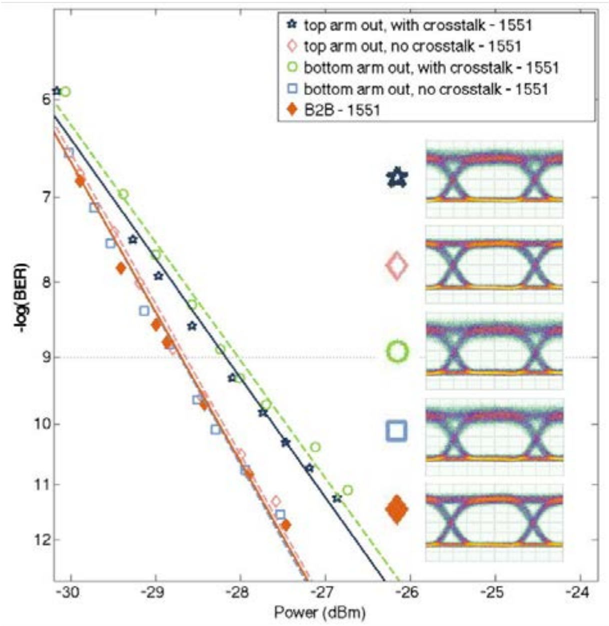

Fig. 3. BER graph of 1 operational wavelength across each arm

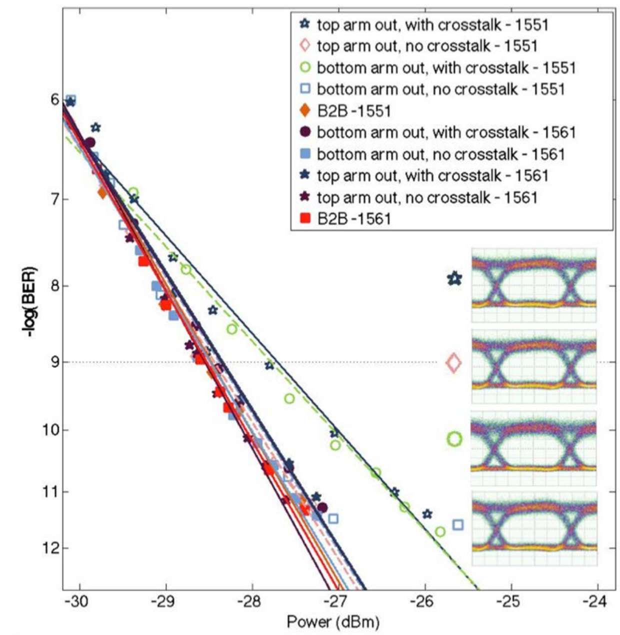

Fig. 4. BER graph of 2 operational wavelengths across each arm

4 RESULTS

The results of the experimental setup demonstrate the feasibility of using MDM and WDM simulataneously. The performance at the 10^{-9} BER point can be gauged from Figures 3, 4, and 5. In these plots, the BER is measured for each MDM channel for the case of 1, 2, and 3 WDM channels respectively. When 1 WDM channel is utilized with MDM, a power penalty of 0.6 dB is measured compared to the back-to-back (Figure 3). A 0.66 dB power penalty is measured for 2 WDM channels, and finally, from Figure 5, it can be seen that a 0.7 dB power penalty is realized using 3 WDM channels.

5 DISCUSSION

A negligible additional power penalty is realized from the addition of multiple wavelengths for each MDM mode. These results suggest that the technique is scalable to more wavelengths and the possibility of substantially increasing the on-chip bandwidth density. The low BER power penalties also show that low crosstalk is realized in the demultiplexer. This means that there is little crosstalk between channels along the MM-WG. Open eye diagrams further illustrate the high data integrity of the transmitted data.

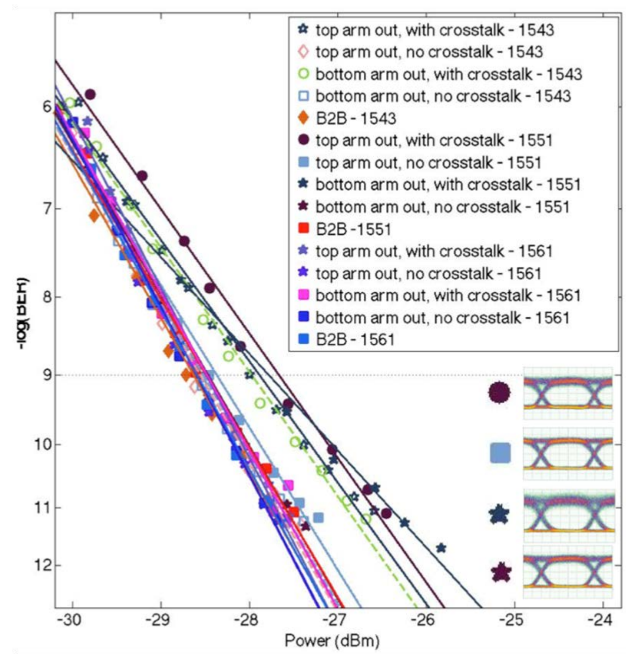

Fig. 5. BER graph of 3 operational wavelengths across each arm

Adjusting the power going into both channels of the waveguide was a major consideration when conducting the experiment in order to equalize performance. Unequal insertion loss between both arms of the multiplexer and the PROFA due to slight fabrication differences, alignment mismatch, and mode-dependent propagation loss lead to unequal distribution of crosstalk between the two MDM channels. We equalize the launch power in order to compensate for these differences in realizing identical levels of crosstalk at the receiver. This consisted of measuring the crosstalk in each arm with only a single MDM channel turned on, and adjusting the launch power of one arm in order to obtain equal levels of crosstalk in each channel.

6 Extension of Modes

Scaling the number of modes that can be supported on a device in a single waveguide is one possible direction for research. This can be realized by using the method described in [5] to explore the viability of making a 3x3 asymmetric Y-junction device for MDM. Accordingly, the device geometry is optimized by minimizing the multiple outfit factor (MOF), defined to be $\text{MOF} = \theta \sum_{i=1}^{N} \sum_{j>i}^{N} \frac{i-j}{\beta_i - \beta_j} \gamma_{ij}$, where N is the number of arms, i and j denote individual arms, and the divergence angle θ between adjacent arms is in radians. $\beta_{i,j}$ is the propagation constant of the fundamental mode and γ_{ij} is the evanescent decay constant of the fundamental mode between two arms.

The device with a 5-degree branch and dimensions of 250 nm $\times$ 1.6 um with length $\times$ width of 250 nm $\times$ 450 nm for arm 1, 250 nm $\times$ 520 nm for arm 2, and 250 $\times$ 680 nm for arm 3 is simulated. The resulting power spectrum is shown in Figure 6.

To verify the design, the crosstalk in each arm is modeled as a function of wavelength using both the effective index method and the 2D eigenmode expansion method and found to be <10 dB across the C-band, with a minimal value of -25 dB for each arm. The regions that overlap lower crosstalk with high extinction ratio indicate potential areas of optimal MDM-WDM operation across the device.

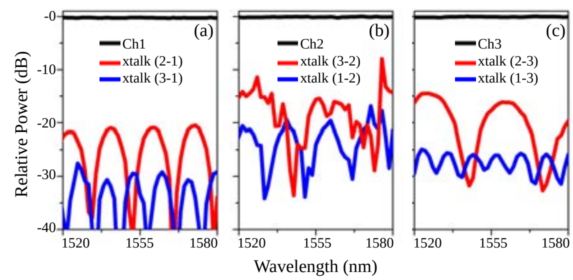

Fig. 6. Power Spectrum of a 3-mode Device

7 Conclusion

This is a singular, systems-level demonstration of error-free data transmission through a silicon photonic waveguide that adiabatically supports two modes simultaneously while transmitting up to three wavelength channels on each modal channel. This demonstration verifies the potential for doing wavelength-division-multiplexing and multimode-division-multiplexing to the advantage of a huge bandwidth increase over the same area with power penalty of <0.7 dB. As such, this system motivates Si, low-loss on-chip optical interconnects.

With further work in improving device characteristics and system design, there is the possibility to support even higher data rates with minimal additional loss by further scaling the number of modal channels and wavelength channels. This exciting work demonstrates the potential for integration of silicon photonic waveguides into existing electronic systems.

Acknowledgments

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