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Ultra-low-loss inverted taper coupler for silicon-on-insulator ridge waveguide

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ABSTRACT

An ultra-low-loss coupler for interfacing a silicon-on-insulator ridge waveguide and a single-mode fiber in both polarizations is presented. The inverted taper coupler, embedded in a polymer waveguide, is optimized for both the transverse-magnetic and transverse-electric modes through tapering the width of the silicon-on-insulator waveguide from 450 nm down to less than 15 nm applying a thermal oxidation process. Two inverted taper couplers are integrated with a 3-mm long silicon-on-insulator ridge waveguide in the fabricated sample. The measured coupling losses of the inverted taper coupler for transverse-magnetic and transverse-electric modes are ~0.36 dB and ~0.66 dB per connection, respectively.

1. Introduction

In recent years, integrated photonic devices have drawn increasing interests as the silicon-on-insulator (SOI) material makes possible the batch fabrication of photonic devices with submicron dimensions by offering high refractive-index contrast and fabrication compatible with complementary metal-oxide semiconductor (CMOS) processing [1]. Compact SOI waveguides with low-loss allows for high-density integration of photonic devices. However, the submicron cross-section of the waveguides makes the fiber-to-chip coupling inefficient due to the large mode mismatch. Grating couplers were proposed to solve these problems and a peak coupling efficiency of 31% has been achieved [2]. The coupling efficiency has been further improved to 69% by adding a gold bottom mirror to the SOI substrate [3]. Very recently, a nonuniform grating coupler with a coupling efficiency of 64% has been demonstrated on a SOI wafer by utilizing the lag effect in the etching process [4]. However, in these designs, an additional lithography and etching step is necessary to make the shallowly etched grating. To ease the fabrication process and improve the coupling efficiency, a fully-etched photonic crystal grating coupler with a peak coupling efficiency of 42% was demonstrated [5]. However, the coupling loss is still relatively large and the coupling response is wavelength and polarization dependent. To further enhance the coupling efficiency and bandwidth, an inverted taper coupler featuring a taper from the normal waveguide dimensions to a smaller tip can be utilized [6–10]. In [8], such a coupler was fabricated using standard CMOS technology and an insertion loss of 1.9-dB was achieved for the transverse-electric (TE) mode. In [9], McNab et al. have optimized the coupler for the TE mode and achieved a 0.5-dB insertion loss. In [10], a similar coupler for a silicon rib waveguide with a 0.7-dB coupling loss for TE mode was also reported. Although promising results have been obtained for TE mode, the coupling loss for the transverse-magnetic (TM) mode is still large due to difficulties in making an ultra-narrow tip [4–6]. It has appeared recently that many devices would perform better under TM polarization and some of them even work only for TM mode. For instance, an integrated tunable device with liquid-crystal cladding offers larger tunability for TM mode [11]; a SOI waveguide provides larger bandwidth for TM-polarized light in wavelength-conversion applications [12], and a refractive index sensor based on photonic crystal pillars only works in TM mode [13]. It is thus important to realize a low-loss coupler for TM mode. In this paper, such an inverted taper coupler is optimized for both TM and TE modes. An ultra-narrow tip end is achieved through thermal oxidation. Two inverted taper couplers are integrated with a 3-mm long silicon-on-insulator ridge waveguide in the fabricated sample. The measured total insertion losses of the waveguide are ~2.03 dB and ~2.6 dB for the TM and TE modes, respectively, and the coupling losses per coupler are ~0.36 dB and ~0.66 dB for the TM and TE modes, respectively.

2. Design

Fig. 1 shows the schematic drawing of the inverted taper coupler, where the width of the silicon waveguide is tapered from 450 nm down to a tiny tip end in order to expand the guided mode. A thin silicon dioxide cladding layer, grown by thermal oxidation, covers the silicon core. The SOI waveguide and the taper are embedded in a polymer waveguide with a cross-sectional dimension matched to the access fibers. The performance of the tapers with different tip end widths and taper lengths were already investigated in [6]. A 200-μm long taper with a 60 nm wide tip is needed to obtain a coupling loss of 1 dB for a $300 \times 300\ nm^2$ ridge waveguide [6], and a 150-μm long taper with 75-nm wide tip end was utilized to achieve the same level of loss for a $220 \times 450\ nm^2$ ridge waveguide [9]. Normally, less than 1-

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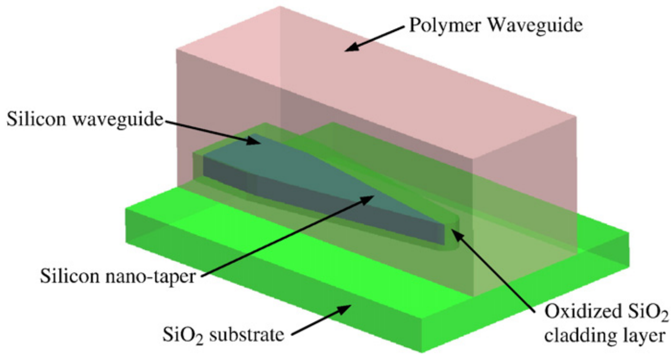

Fig. 1. Schematic drawing of the nano-taper coupler.

dB coupling loss can be achieved for TE mode with a taper tip width around 80 nm. However, the coupling loss of these couplers for TM mode is relatively large (~2 dB) [9]. Fig. 2(a) shows the calculated coupling loss as a function of the tip width for a $340\times450\ nm^2$ ridge waveguide. Here, a semi-vectorial beam-propagation method is employed for the numerical simulations. Clearly, the coupling for TM mode is very sensitive to the tip width and a taper with less than 20-nm tip width is necessary to achieve a coupling loss less than 1 dB. However, it is difficult to fabricate the ultra-narrow tip by etching, since the tip end will be fragile during the post fabrication processes due to its high aspect ratio. In our design, a taper with a relatively wide tip is first fabricated and then the tip width is further reduced through a thermal oxidation process. The thin oxide cladding layer formed by the oxidation process protects the tiny tip end during the post fabrication processes. We also calculated the performance of the tapers for different SOI waveguide heights, as shown in Fig. 2(b). Here, we assumed that the tip width of the taper is 80 nm. The coupling loss for the TM mode is reduced significantly as the height decreases, while the coupling loss for TE mode remains almost the same. To understand this phenomenon, we illustrate in Fig. 3 the mode field distributions at the tip ends of the taper with different waveguide heights (320 nm and 240 nm) for both TE and TM modes. As shown in Fig. 3(a) and (b), for TE polarization, the mode can be fully expanded for both heights. However, for TM polarization, the mode field is still well confined within the silicon core region when the height of the SOI waveguide is 320 nm, which will lead to a large mode mismatch loss. Thus, in order to make a low-loss inverted taper coupler for TM mode, it is desirable to use a SOI wafer with a top silicon layer thickness less than about 250 nm, together with the technique of thermal oxidation to further reduce the tip width.

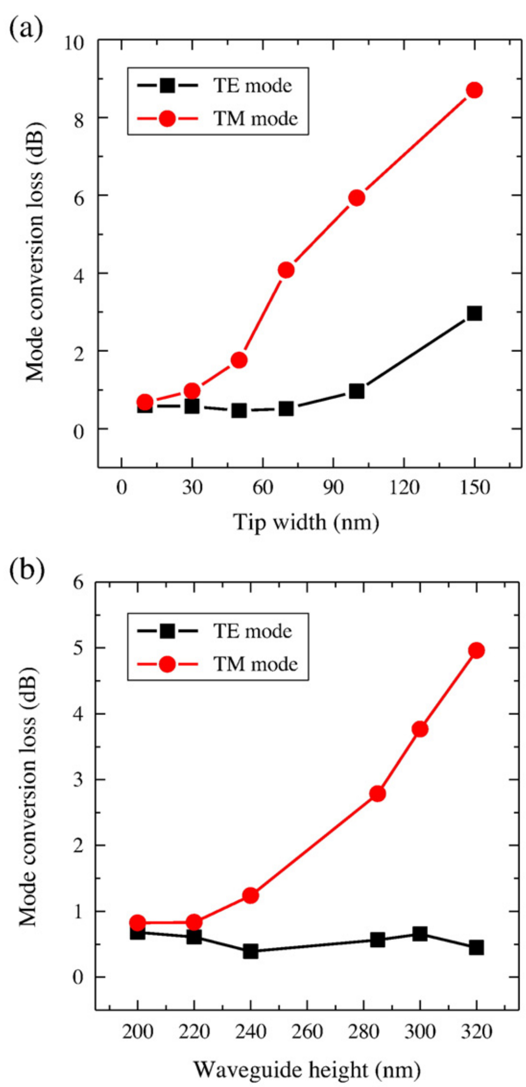

Fig. 2. Calculated mode conversion loss for nano-taper couplers with different tip widths (waveguide height = 340 nm) (a) and different waveguide heights (tip width = 80 nm) (b). Here, the taper length is always assumed to be 300 μm.

3. Fabrication

The sample investigated here was fabricated in a SOI chip with a top silicon thickness of 250 nm and a 3-μm buried silicon dioxide layer. Electron-beam resist ZEP520A was spin-coated on the wafer to create a 110-nm thick masking layer. The waveguide and taper structure was defined in the ZEP520A layer by utilizing electron-beam lithography. In the electron-beam lithography, the waveguide width, tip width and taper length are designed to be 480 nm, 40 nm and 300 μm, respectively. SOI waveguides with different lengths (3 mm–28 mm) were prepared. The patterns were subsequently transferred to the top silicon layer by employing inductively coupled plasma reactive ion etching. Then, a dry thermal oxidation was applied at 900 °C for 270 min. Fig. 4(a) and (b) show the scanning electron microscope pictures for a 40-nm wide taper tip before and after the oxidation process, respectively. After the oxidation process, a 30-nm thick silicon dioxide layer was formed around the silicon which corresponds to a consumption of the silicon material of ~14 nm, since the amount of silicon consumed during the oxidation process is about 46% of the total thickness of the oxide layer according to the relative densities and molecular weights of silicon and silicon dioxide. Thus, the waveguide and the taper both become narrower. The estimated widths for the silicon waveguide and the taper tip end are ~452 nm and ~12 nm, respectively. The thickness of the silicon waveguide was also reduced to ~238 nm. A top cladding of 3.4-μm polymer (SU8-2005) was then spin-coated on the chip. The polymer waveguide structures were also defined by electron-beam lithography and directly formed after developing. Fig. 4(c) and (d) show the top-view and cross-section view of the inverted taper coupler, respectively.

4. Characterization

The light transmission experiment was performed through an end-fire configuration by connecting two tapered fibers with 2.9-μm spot diameter to the inverted taper couplers at both edges of a cleaved sample. Fig. 5 shows the transmission spectrum of a 3-mm long SOI ridge waveguide integrated with two inverted taper couplers. The inset of Fig. 5 shows the additional loss with misalignment in vertical and horizontal directions for the TM mode. The misalignment tolerance of the inverted taper coupler is relatively large, with 3 dB of additional loss for ±1.5 μm misalignment in both vertical and