Design and Fabrication of a Bi-directional Mode-Division Multiplexer (BMDM) for Optical Interconnects

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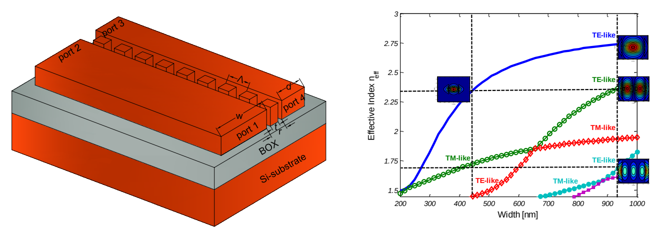
***Abstract*—A bi-directional mode-division multiplexer (BMDM) based on strip waveguides is presented. The device is fabricated and tested to prove the concept. Insertion losses less than -3.5 dB with crosstalks less than -15 dB are measured for all multiplexed modes at 1550 nm.**

I. Introduction

Mode-division multiplexing (MDM) techniques enable a new degree of orthogonality to increase the capacity of optical communications links. An essential device for this technology is the (de)multiplexer. Many MDM devices for silicon-on-insulator (SOI) have been proposed in literature [1]–[5]. Multiplexers that are based on Y-splitter and multimode interference require large footprints and precise waveguide fabrication [1]. In [2] a multiplexer, that is based on asymmetrical directional coupler, has been proposed to demultiplex four or more channels. Although the device has a good insertion loss, its footprint is relatively large. A ring assisted Bragg grating has been proposed to achieve small footprint [3]. The concept of bi-directional mode-division multiplexer (BMDM) has been introduced in [4] to (de)multiplex 3 modes. the device is composed of two slab waveguides and a Bragg grating. In this paper, we present 3D-FDTD simulation results for a BMDM that is based on strip waveguides. In addition, the device is fabricated and tested to measure both the insertion losses and crosstalks of all modes.

II. Design and Simulation Results

Figure 1 shows the proposed BMDM with the mode chart of strip waveguide of height $220\,\mathrm{nm}$. The input waveguide width, $w = 936\,\mathrm{nm}$, is chosen from the mode chart to support three TE-like modes, while the output waveguide width, $d = 450\,\mathrm{nm}$, is chosen to support single mode. The fundamental mode is kept in the input waveguide to port 2 while the first- and second-order modes couple to the output waveguide in forward and backward directions, respectively. The first-order mode couples through a conventional directional coupler to port 3 in the output waveguide. The Bragg grating is designed to couple the second-order mode in the backward direction



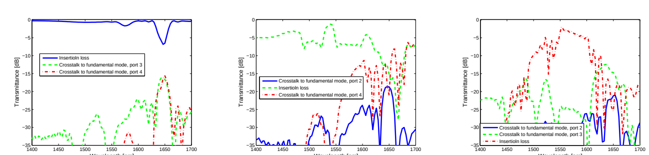
(a) (b)

Fig. 1: (a) Schematic diagram of proposed BMDM. (b) Mode chart of a strip waveguide at a wavelength of $1550\,\mathrm{nm}$.

of the output waveguide to port 4. The corresponding phase-matching conditions for both modes are:

$$\beta_1 = \beta_s \qquad \text{and} \qquad \beta_2 + \beta_s = \frac{2\pi}{\Lambda}, \tag{1}$$

where β_i is the propagation constant for mode i, $i \in \{m, s\}$. Here, $m \in \{0, 1, 2\}$ denotes the mode order in the input waveguide, while s denotes the fundamental mode in the output waveguide.



(a) (b) (c)

Fig. 2: 3D-FDTD simulations of proposed (de)multiplexer with coupler gap $r = 192\,\mathrm{nm}$, gating period $\Lambda = 378\,\mathrm{nm}$, and length $L = 18\,\mu\mathrm{m}$ when excited with: (a) fundamental, (b) first-order, and (c) second-order mode.

BMDM design parameters have been chosen via 3D-FDTD sweeps to get best insertion losses for fundamental, first-order, and second-order modes simultaneously while agreeing with the shot pitch for the fabrication process. Coupler gap r, grating period Λ, and coupler length L are chosen to be

192 nm, 378 nm, and 18 μm, respectively. The duty cycle of the grating is 20% with tooth width $t = r$.

The 3D-FDTD simulation results are shown in Fig. 2. At 1550 nm, the insertion loss (IL) for the fundamental, first-order, and second-order modes are -0.5987 dB, -5.8450 dB, and -1.9890 dB, respectively. It is worth noting that the IL of the first-order mode can be reduced further by operating at a slightly different wavelength. In this case, the complexity of the system will increase a bit by requiring another light source with different wavelength. Specifically, at 1540 nm, the IL of this mode would be reduced to -1.1670 dB as shown in Fig. 2(c). Finally, it is clear from the figure that the crosstalks for all cases are always less than -25 dB.

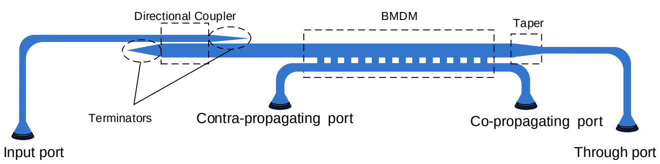


Fig. 3: Schematic diagram of the whole device (not to scale).

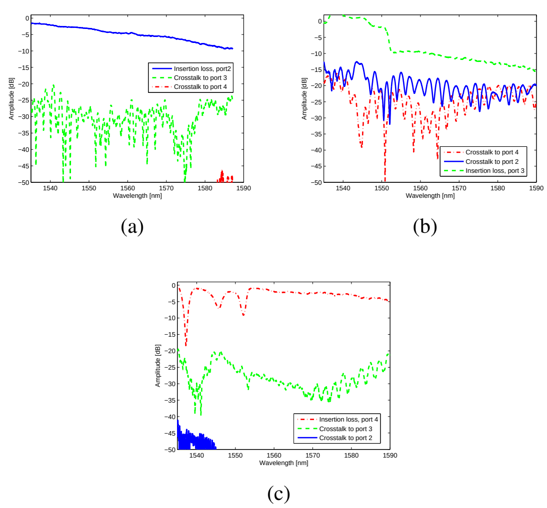


Fig. 4: Measured transmission spectra for fundamental, first-order, and second-order modes.

III. Fabrication and Measurement

Our device has been fabricated using 100 keV electron beam lithography. A SOI wafer with 220 nm silicon device layer and 2 µm buffer oxide layer has been used. After fabrication, the device has been inspected using a scanning electron microscope (SEM) to verify patterning and etch quality. A 2.2 µm oxide cladding has been deposited using plasma-enhanced chemical vapor deposition (PECVD) process to protect the functional device. To characterize our device, spectral responses have been measured using an Agilent 81600B tunable laser source with a wide tuning range (1500 nm to 1600 nm) in 10 pm steps. A polarization maintaining fiber array has been used to couple light in/out of the chip. The fibers have been spaced by 127 µm from each other. To allow automated measurements for the device, all on-chip grating couplers have been spaced with the same distance.

Figure 3 shows a schematic for the whole circuit. As we need different mode orders, we have designed two directional couplers (DCs) to couple from the fundamental mode, out of the grating coupler, to the desired mode order. The first DC has a length of 21 µm and a gap of 144 nm and couples to the first-order mode. To couple to the second-order mode we have used a DC of 12 µm length and a gap of 174 nm. At 1550 nm wavelength, first and second DCs show an insertion loss of -0.4652 dB and -1.55 dB, respectively. Terminators have been used to end all waveguides with tip of 60 nm, which is the minimum feature size for the fabrication process. All terminators have a back-reflection less than -25 dB. Tapers are also designed to transform between waveguides with different widths.

Figure 4 shows the experimental results for the fabricated BMDM. A reference circuit has been designed for each mode to get the insertion loss for our proposed BMDM only. We limit our analysis to the top 10 dB of the grating coupler response to avoid noise at the end of spectrum. The insertion loss at 1550 nm for the fundamental, first-order, and second-order modes are -3.127 dB, -1.465 dB, and -2.384 dB, respectively. Working at a wavelength of 1.54 nm can improve the IL of the fundamental and second-order modes to -2.042 dB and -0.9292 dB, respectively. The results from the simulation and fabrication process are similar over the wavelength range between 1535 nm and 1559 nm. The deviation from simulation can be attributed to some irregularities in the fabrication process that cannot be avoided. For example the Si layer non-uniformity and the waveguide side wall tilt from the vertical position.

IV. Conclusion

A three-mode division (de)multiplexer has been proposed. The structure has the advantage of being simple and compact, only 18 µm length. The device has been designed (using 3D-FDTD simulations) and fabricated. Fabrication results show acceptable ILs and crosstalks for all modes.

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