Mode-Selective Reconfigurable Optical Add-Drop Multiplexers Experimentally Validated with 40 Gbps NRZ/PAM4

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Abstract: We experimentally demonstrate a mode-selective ROADM for two transverse-electric modes using a mode-selective phase shifter in the switch. We show 40 Gbps NRZ transmission and 20 GBaud PAM4 transmission for two simultaneously transmitted optical modes.

1. Introduction

The escalating demand for data transfer capacity remains a major challenge to be addressed in today's data communication systems. This necessitates the deployment of sophisticated modulation techniques to enhance data capacity per symbol, while also expanding capacity through additional wavelength channels via Wavelength Division Multiplexing (WDM). Furthermore, the emerging paradigm of Mode Division Multiplexing (MDM) introduces a novel dimension by harnessing spatial multiplexing, achieved through employing multiple orthogonal spatial modes [1]. These modes serve as orthogonal communication channels within multimode optical waveguides, free space, and few-mode fibers. Towards employing MDM in datacom systems, data transmission at a rate of 1.12 Tb/s has been achieved using four transverse electric (TE) modes via chip-to-fiber couplers and a few-mode fiber [2]. A recent demonstration showcased a 3D polymer waveguide that can couple three TE and one transverse magnetic (TM) modes to a few-mode fiber, supporting data transfer up to 1.92 Tb/s through the combined use of WDM/MDM [3]. In addition to datacom, MDM can also contribute to enhancing accuracy in programmable optics by leveraging higher-order modes for optical phase monitoring [4]. And more recently, it has been proposed in integrated quantum optics, offering an extra layer of freedom for encoding quantum information [5, 6].

The Reconfigurable Optical Add/Drop Multiplexer (ROADM) introduced in 2000s for WDM networks responded to evolving network traffic demands and to provide network flexibility [7]. ROADMs enable remote path modification of optical wavelength channels through wavelength-selective switches, allowing the addition and removal of specific wavelengths at a location in response to changes in traffic patterns. As a successor to WDM, the WDM/MDM network requires a "mode-selective switch" to perform a similar operation (see fig. 1). Despite significant progress in the development of MDM components in the realm of silicon photonics (SiPh), selectively accessing specific modes without causing unwanted interference with others has proven to be challenging. Modal crosstalk becomes even more pronounced when one needs to extract the fundamental mode from the multimode bus waveguide while leaving the higher-order modes unchanged. Recent approaches have employed modal field redistribution to effectively enable selective access to different modes by confining them to distinct regions of the bus waveguide [8]. Although efficient, this technique does employ energy redistribution among transverse modes within the waveguide. In this study, we present a mode-selective switch designed to route various modes to distinct ports without redistributing the modal fields. This is achieved by utilizing a mode-selective thermo-optic phase shifter (MSTOPS) capable of applying distinct phase shifts to individual modes [9, 10]. By incorporating MSTOPS within a Mach Zehnder interferometer (MZI), we successfully demonstrate the selective addition and removal of the first two TE modes (TE_0 or TE_1) from a multimode bus waveguide in SiPh.

2. Design and Fabrication

Figure 1 (b) shows the schematic of the mode-selective switch. The switch is a Mach-Zehnder interferometer (MZI) comprising two multimode interferometers as 3-dB splitter/combiners. In one arm, we used two cascaded thermo-optic phase shifters (TOPS). The mode-insensitive TOPS (MITOPS) applies an identical phase shift to both TE_0 and TE_1. The MSTOPS is a (SWG)-based TOPS, in which TE_0 passes through the center of the TOPS filled with Silicon (Si), while TE_1, which is less confined, passes through the two sides with a subwavelength grating (SWG) periodic structure composed of Si and Silicon dioxide (SiO_2). Due to the one-order-in-magnitude difference in the thermo-optic coefficients between Si and SiO_2, TE_0 and TE_1 experience different phase shifts in the MSTOPS with a fixed ratio over temperature and wavelength. We have previously demonstrated that for an SWG duty cycle ratio of 0.4, MSTOPS applies approximately 1.44 times larger phase shift to TE_0 compared to TE_1 [10]. The design parameters of MSTOPS are shown in the subset of fig. 1(b) and thoroughly discussed in [10]. Considering the TE_1 phase shifts of φ and δ imposed by the cascaded MITOPS and MSTOPS modules, respectively, the total phase shift undergone by TE_1 is $\varphi + \delta$, while it is $\varphi + 1.44\,\delta$ for TE_0. By applying different biases to MITOPS and MSTOPS, and thus different values of φ and δ, we can achieve arbitrary and distinct phase shift values for TE_0 and TE_1. As shown in Figure 1(b), the mode-selective switch can be configured to either pass or drop both modes, or drop one of them. In a reversed configuration, it can also be used to combine two modes applied to the two inputs of the MZIs. As shown in [10], the SWG region in the MSTOPS is designed to maintain the modal field distribution of the modes without converting them into supermodes, while introducing distinct temperature coefficients for TE_0 and TE_1. The design is fabricated at the Applied Nanotool (ANT) foundry using an electron beam lithography. The silicon layer thickness is 220 nm. The TOPSs employ 200 nm thick Titanium Tungsten (TiW) metal heater deposited on top of the 2.2 µm oxide cladding.

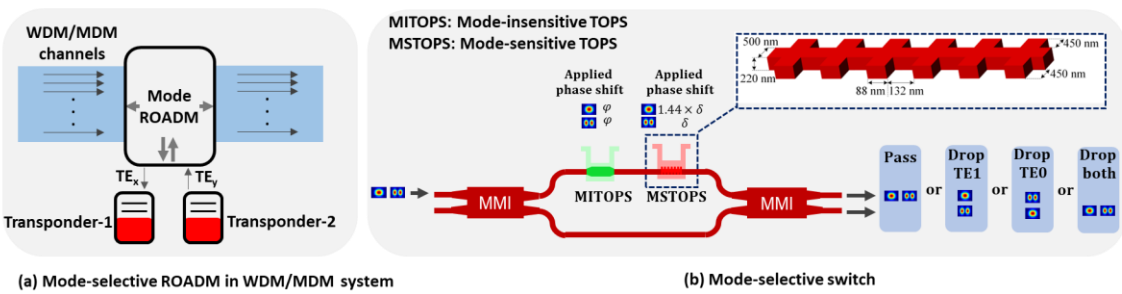

Fig. 1. (a) Mode-selective ROADM in a WDM/MDM system dropping TE_x channel and adding TE_y, (b) schematic of a mode-selective switch used in Mode-selective ROADM capable of adding/dropping TE_0 or TE_1

3. Experimental Validation

For continuous wave (CW) measurements, we couple the fundamental mode to the chip through grating couplers. Adiabatic directional coupler-based mode multiplexers (MUX) and de-multiplexers (deMUX) are employed at the input and output for mode conversion. In Figure 2(a), we display the normalized transmission measurements for MSTOPS with a fixed MITOPS bias current and for MITOPS with a fixed MSTOPS bias current. Figure 2(b) illustrates 2-D transmission contour maps s at 1560 nm for TE_0 and TE_1 as a function of the current bias applied to the MITOPS and MSTOPS. The contours are normalized to peak transmission. From the transmission contours, the bias points indicated by the circles correspond to the state where TE_0 is in the crossbar state, and TE_1 is in the bar state (i.e., only TE_0 is dropped by the mode-selective ROADM). Similarly, the diamond and triangle symbols represent the states of dropping TE_1 and passing both modes, respectively. Notably, it can be observed that arbitrary transmission levels for the two modes are achieved by appropriately adjusting the bias of MITOPS and MSTOPS. At 1560 nm, the insertion loss and crosstalk are 2 (1.5) dB and -18.2 (-16) dB for TE_0 (TE_1).

Figure 3(a) presents the testbed used for payload transmission over the mode-selective switch. Payload transmission is carried out under the condition where TE_0 is in the bar state and TE_1 is in the cross state (corresponding to the diamond bias point in Figure 2(c)). Similar results are obtained for transmission in other states. In Figure 3(c), eye diagrams for TE_0 and TE_1 transmission using PRBS31 non-return-to-zero (NRZ) and PRBS31Q pulse-amplitude modulation (PAM)-4 are shown for the two modes. Payload transmission is performed with both modes being simultaneously transmitted through the switch such that degradation due to modal crosstalk is present. Corresponding bit error rate (BER) curves are presented in Figure 3, demonstrating error-free NRZ transmission at 16 Gbps and a BER below 10^{-6} for 40 Gbps. For PAM4 transmission, the BER still falls below the KP4 forward error correction (FEC) limit of 2.2×10^{-4} for TE_0 and even below the HD FEC limit of 3.8×10^{-3} for TE_1 at 20 GBaud. This innovative work serves as a proof of concept for a mode-selective switch and was constrained by the single-etched SOI fabrication resulting in grating coupler with 8 dB of coupling loss. This led to challenging fiber-to-fiber insertion loss subsequently impacting the BER measurement from the amplified spontaneous emission (ASE) noise from the required EDFA optical gain in the testbed. Additionally, coupling in and out of the chip occurs at fundamental mode, with adiabatic mode multiplexers/demultiplexers converting higher-order modes to fundamental modes. Lower modal crosstalk in the mode-selective switch can be achieved through multimode couplers and few-mode fibers at the interface, eliminating the effects of mode multiplexers/demultiplexers.

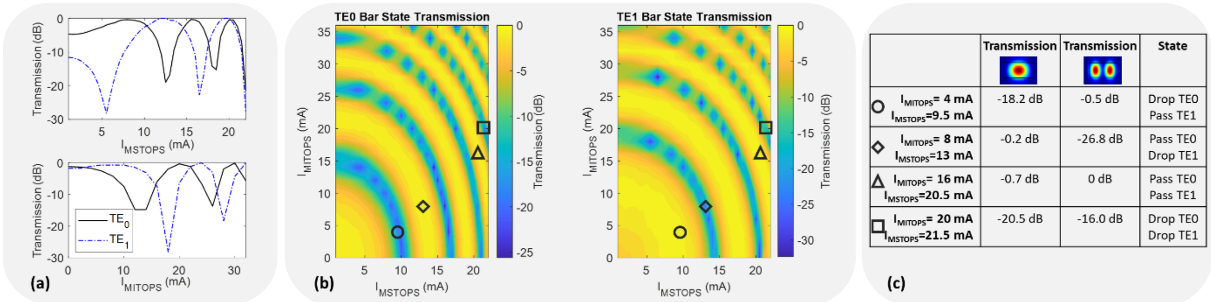

Fig. 2: (a) Normalized optical transmission of the mode-selective switch for TE_0 and TE_1 at 1560 nm, (b) Transmission contours of the switch for both modes (○: TE_0 drop state, ◊: TE_1 drop state, Δ: all-pass state, □: all-drop state, (c) Summary table of bias points and normalized optical transmission for all four ROADM operational states.

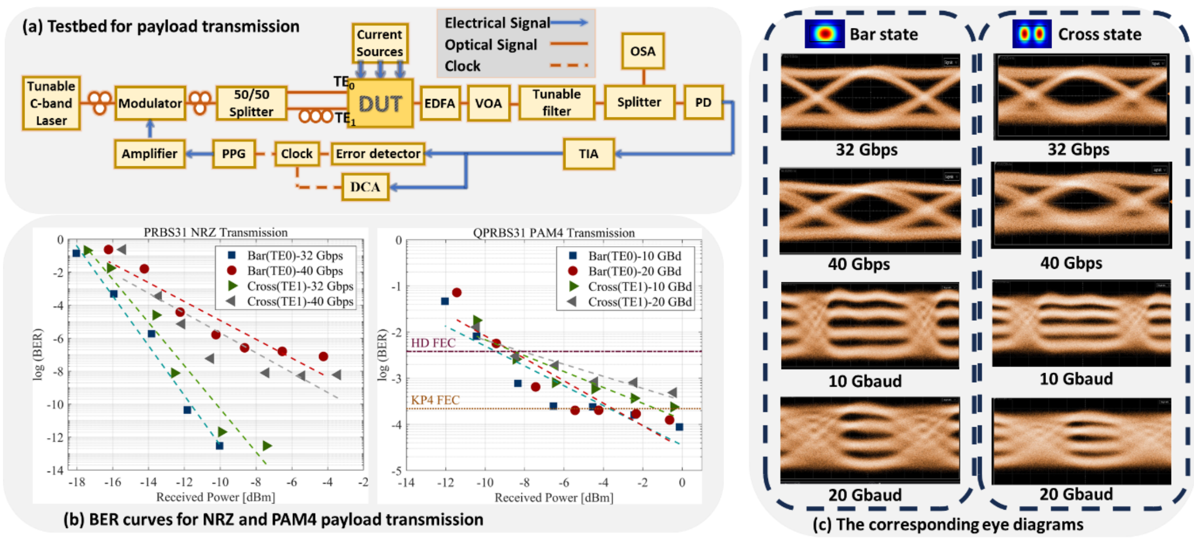

Fig. 3. (a) Testbed for the two-mode payload transmission, (b) NRZ and PAM4 BER curves for TE_0 (Bar state output port) and TE_1 (crossbar state output port), (c) corresponding eye diagrams with 100 mV/div y-axis. (BER: Bit Error Rate; PRBS: Pseudo-random Bit Sequence; VOA: Variable Optical Attenuator, OSA: Optical Spectrum Analyzer, PD: Power Detector, PPG: Pulse Pattern Generator, DCA: Digital Communication Analyzer, TIA: Transimpedance Amplifier, EDFA: Erbium Doped Fiber Amplifier).

To summarize, we successfully demonstrated a mode-selective switch for TE_0 and TE_1, suitable for mode-selective ROADM applications. The TOPS-based switch allows independent phase shifts for two optical modes without modal field redistribution. Our experimental validation includes error-free 32 Gbps PRBS31 NRZ and 40 Gbps NRZ with BER below 10^{-6}, as well as 20 Gbaud PAM4 payload transmission.

4. References

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