Polarization-insensitive, silicon-photonics circuit, four-mode spatial multiplexer matched to a rectangular core fiber

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Abstract: We design and test a SiPh mode multiplexer circuit, utilizing 3µm-thick ridge waveguides having low polarization dependence. The multiplexer achieves low loss (2-3dB) and low PDL (<0.8dB) across the C-band. Output modes are coupled to rectangular core fiber. © 2024 The Author(s)

1. Introduction

Mode-division multiplexing (MDM) is a promising path towards increased-capacity fiber communications, facing two key challenges: Mode multiplexing typically requires spatial manipulations that are often implemented using free-space optics [1], but this solution is incompatible with the size scale required for pluggable optics; Furthermore, mode-mixing, whether in the fiber medium or the ancillary components, requires additional digital signal processing and coherent reception to unravel the mixing, which impacts delay, power and cost. Both challenges can be addressed by employing a rectangular core fiber (RCF), whose geometry is designed to support a single mode confined along the rectangle's height and multiple spatial modes along the rectangle's width, the number of modes commensurate with the width. The supported spatial modes are distinct, being only polarization degenerate. The supported modes have well-separated propagation constants [2], strongly reducing the likelihood of mode mixing between mode groups, rendering MIMO processing to within each polarization mode group (as occurring in SMF-based coherent systems today). Furthermore, the one-dimensional spatial mode information can be transferred to photonic integrated circuits (PIC) for performing mode mux/demux on chip.

Recently a demonstration of a WDM/SDM RCF link utilizing Si PIC transmitter and receiver was demonstrated [3], with inverse designed mode multiplexers and grating couplers. However, the inverse designed components, albeit extremely compact, supported only the TE polarization state. In lieu of free-space, guided multiport interference with phase adjusters has been demonstrated for mode demultiplexing [4], with on-chip polarization diversity. Alternatively, sequential mode stripping of higher order modes from a bus waveguide can be employed [5], further separated to its two orthogonal polarizations.

Here we design, implement and test a low-loss, dual-polarization mode mux/demux based on mode stripping from a bus waveguide utilizing 3µm thick silicon photonics platform [6]. The PIC is further interfaced to a RCF by edge coupling, demonstrating mixing-free excitation of the fiber modes. Such capabilities enable efficient MDM fiber communication using existing SMF transceivers, in compact form factor and eliminating the need for MIMO-DSP.

2. Silicon-photonics mode multiplexer design

We adopt the 3µm thick silicon platform solution in this work for its favorable attributes: Using a ridge waveguide design, the propagation loss is very low, the polarization dependencies are low and mode profiles nearly identical, greater tolerance to fabrication and dimensional variations, and facilitates direct butt-coupling with optical fibers. On the other hand, bend radii must be sufficiently large and waveguide tapers must be moderate, yielding designs that occupy a large footprint. Our design, inclusive of a multimode waveguide taper for directly coupling to RCF, utilizes the full chip length (9.5mm), Fig. 1-D. (The width is determined solely by the single mode waveguide/fiber pitch).

The RCF, as well as our multiplexer, supports four polarization-degenerate spatial modes. We simulate the SiPh ridge waveguide dispersion curves, Fig. 1-A, showing the typical excitation of additional modes as the width increases. Being highly confined within silicon, the effective indices do not vary much. Hence, to selectively excite one mode at a time, the coupling strength must be low and the evanescent coupler long to gain the required selectivity and efficiency. In our case, the couplers are about 0.5mm long, with additional range required for the access single mode waveguide to approach the multimode bus waveguide given the bend radius limit. We establish the modes' momenta at the couplers at n_{eff}=3.4525, which sets the bus and access waveguide widths at each coupler position (see thin black lines). This position ensures good separation/selectivity, given the dispersion curves. The guided modes' field profile within the thick silicon ridge waveguide, at ridge width ~9µm, is shown in Fig. 1B. The evanescent coupling of the 3rd mode to the access waveguide, over the coupler length, appears in Fig. 1C. Complete transfer of energy from the higher order mode in the bus waveguide to the single mode waveguide is achieved. In order to support the multiplexing of two polarization states, the single mode waveguide in the coupler region is slightly tapered, while keeping the distance of the two ridge edges from one other constant for fabrication consistency. The complete mux, Fig. 1D, is terminated by a long adiabatic taper designed to reach a width that best matches the RCF mode profiles. The RCF core is 32μm wide, but being a low index contrast design, its modes are best matched to the Si ridge waveguide at 36μm width (Fig. 1E). The taper expands the ridge waveguide width from 9μm to 36μm over ~3.5mm length, doing so adiabatically as to not excite higher order modes in the taper.

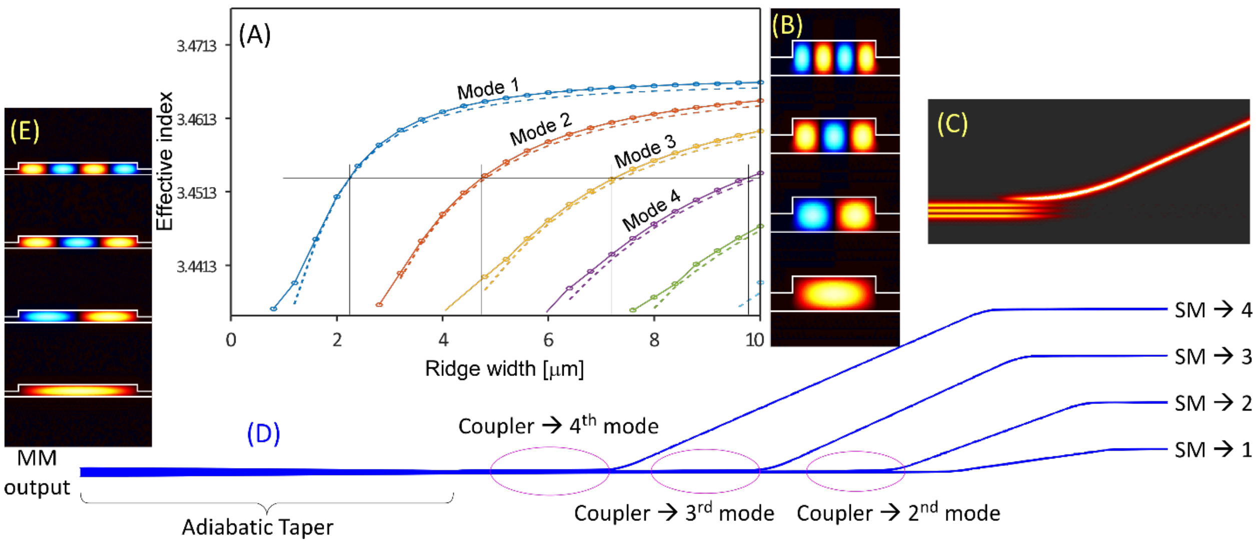

Figure 1 – Design of mode mux: (A) Dispersion curves of silicon photonics ridge waveguides. Horizontal line denotes design condition for coupling between fundamental and higher order modes. (B) Profiles of supported modes in 10 mm ridge width. (C) Simulation of evanescent coupling of 3rd spatial mode to matched single mode waveguide. (D) Design of four-mode mux by sequential evanescent couplers, with length compressed 50%. Adiabatic taper designed to match the modal distribution of RCF. (E) Profiles of first four spatial modes in 36 mm ridge width.

The chip was designed using simulation tools from Lumerical (MODE, EME and FDTD) and optimized to achieve excellent performance specifications over the C-band (1528-1563nm). Each coupler required fine tuning the design in order to support the wavelength range and the two polarizations. The simulated insertion loss for each mode is better than -0.1dB (Fig. 2A). The modal crosstalk, which originates mostly at the taper, is below -29dB (Fig. 2B). This value is sufficiently low to suppress coherent crosstalk impairments. Note that modal crosstalk, or scattering, is more pronounced between modes of same symmetry: symmetric modes 1↔3, and antisymmetric modes 2↔4.

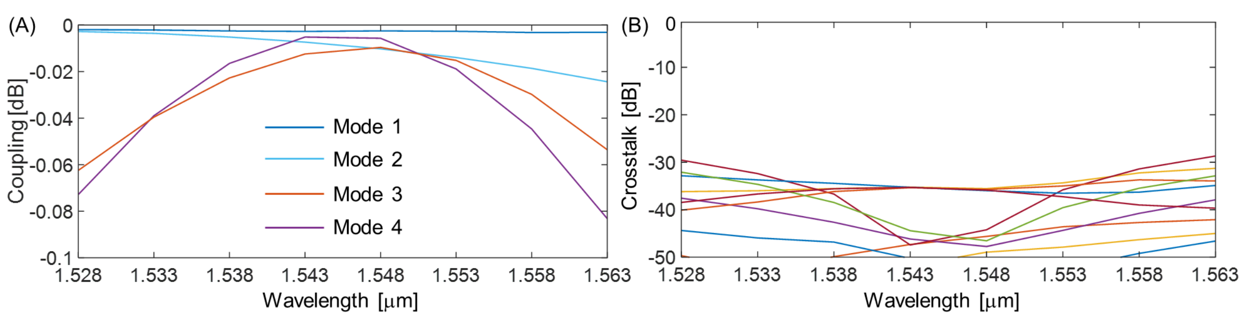

Figure 2 – (A) IL of four-mode spatial multiplexer across C-band. (B) Modal crosstalk to other modes than target.

3. Characterization of SiPh four-mode spatial mode mux

Following MPW fabrication at a commercial foundry (VTT), SiPh chips were tested in our lab. Chips were mounted on vacuum chuck and the single mode waveguides were excited individually with a single-mode lensed fiber. The multimode output was collimated with a microscope objective and split into two outputs with a beamsplitter. One output was used for direct NIR imaging and the other for power measurements with a broad area sensor. A polarization controller on the input side allowed us to set any polarization state. All power measurements are referenced to a straight single mode waveguide, hence our measurements attempt to assess on-chip losses.

The output power from the chip, normalized to the reference waveguide, exhibited an excess loss between -2.2dB and -2.9dB across the 1530-1560nm range and for all spatial modes, attributed to the on-chip multiplexing operation. Slight variation due to coupling efficiency variations from port to port may impact this assessment, though high quality translation stages and piezo actuators were used to minimize this. The PDL was measured by scrambling the polarization state across the Poincare sphere and finding the extremum difference. PDL was below 0.8 dB across the wavelength and mode ranges. Interestingly, there is no clear trend in the graphs, i.e., a better performing mode or wavelength (Fig. 3A). Images of the output facet, Fig. 3B, show the clear signature of the expected spatial modes. There is no evidence of other mode excitations in these images, even if we increase the power significantly and over saturate the image. Using a camera as an assessment tool is imprecise, due to its limited dynamic range.

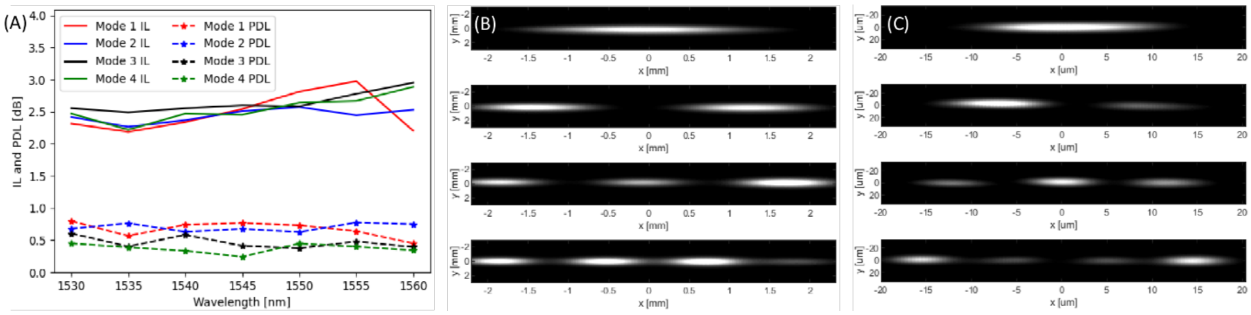

Figure 3 – Characterization of SiPh mode mux: (A) IL and PDL per mode and wavelength. (B) Images of output chip facet at individual excitation. (C) Images of RCF output facet, after mode excitation by butt-coupling to SiPh chip.

The RCF (~5m long) was then butt-coupled to the chip. In this work we matched the modal information in the horizontal direction but made no attempt to match the mode heights. Hence, we do not provide a coupling loss and focus instead on the modal excitation. The RCF needs to be accurately placed along the horizontal axis, as a misalignment along this axis leads to mode mixing [2]. The greatest alignment sensitivity is achieved when exciting the fourth mode, as it carries the highest spatial information. Alignment is done by observing the modal distribution at the RCF's distal end. Vertical axis alignment is not critical, as it does not lead to mode mixing and due to the vertical mode size of the RCF (~6μm) is not too sensitive for good coupling. We then acquire images of the individually excited fiber modes (Fig. 3C) and again achieve pure modal profiles, as limited by the imaging dynamic range.

4. Conclusions

The key attributes of the Si PIC spatial mode multiplexer of high modal purity in the multiplexing operation, preserved through the tapering to meet the RCF dimensions, and in coupling to the fiber have been achieved. This is critical to satisfying MIMO-free reception of MDM communication channels. The excellent performance of the mode multiplexer—low IL and PDL—is further mode and wavelength insensitive. This will enable efficient implementations of high capacity WDM-SDM communications, applicable towards datacenters and computing clusters, and possibly expanded towards campus and metropolitan range scales. Moreover, the high purity modal operations allow for quantum states to be carried and preserved across the spatial modal basis.

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