# Experimental Demonstration of Spatial Scaling for High-Throughput Transmission Through A Si Mode-Division-Multiplexing Waveguide

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**Abstract:** Scaling the throughput through a multimode waveguide is experimentally demonstrated by extending operation from 2 to 3 spatial modes. The asymmetric, y-junction device is shown to support transmission of an aggregate bandwidth of 3x10-Gb/s data.

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## 1. Introduction

The future of high-performance computing systems requires sustaining both speed and functionality for high volume data transmission. The electrical bottleneck due to rising power consumption for maintaining this growth in data rate can be potentially alleviated through the use of low-loss waveguides in silicon photonics. By adding a manifold factor to bandwidth, great strides can be made in the direction of scaling bandwidth at low energy costs.

Wavelength division multiplexing (WDM) has been the dominant direction in scaling the total bandwidth of a system. However, recent research has examined adding multiple modes on top of WDM, thereby leveraging the orthogonal degree of freedom inherent in the structure of the interconnect. Mode division multiplexing (MDM) and demultiplexing systems, then, have the capability to transmit multiple modes on-chip with minimal crosstalk leakage from one mode to the next. Designs have included asymmetric couplers [1], microring-resonators [2], and asymmetric y-junctions [3], the latter of which is utilized in this paper to multiplex and demultiplex 3 modal channels.

Data rates can be increased substantially for a given spatial density with these multi-mode devices (MMD). Previous demonstration has shown a silicon photonic interconnect with 2 modal channels and 3 wavelengths propagating data simultaneously [4]. In this paper, it is shown that it is possible to scale the waveguide from 2 modal channels, supporting 2x10-Gb/s data transmission with a power penalty (PP) of 2 dB, to 3 modal channels, supporting 3x10-Gb/s data transmission, but not without sustaining PP 3 to 5 dB greater than that of dual mode operation. With further design and fabrication optimization of the device, the PP can potentially be reduced.

## 2. Silicon Waveguide

An asymmetric, 3-channel Y-junction device designed as described in [4] was used in this experiment as a mode multiplexer and demultiplexer. Prior to testing, device characterization was done to find the optimal operating regimes that minimized the crosstalk between channels.

Each input channel is spread over both the even and odd modes of the multimode waveguide given a chosen angle and quasi-transverse-magnetic (QTM) excitation of the device [3]. One particular experimental difficulty was to match wavelength regions having low crosstalk due to its two neighboring waveguide channels for all three arms. Experimental complexity is increased by having to find wavelengths where all three arms exhibit low cross-talk, compared with two arms in the previous experiment. These crosstalk levels are illustrated in Fig. 3. As can be seen, slight shifts between optimal regions of operation for the two outer channels induce higher power penalties. Simulation work can be done to finetune the optimal wavelengths for each arm to ensure matching regions of operation.

## 3. Experimental Setup and Results

The experimental setup is shown in Fig. 1, while the BER measurements of all arms operating simultaneously, along with the respective eye diagrams for 1559.65 nm operation, is given in Fig. 2. In our setup, a continuous-wave (CW) tunable laser signal was modulated with a pulsed-pattern generator (PPG) to generate a non-return-to-zero (NRZ) $2^{31}$-1 pseudo-random bit sequence (PRBS) signal. The signal is then amplified by an erbium-doped fiber amplifier (EDFA).

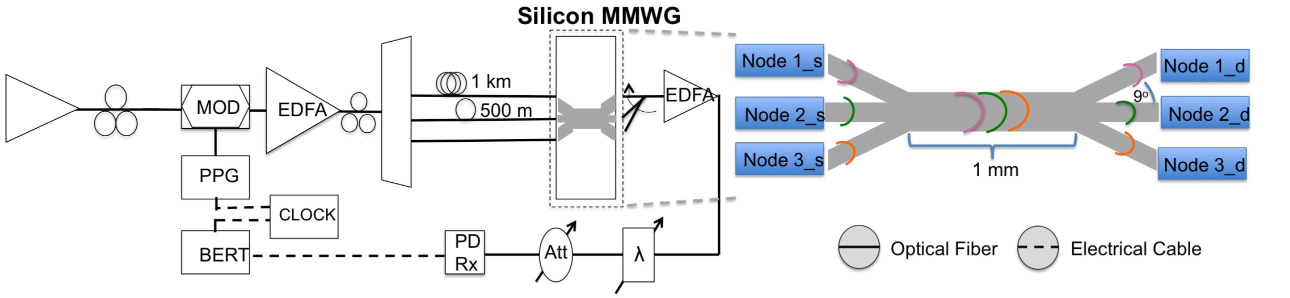


Fig. 1. Experimental setup, the integrated waveguide supporting 3 modes simultaneously, with data being transmitted on-chip along the Quasi-TM mode from Node1_s to Node1_d, Node2_s to Node2_d, and Node3_s to Node3_d, with indices denoting source and destination.

An inline 3-to-1 power splitter splits the signals into three channels, and a decorrelating standard single mode fiber (SSMF) of 1 km and 500 m, with one channel going straight through, were used to provide a many-bit delay amongst the three signals. A polarization controller (PC) ensures QTM mode excitation in the waveguide. A pitch reducing optical fiber array (PROFA) with 38 um pitch was used to simultaneously inject all three input Y-junction arms with a separate data channel. The PROFA was calibrated prior to use, to maximize coupling of all channels to the waveguide. The signal exiting the chip is alternately taken from various arms using a lensed tapered fiber, with ~22 dBm insertion loss, similar for all three arms. The signal is amplified by a low-noise-figure EDFA and filtered to reduce ASE noise. The signal is passed into a variable optical attenuator (VOA) to attenuate it over a range of powers for bit error rate (BER) measurements. The optical signal was received and converted to an electrical signal using a PIN-TIA avalanche photodetector (PD) followed by a limiting amplifier (LA) to amplify the signal going into the BER tester. A digital communications analyzer (DCA) was used to record eye diagrams, and the chip was bypassed for back-to-back (B2B) comparison.

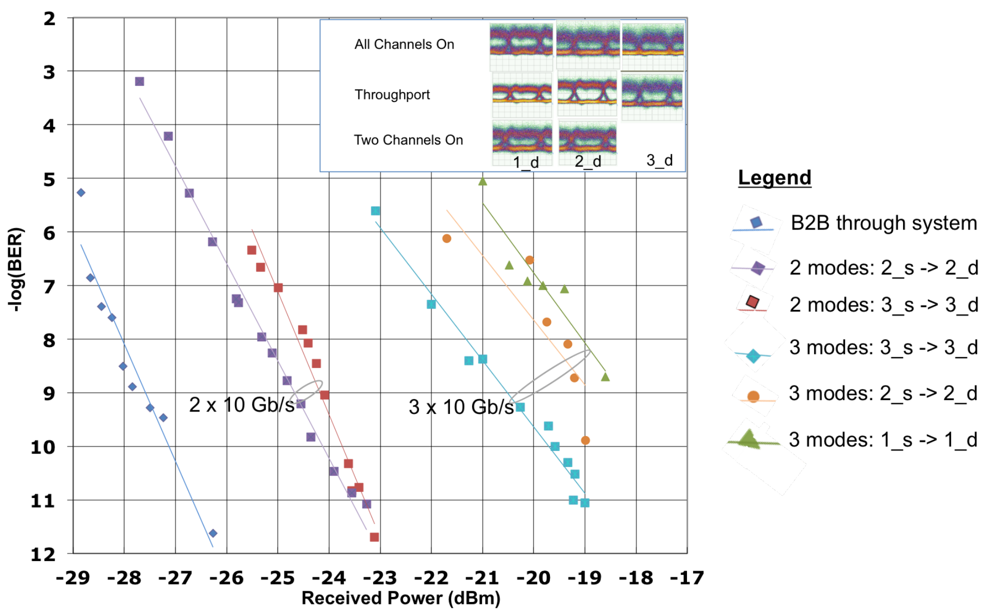


Fig. 2. BER measurement with two arms (1_s and 2_s) and three arms transmitting 10 Gb/s data simultaneously. Eye diagrams taken at the 3 channels (vert.) featuring labeled characteristics (horiz.).

When transmitting the signal along the three modal channels, the amount of crosstalk leaking from one modal channel to the next was minimized by choosing the spectral regions that exhibited minimal crosstalk (Fig. 3). Regimes with minimal crosstalk were chosen, keeping in mind some dynamical variation due to shifts in polarization over time.

Figure 3 provides an illustration of the level of crosstalk per channel. The case of a 2 mode MDM and 3 mode MDM operation are expressed. From these curves, the power penalty at BER = $10^{-9}$ average out to be 2 dB for 2 modes and

5 to 7 dB for 3 modes with respect to the system B2B. While the two mode system described in [4] exhibited a 0.6 dB PP in MDM operation, it is noted that regions were chosen in consideration of optimality for all three arms in this three modal arm device. Regions with lower amount of crosstalk could be chosen for just two arms. However, to maintain consistency, the 2 MDM operation was done on the same wavelength as the 3 MDM operation.

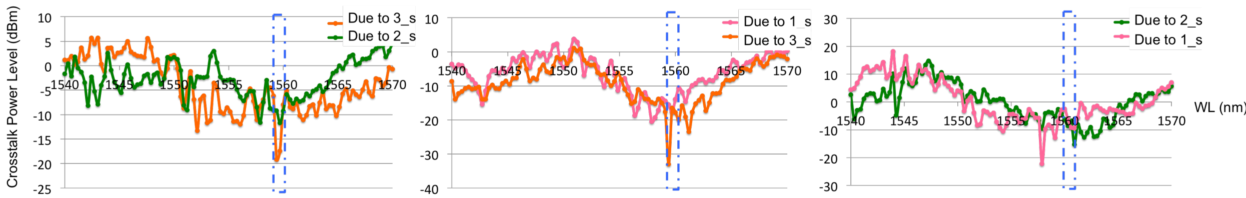


Fig. 3. Graphs of crosstalk level at 1_d, 2_d, and 3_d channels of the waveguide across varying wavelengths due to combinations of 1_s, 2_s, and 3_s. Dashed line indicates region selected for best crosstalk levels across all 3 channels.

## 4. Extending Modes for Mux-Demux Operation

Designing a waveguide for optimality is done by the procedure stated in [5]. In this approach, the author approximates the device geometry by minimizing a multiple output factor (MOF), defined as

$$\mathrm{MOF} = \theta \sum_{i=1}^{N} \sum_{j>i}^{N} \left| \frac{i-j}{\beta_i - \beta_j} \right| \gamma_{ij} \tag{1}$$

where $N$ is the number of arms, $i$ and $j$ denote individual arms, $\theta$ is the divergence angle between adjacent arms (in radians), $\beta_{i,j}$ is the propagation constant of the fundamental mode of an arm, and $\gamma_{ij}$ is the evanescent decay constant of the fundamental mode between two arms.

However, in this experimental demonstration, it was found that there were fewer wavelength regimes having low levels of crosstalk than expected. Further iterations will optimize the waveguide arm widths to ensure the wavelengths with minimal crosstalk levels of each arm overlap, while maintaining modal orthogonality. Also, future work in the area of MIMO and post-processing techniques [6] to achieve higher performance can be examined.

## 5. Conclusion

An experiment with on-chip, mode-division multiplexing having a BER of $10^{-9}$ through a high-speed optical system is demonstrated, allowing for scale up of the number of supported modes from two to three. In the shift towards integrating silicon photonics into current communications and computing systems, devices such as this spatially small 3x3 MMD device can sustain functional high bit-rate capability. The described system motivates the use of all-Si, low-loss on-chip optical interconnects. Further work will focus on improving device characteristics for supporting more modes with reduced penalty in an effort to achieve even higher data rates.

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