Compact Silicon-on-Insulator Lower-Order Mode Suppressor

Mohammad H. Sharaf[§¶], Ahmed Shalaby[‖], and Hossam M. H. Shalaby[§]
[§] Egypt-Japan University of Science and Technology (E-JUST), Alexandria 21934, Egypt
[¶]Faculty of Engineering, Al-Azhar University, Cairo, Egypt
[‖]Computer Science Department, Faculty of Computer Science, Banha University, Qalyubia, Egypt
Email: mohammad.sharaf@ejust.edu.eg, shalaby1983@hotmail.com, shalaby@ieee.org

***Abstract*—A Silicon-on-Insulator device is proposed for suppressing lower order modes. The device is compact and has a simulated mode-extinction ratio of about 11.3 dB in the operation band around 1550 nm (C-band).**

I. Introduction

The demand of high transmission rates is rapidly increasing currently, which needs further expansion and improvement of the data multiplexing techniques to cope with the exponentially increasing demand. Wavelength-division multiplexing (WDM) technology has reached its physical limits and several alternatives have been proposed. Polarization-division multiplexing techniques have a limited capacity. Space-division multiplexing is complex in implementation and the devices are bulky. Mode-division Multiplexing (MDM) is the most promising solution especially with the emerging development of few-mode fibers (FMF) as an improved medium to transfer data [1].

Several devices have been proposed for MDM in the last few years, including mode (de)multiplexers [2], mode exchangers [3], mode converters [4], and mode switches [5]. Mode filters are important devices in MDM systems. Suppressing higher-order modes is an easy task due to having weak confinement in the optical waveguides. This can be done using a structure with long taper to decrease crosstalks. Suppressing fundamental and lower-order modes is more involved as they have stronger confinement than higher order modes. Several devices have been proposed to solve this issue. A 1D photonic crystal based higher-order mode-pass filter has been proposed in [6]. An optical fiber mode filter has been demonstrated in [7] using FMF. A mode filter to suppress fundamental TE (Transverse Electric) mode while enabling all other modes to pass has been demonstrated in [8]. A higher-order mode-pass filter for optical fiber systems based on mode converters has been proposed in [9] but it was demonstrated as a concept and the size of the device was relatively large.

In this paper, we extend the concept of [9] and [10] to suppress lower-order modes by implementing the device on silicon-on-insulator (SOI). The demonstrated device has very small size with comparable performance.

This work was supported by the Egyptian Ministry of Higher Education (MoHE), Egypt-Japan University of Science and Technology (EJUST) and Japan International Cooperation Agency (JICA).

II. Device Design and Operation

Figure 1 shows the device components.

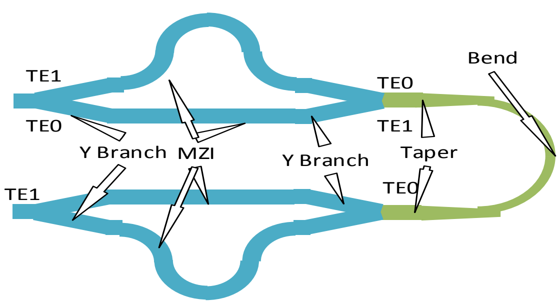

Fig. 1: Schematic diagram of proposed low-order mode suppressor.

The device principle of operation is suppressing a lower-order mode from a few-mode optical system. It can be divided into three parts, Two mode converters and a mode suppressor:

1) Mode Converter (Blue), composed of:
   - A Y-branch.
   - A Mach-Zehnder interferometer (MZI).
   - A Y-branch.
2) Mode Suppressor (Green), composed of:
   - A taper.
   - An adiabatic bend.
   - A reverse taper.

The height of the silicon waveguides are 220 nm. The input and output waveguides have a width of 0.8 μm for two mode operation, while the width of Y-Branch arms, MZI arms, and bend are 0.4 μm for single-mode operation. The Y-branch has a length of 2 μm and a half flare angle of 0.9^o. The MZI has a length of 4.1 μm. The taper length is 4 μm. The adiabatic bend has a radius of 2 μm.

We assume that two modes, the fundamental transverse electric mode (TE_0) and first-order transverse electric mode (TE_1), are inserted to the input port. The first Y-branch will divide TE_0 into two in-phase fundamental-mode components in both single-mode branches of the Y. In addition, TE_1 will be split into two out-of-phase fundamental-mode components in the two single-mode branches. The unbalanced MZI with path difference ΔL converts the two in-phase components of the input TE_0 mode into two out-of-phase components, which will be combined into a TE_1 mode after the second Y-branch. On the other hand, the out-of-phase components of the input TE_1 mode will be converted into two in-phase components by the MZI then combined into a TE_0 mode after the second Y-branch. The phase difference between the two half components has to be $\pi/2$, thus the length difference between the MZI arms is $\Delta L = \lambda/(4{*}n_{\text{eff}})$, where n_{eff} is the effective refractive index of the fundamental mode in the single mode waveguides. After the two modes are converted, the taper and the single-mode adiabatic bend filter out the TE_1 mode. The second taper adjusts the spot size of the TE_0 mode from a single mode waveguide to the spot size of a two-mode waveguide. Finally, the TE_0 mode is inserted to the second mode converter to return to its original form as TE_1 mode.

III. Simulation and Results

We carried out Finite-Difference Time-Domain (FDTD) simulation on our proposed device. In this section, we present the results of our simulation. The device has a compact size of 18.3 μm $\times$ 12.9 μm. Figure 2 shows the transmitted power through the output port when inserting a fundamental TE_0 mode. It is clear from figure that the output power is about -10 dB with a 3-dB bandwidth of 80 nm around a wavelength of 1550 nm (C-band).

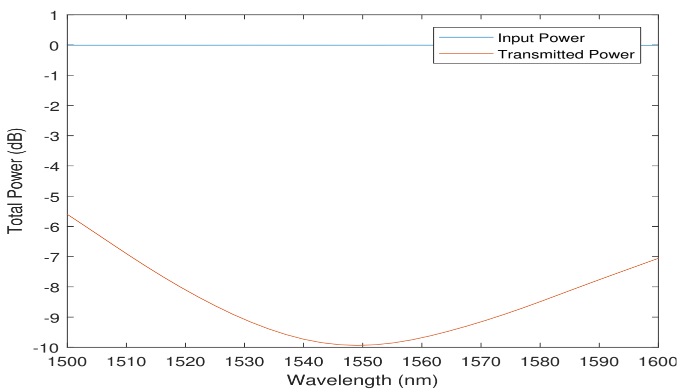

Fig. 2: Transmitted power (dB) versus wavelength (nm) when inserting TE_0 mode.

Figure 3 depicts the transmitted power through the output port when inserting a first-orde TE_1 mode. It is clear that the excess loss is 2.3 dB at a wavelength of 1550 nm.

Finally, the mode-extinction ratio (MER) is shown in Fig. 4. A MER of 11.3 dB is achievable at wavelength 1550 nm.

IV. Conclusion

A compact SOI lower-order mode suppression device has been illustrated. The performance of the device has been presented through FDTD simulation results. The device can be used to suppress other higher order TE modes and TM modes by using proper mode converters.

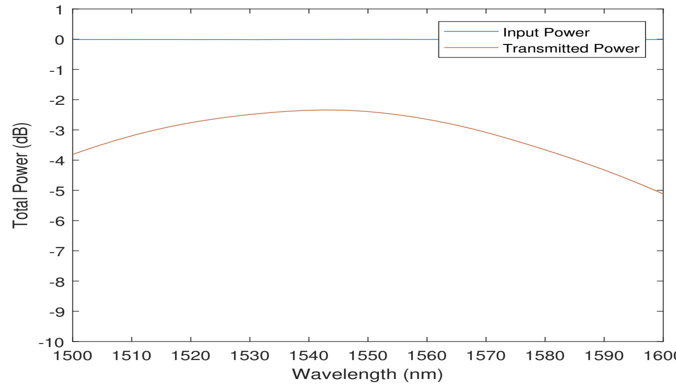

Fig. 3: Transmitted ower (dB) versus wavelength (nm) when inserting a TE_0 mode.

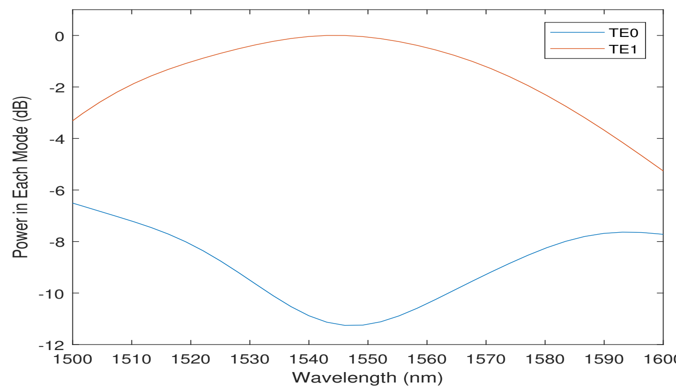

Fig. 4: Normalized transmitted power of both TE_0 and TE_1 modes versus wavelength (nm).

References

[1] L. Chrostowski and M. Hochberg, *Silicon photonics design: from devices to systems*. Cambridge University Press, 2015.

[2] O. M. Nawwar, H. M. Shalaby, and R. Pokharel, "Compact mode-division de (multiplexer) with anti-reflection grating for optical interconnects," in *Asia Communications and Photonics Conference*. Optical Society of America, 2016, pp. AF1G–7.

[3] Z. Zhang, X. Hu, and J. Wang, "On-chip optical mode exchange using tapered directional coupler," *Scientific reports*, vol. 5, p. 16072, 2015.

[4] W. Jin and K. S. Chiang, "Mode converters based on cascaded long-period waveguide gratings," *Optics letters*, vol. 41, no. 13, pp. 3130–3133, 2016.

[5] B. Stern, X. Zhu, C. P. Chen, L. D. Tzuang, J. Cardenas, K. Bergman, and M. Lipson, "On-chip mode-division multiplexing switch," *Optica*, vol. 2, no. 6, pp. 530–535, 2015.

[6] X. Guan, Y. Ding, and L. H. Frandsen, "Ultra-compact broadband higher order-mode pass filter fabricated in a silicon waveguide for multimode photonics," *Optics letters*, vol. 40, no. 16, pp. 3893–3896, 2015.

[7] Y.-m. Jung, S.-U. Alam, and D. J. Richardson, "All-fiber spatial mode selective filter for compensating mode dependent loss in mdm transmission systems," in *Optical Fiber Communication Conference*. Optical Society of America, 2015, pp. W2A–13.

[8] Z. Chang and K. S. Chiang, "Mode filter based on graphene-embedded waveguide," in *Optical Fiber Communication Conference*. Optical Society of America, 2016, pp. Th3E–6.

[9] K. T. Ahmmed, H. P. Chan, and B. Li, "Broadband high-order mode pass filter based on mode conversion," *Optics letters*, vol. 42, no. 18, pp. 3686–3689, 2017.

[10] W. Y. Chan and H. P. Chan, "Two-mode mode multiplexer/demultiplexer in polymer planar waveguide," *Applied optics*, vol. 53, no. 3, pp. 496–502, 2014.