Towards Tbps Single-λ Interconnect by a Multimode Integrated Optical I/O on Silicon for Few-Mode Fibers

Hao Chen, Wu Zhou, Yeyu Tong*

Microelectronics Thrust, The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, Guangdong, PR China

**E-mail address: yeyutong@hkust-gz.edu.cn*

Abstract: A six-channel multimode integrated optical I/O supporting two orthogonal polarizations of LP_{01}, LP_{11a}, and LP_{11b} modes in a few-mode fiber was experimentally demonstrated, showing chip-to-fiber coupling efficiencies > –6.1dB for future Tbps-per-wavelength optical interconnects.

1. Introduction

Communication capacity of the single-mode fiber (SMF) based systems has been significantly enhanced by employing wavelength-division multiplexing, advanced multi-level modulation formats, and forward error correction (FEC), approaching the nonlinear Shannon limit [1]. Alternative physical dimensions have thus been investigated including different orthogonal modes in a multimode fiber (MMF) or few-mode fiber (FMF), which is known as mode-division multiplexing (MDM). Although there have been notable advancements in mode multiplexers through the use of photonic lanterns, 3-dimensional waveguides, and multi-plane light conversion [2], implementing MDM techniques in optical fibers remains a challenge, especially in data centers where a compact, cost-effective, and scalable mode multiplexer is required. Prior studies have shown that integrated grating couplers serving as a multimode optical I/O can also be used as mode multiplexers for FMFs. However, it is difficult to attain high coupling efficiencies while supporting more than four spatial channels [3–5]. Here, we show the first experimental demonstration of a multimode integrated grating couplers for FMFs supporting six linearly polarized (LP) modes, including $LP_{01\text{-}x}$, $LP_{01\text{-}y}$, $LP_{11a\text{-}x}$, $LP_{11a\text{-}y}$, $LP_{11b\text{-}x}$, and $LP_{11b\text{-}y}$. The proposed multimode optical I/O is based on a 2-dimensional grating coupler on the silicon photonics platform with experimental peak coupling efficiencies above –6.1 dB for all the optical modes. To demonstrate the feasibility of Tbps-per-λ optical interconnects in the future, a proof-of-concept experiment is conducted, where each of the six spatial channels is encoded with a 180-Gbps four-level-pulse amplitude modulation (PAM-4) signal. The bit error rates (BERs) at the receiver side are all below the hard-decision FEC (HD-FEC) coding limit. The proposed multimode optical I/O shows great promises for future low-cost, high-volume, and small-form-factor optical interconnects applications in datacenters.

2. Device Design and Simulation

The 2D multimode grating coupler is designed for a graded-index two-mode FMF provided by *OFS*, which has a mode field diameter of 11.0 µm for both the LP_{01} and LP_{11} modes. Selective mode excitation of the LP_{01} and LP_{11} mode is implemented by out-of-plane coupling of the two counterpropagating quasi transverse-electric (TE) modes TE_0 and TE_1, respectively, as shown by Fig. 1(a). For example, $LP_{01\text{-}x}$ mode can be launched by two counterpropagating TE_0 mode with no relative phase shift, while $LP11_{b\text{-}x}$ would be launched when the relative phase shifts turn to π. By using the two counterpropagating TE_1 modes with zero relative phase shift, $LP_{11a\text{-}x}$ mode can be coupled into the FMF. Because the TE_0 and TE_1 modes exhibit similar effective indices in the waveguide grating with

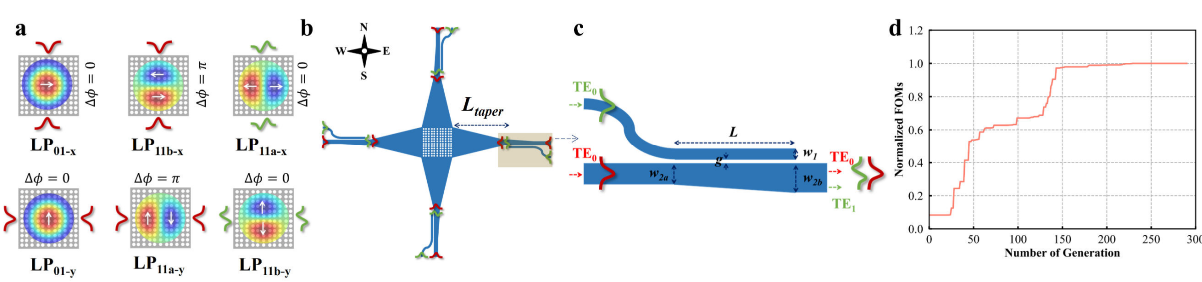

Fig. 1. (a) Illustration of fiber mode multiplexing using the multimode grating coupler. (b) Schematic of integrated multimode optical I/O, consisting of a two-dimensional waveguide grating, tapered adiabatic directional couplers, and asymmetrical directional couplers. (c) Schematic of the asymmetrical directional coupler for TE_0-TE_1 mode multiplexing. (d) Evolutional diagram of normalized coupling efficiency of the grating coupler.

a width of 13μm, they can be effectively diffracted relying on the same grating region. The integrated multimode optical I/O, comprising of four asymmetrical directional couplers (ADCs) and linearly tapered waveguides with a length of 350 μm, is illustrated in Fig. 1(b). The 2D multimode grating coupler is used for mode diffraction. The phase difference between the two counterpropagating TE modes is controlled by a heater-based optical phase shifter. The corresponding excitation conditions of each fiber LP mode are illustrated in Fig. 1(a). The TE_0-TE_1 mode multiplexer is implemented by the tapered ADCs as shown in Fig. 1(c). Our design employs a perfect vertical coupling approach to ensure consistent coupling performance for all optical modes originating from the four waveguides placed orthogonally. Genetic algorithm is used to chirp the grating periods of the multimode grating coupler working at around 1550 nm. The corresponding evolutional diagram against the iteration generations is shown in Fig. 1(d).

3. Fabrication and Experiment results

The multimode optical I/O is fabricated on silicon-on-insulator (SOI) wafer with a buried oxide thickness of 2μm. The top crystalline silicon layer has a thickness of 220 nm. The low-index refractive index region is formed by shallow-etched holes with an etching depth of 70nm. Fig. 2(a) shows the microscopic image of the multimode optical I/O for selective mode launching, which includes the input single-mode grating couplers, beam splitters, tunable optical phase shifters based on heaters, ADCs, linearly tapered waveguides, and the 2D multimode grating coupler. The measured chip-to-fiber coupling loss spectra for LP_{01}, LP_{11a}, and LP_{11b} modes in the x polarization is presented in Fig. 2(b), showing a peak experimental efficiency of −3.5 dB, −6.1 dB, and −4.3 dB at 1532nm, 1517nm, and 1515nm respectively. As the grating utilizes a symmetric structure for the orthogonal polarizations, similar coupling efficiencies for the y-polarized LP modes are obtained. The scaning microscopic image of the multimode grating coupler is shown in Fig. 2(c). To validate that the selective launching of the LP modes in different polarizations, an infraded camera with a 10× microscope objective is utilized to capure the optical field profile of the FMF when using the ingrated multmode optical I/O. As shown by Fig. 2(d), the multimode optical I/O can selectively launch the LP mode in a FMF. For a proof-of-concept demonstration of future Tpbs-per-λ optical interconnects, Fig. 3(a) shows the experimental setup when each of the 6 spatial channels is working at a data rate of 180-Gbps with PAM-4.

At the transmitter side, a tunable laser source centered at 1530 nm is utilized with a $LiNbO_3$ Mach-Zehnder Modulator (MZM) to modulate the optical signal. An arbitrary waveform generator (Keysight M8199A) with a sampling rate of 256GSa/s generates the PAM-4 electrical signal, which drives the MZM through an electrical amplifier (EA) with a peak-to-peak voltage of approximately 3.5V. The bit sequence is initially mapped to PAM-4 symbols, and a training sequence is added to the PAM4 symbols to synchronize at the receiver end. The signal is then resampled and shaped with a raised cosine (RC) filter, with a roll-off factor of 0.12 for 180-Gbps PAM-4 transmission. Pre-equalization is performed at the transmitter end to compensate for high-frequency fading. The modulated high-speed single-mode optical signal is launched into the photonic chip with a polarization controller (PC) to maximize coupling efficiency. Selective mode launching of the FMF is implemented by controlling the integrated phase shifters using a source measurement unit (Keithley 2410). The FMF has a length of 5 meters in our experiment.

At the receiver side, a fiber-based photonic lantern is then used to demultiplex the multimode signals into three SMFs, where one of the optical ports is used with an erbium doped fiber amplifier (EDFA). The optical signal power is amplified to ~8 dBm. Before signal detection by a photodiode (PD) with 70 GHz bandwidth biased at –3V, a variable

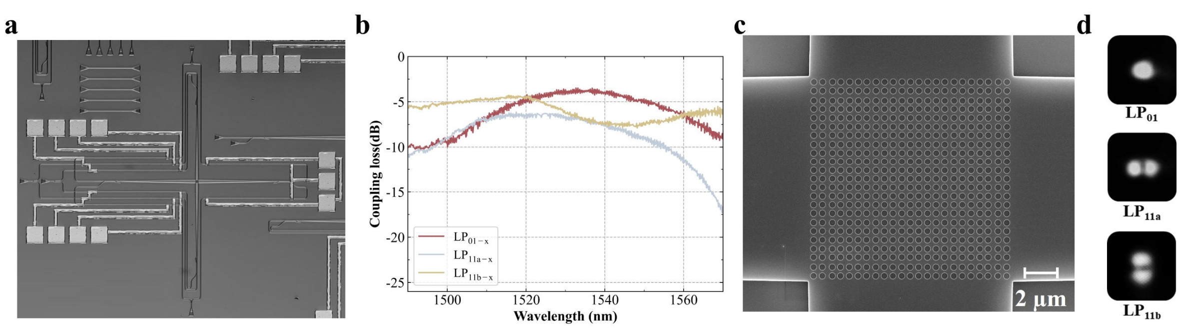

Fig. 2. (a) Microscopic image of the integrated silicon multimode optical I/O, including input single-mode grating couplers, beam-splitters, asymmetrical directional couplers, linearly tapered waveguides, multimode grating couplers, and tunable heaters with bondpads for phase control. (b) Chip-to-fiber experimental coupling efficiency spectra for LP_{01}, LP_{11a}, and LP_{11b} modes in x polarization. (c) Scanning microscopic imaging of the multimode grating couplers with 70-nm shallowly etched circular holes. (d) Optical field profiles of the FMF captured by an infrared camera with 10× objective lens when various LP modes are selectively excited by the integrated multimode optical I/O.

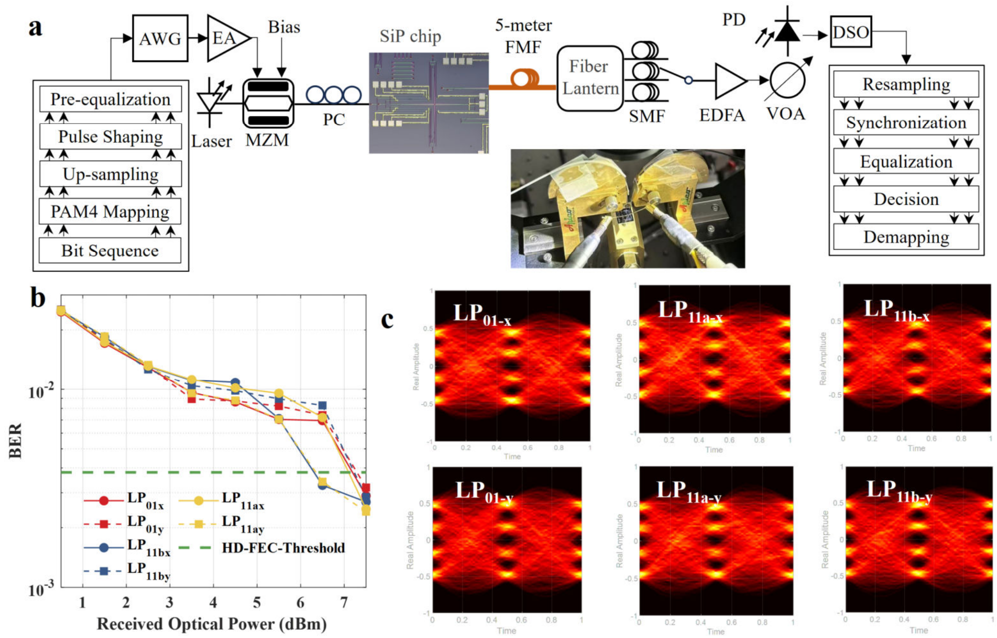

Fig. 3. (a) Experimental setup for proof-of-concept demonstration of Tbps-per-λ optical interconnects, including AWG: arbitrary waveform generator, EA: Electrical amplifier, SSMF: standard single-mode fiber, FMF: few-mode fiber, EDFA: erbium-doped fiber amplifier, VOA: variable optical attenuator, PD: photodiode, DSO: digital storage oscilloscope. (b) Bit error rate (BER) against the received optical power for 180Gpbs PAM-4. (c) Eye diagrams of the 180Gbps PAM-4 for the 6 LP modes in different polarizations.

optical attenuator (VOA) is used for BER curve measurement. The received signal is sampled by a digital storage oscilloscope (DSO) with a sampling rate of 256GSa/s. Offline digital-signal processing is performed, including resampling, symbol synchronization and adaptive equalization, and BER counting. A three-order memory polynomial equalizer (MPE) is used here to mitigate the signal impairment resulting from inter-symbol interference. BER of various LP modes against the received optical power is shown in Fig. 3(b). For all the LP modes in the two orthogonal polarizations, BERs below the HD-FEC threshold at 3.8×10^{-3} can be observed when the received optical powers is larger than 6.5 dBm. Fig. 3(c) shows the recovered eye diagram of the PAM-4 signal for each LP mode.

4. Conclusion

In this work, we have demonstrated a six-channel multimode optical I/O on the silicon photonics integration platform. The multimode optical I/O has the capability to selectively launch the full set of LP modes in the two orthogonal polarizations in a two-mode FMF. High experimental coupling efficiencies ≥–6.1dB for all the LP modes were obtained. A proof-of-concept demonstration of Tbps-per-λ interconnect was realized by using 6 channels at the same wavelength. Mode demultiplexing and signal descrambling will be needed in the future MDM communication systems. The proposed multimode integrated optical I/O shows great potential for future cost-effective optical interconnects.

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5. Reference

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