Ultra-Compact and Broadband Silicon Two-Mode Multiplexer based on Asymmetric Shallow Etching on a Multi-Mode Interferometer

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Abstract: We present a silicon two-mode multiplexer with a footprint of 1.5×7.24 μm^2. The operation principle is based on simultaneous multi-mode conversion. In the wavelength range of 1521nm~1571nm, the crosstalk is below –15 dB. © 2020 The Author(s)

1. Introduction

Mode multiplexer is a key component in mode-division-multiplexing (MDM) systems, which can enhance the capacity of a single-carrier optical link [1]. Asymmetric direction coupler (DC) has been widely employed to couple a fundamental mode to a high order mode [2]. The footprint of a two-mode multiplexer based on an asymmetric DC was 1.34 × 50 μm^2 due to the weak coupling between the waveguides, and the fabrication tolerance was limited to ±20 nm due to the effective index mismatching [3]. Multimode interferometer (MMI) features large operation bandwidth, and it can work as a mode multiplexer with a phase shifter with a size of 4.28 × 48.8 μm^2 [4]. Recently, the index-manipulation on silicon waveguide provides a potential method to design a compact device with high fabrication tolerance and large operation bandwidth [5].

In this paper, we propose and experimentally demonstrate a silicon two-mode multiplexer based on asymmetric shallow etching on an MMI structure. The device is ultra-compact with a footprint of 1.5 × 7.24 μm^2.

2. Device design and fabrication

As shown in Fig. 1(a), three TE$_i$ (i = 0,1,2) modes are excited in the multimode waveguide by the input TE$_0$ light from Input #1 or Input #2 port, and the three modes couple to each other due to the perturbation caused by the partially-etched waveguide. Therefore, after propagating through a well-designed shallow etching area, the three TE modes evolve to TE$_0$ or TE$_1$ mode depending on the input port, and the other mode is suppressed in both cases. By these means the two input TE$_0$ signals are multiplexed and converted to TE$_0$/TE$_1$ modes.

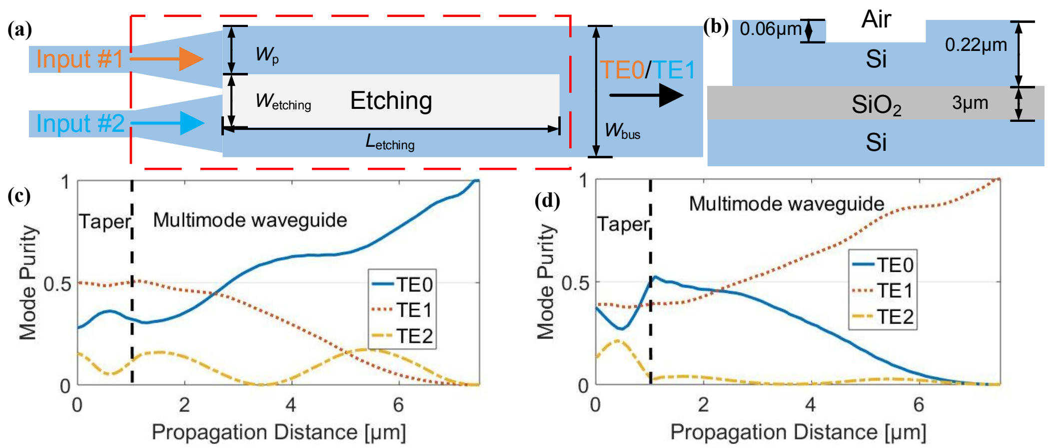

Fig. 1. (a) The top view and (b) the cross-section of the proposed device, (c,d) the mode purities of three guided modes (TE$_0$, TE$_1$ and TE$_2$) for Input#1 and Input#2 inputs, respectively.

The cross-section of the proposed two-mode multiplexer is shown in Fig. 1(b). The two-mode multiplexer is designed on a silicon-on-insulator (SOI) wafer with a top silicon layer of 220 nm and air cladding. The mode coupling theory (MCT) is utilized to design the device [6], and particle swarm optimization (PSO) is used to optimize the geometrical parameters of shallow etching area. The width of multi-mode waveguide is W_{bus} = 1.5 μm. The depth of shallow etching is 60 nm, and the optimized width and length of shallow etching area are $W_{etching}$ = 633 nm and L_{etching} = 6.243 μm, respectively. W_p = 517 nm denotes the position of the asymmetric etching area. As shown in Fig. 1(c) and (d), after an adiabatic taper (0.4μm→0.65μm, L_{taper} = 1 μm), the light enters the multimode waveguide, and then is divided to three TE modes. Attributed to the index perturbation caused by the shallow etching region, these three modes can be coupled into one single mode, and the amplitude of each mode along the propagation direction is determined by a set of differential equations [5]:

$$
\begin{aligned}
-\frac{\partial A_1}{\partial z} &= j\kappa_{12}A_2 e^{j(\beta_1-\beta_2)} + j\kappa_{13}A_3 e^{j(\beta_1-\beta_3)}, \\
-\frac{\partial A_2}{\partial z} &= j\kappa_{21}A_1 e^{j(\beta_2-\beta_1)} + j\kappa_{23}A_3 e^{j(\beta_2-\beta_3)}, \\
-\frac{\partial A_3}{\partial z} &= j\kappa_{31}A_1 e^{j(\beta_3-\beta_1)} + j\kappa_{32}A_2 e^{j(\beta_3-\beta_2)},
\end{aligned}
\tag{1}
$$

where A_i is the complex amplitude of the TE$_i$ mode, β_i is the propagation constant of the TE$_i$ mode (i, k = 0,1or 2), the mode coupling coefficient κ_{ik} between TE$_i$ and TE$_k$ modes is defined by:

$$\kappa_{ik}(z) = \frac{\omega}{4}\iint_S E_i^*(x,y)\cdot\Delta\varepsilon(x,y,z)\cdot E_k(x,y)dxdy. \tag{2}$$

In the design, $\kappa_{12} = -2.45\times10^5$ m^{-1}, $\kappa_{13} = -5.92\times10^5$ m^{-1}, $\kappa_{23} = -1.34\times10^5$ m^{-1}, and $\kappa_{ik} = \kappa_{ki}$. The eigen-mode expansion method is utilized to calculate the amplitudes of TE$_i$ modes at $z = L_{\text{taper}}$, $A_0 = -0.3 + j0.21$, $A_1 = -0.0162 + j0.185$, $A_2 = 0.63 - j0.04$ or $A_0 = 0.3 - j0.21$, $A_1 = -0.0162 + j0.185$, $A_2 = -0.63 + j0.04$ for Input #1 or Input #2 inputs, respectively. According to Eq. (1), the mode purity of TE$_0$ or TE$_1$ mode ($|A_0|^2$ or $|A_1|^2$) grows to 1 at $z = L_{\text{taper}} + L_{\text{etching}}$ while the other modes vanish, as displayed in Fig. 1(c) and 1(d). Figs. 2 (a-d) show the E_y and power fields. In the fabrication, E-beam lithography (Vistec EBPG 5200$^+$) and inductively coupled plasma dry etching were used to define the two-mode multiplexer structure on a SOI wafer. Magnified optical micrograph and scanning electron microscope (SEM) images of the fabricated devices are provided in Fig. 2(e) and (f), respectively. The grating couplers were used to couple light input and output of the device in the experiment, the period and duty cycle of the grating are 630 nm and 50%, respectively. The etching depth is 60 nm, which is equal to that on the multimode waveguide. An asymmetric DC with a well-known performance is cascaded after the proposed device to couple the TE$_1$ mode from the bus waveguide.

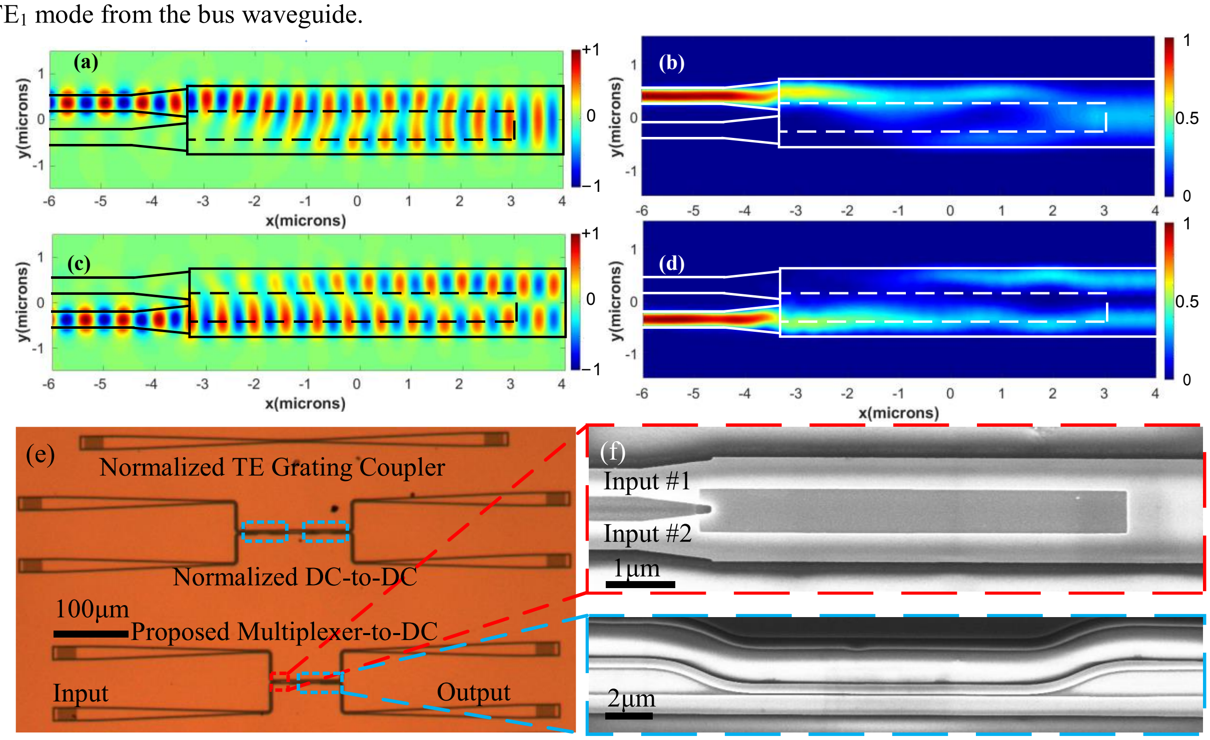

Fig. 2. Simulated E_y distribution of the two-mode multiplexer for TE$_0$ input from (a) Input#1 port, (b) Input#2 port. Simulated power distribution for TE$_0$ input from (c) Input #1 port, (d) Input #2 port. (e) optical micrograph of the fabricated devices, (f) SEM photo of a fabricated two-mode multiplexer and an asymmetric DC (gap = 100 nm, width = 400 nm and 810 nm).

3. Measurement results and discussion

Figure 3(a) shows the measured and simulated spectra of the two-mode multiplexer for TE_0 and TE_1 mode input lights, respectively. For the Input #1 and Input #2 ports, the ILs are 0.74 dB and 1.182 dB, and the crosstalk values are −20.81 dB and −20.21 dB at 1550 nm, respectively. In a wavelength range of 1521 nm ~ 1571 nm (bandwidth = 50 nm), the ILs are lower than the 2 dB while the crosstalk values are below −15 dB.

The fabrication tolerances of the device parameters are also numerically analyzed at 1550 nm by changing the depth, width and length of the shallow etching area. As shown in Fig. 3(b), (c) and (d), the IL and crosstalk values of the device remain < 1 dB and <−15 dB for both inputs with an etching depth variation from −10 nm to +5 nm, $W_{etching}$ variation of −100 nm ~ +60 nm, and $L_{etching}$ variation from −0.25 to +0.25 μm. The simulated results demonstrate that the proposed two-mode multiplexer has high fabrication tolerance to the waveguide partial-etching variations.

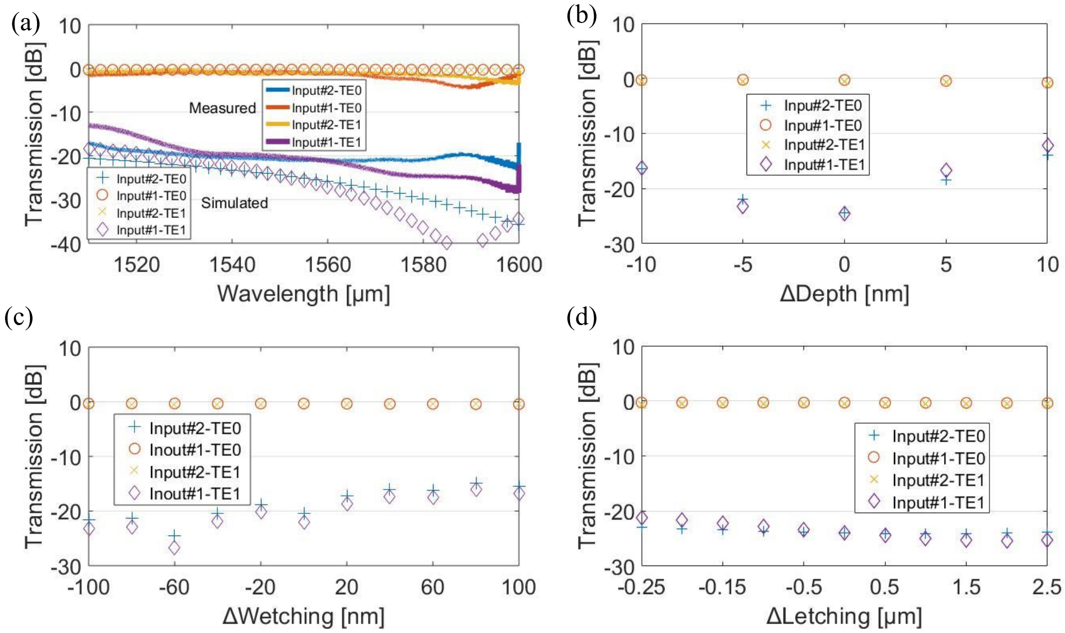

Fig. 3. (a) The measured and simulated transmissions of the proposed device for Input #1 and Input #2 inputs, respectively. The fabrication tolerances for (b) depth, (c) $\Delta W_{etching}$ and (d) $\Delta L_{etching}$ of shallow etching.

4. Conclusion

We have experimentally demonstrated an ultra-compact silicon two-mode multiplexer. Attributed to the index perturbation induced by asymmetric partial etching on a MMI structure, the TE_0 input light from Input #1 / Input #2 port is converted to TE_0 / TE_1 mode, respectively, and thus two-mode multiplexing can be achieved. The footprint of the device is 1.5 × 7.24 μm^2. The insertion losses are < 2 dB and the crosstalk values are < −15 dB in the wavelength range of 1521 nm ~ 1571 nm, respectively. The tolerance of the two-mode multiplexer is also numerically analyzed. If the depth, width and length of the shallow etching area vary by 15 nm, 160 nm or 0.5 μm, respectively, the IL and crosstalk value remain less than 1 dB and −15 dB at 1550 nm, respectively.

5. References

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