High-Efficiency Fiber-Chip Edge Coupler Design for Visible Light on Alumina-on-Insulator Photonics

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Abstract: We propose a fiber-chip edge coupler at the wavelength from 405 nm to 500 nm based on the alumina optical waveguides. Simulation result shows lower than 1.6 dB insertion loss for the TE-polarized light.

1. Introduction

The operation wavelengths in visible and even ultraviolet (UV) regimes are desired for a large number of applications ranging from augmented reality, atomic-molecular-optical physics to biosensing [1]. However, devices based on silicon-on-insulator (SOI), the most popular integrated photonic platform nowadays, can only operate in the infrared band due to the limited transparent window of silicon material [2,3]. To further extend the operation wavelength range of integrated photonic devices, amorphous aluminum oxide (alumina)-on-insulator is considered as a promising candidate for the visible and UV bands [4]. Alumina films deposited by atomic layer deposition (ALD) are conformal and uniform, which lead to low optical absorption losses even at the wavelength down to 220 nm [5]. The measured refractive index of alumina is approximately 1.65 ~ 1.72 in the visible and near-ultraviolet (NUV) spectra [1]. An alumina waveguide covered by SiO_2 has been demonstrated with a low propagation loss of 0.5 dB/cm at λ = 461 nm and < 3 dB/cm at λ = 370 nm [1]. Besides the low-propagation-loss waveguide, the high-efficiency fiber-chip coupler is also essential for both measurement and applications. While surface grating couplers with an end-to-end loss of 24 dB at 380 nm and on-off chip couplers with ~3 dB/facet loss have been reported, respectively [1,6], it is highly desired to design a fiber-chip coupler with even higher efficiency on alumina-on-insulator platform.

In this paper, we propose a high-efficiency fiber-chip edge coupler utilizing symmetric double-tip taper based on alumina-on-insulator platform. Instead of using the direct strip-slot structure [7], we add two S-bend waveguides to smoothly connect the two tapers to the strip waveguide. A single mode fiber with a mode field diameter of 2.5 ~ 3.4 μm at 480 nm is utilized to couple with the proposed structure. The simulated insertion losses are lower than 1.6 dB for the TE-polarized light in the wavelength range of 405 nm to 500 nm.

2. Design and simulation

Fig. 1 (a) shows the schematic of the fiber-chip edge coupler using symmetric double-tip taper. The insets show the electric field distributions of the fundamental TE modes at selected cross-sections, respectively. Despite the small refractive index difference between alumina and SiO_2, the strong confinement of the waveguide at short wavelengths makes it hard to match the electric field distribution of a fiber with the chip facet. By introducing multiple inverse tapers at the initial stage, the electric field distribution of the chip facet can be expanded [8]. Considering an input light beam injected from a single mode fiber at the left side, the linearly polarized (LP) mode output from the fiber couples to the symmetric double-tip tapers with a high modal overlap, leading to an acceptable coupling loss. The modal overlap between the fiber and the chip facet can be defined as [9]:

$$Overlap = \frac{\left|\int E_1 E_2 dA\right|^2}{\int |E_1|^2 dA \int |E_2|^2 dA} \tag{1}$$

where E_1 and E_2 are the complex electric field amplitudes of the LP mode in the fiber and the on-chip waveguide mode (at the chip facet), respectively. The fiber we use to transmit visible light is Thorlabs' SM400 fiber which consists of an un-doped, pure silica core surrounded by a depressed, fluorine-doped cladding. It has a numerical aperture of 0.12 – 0.14 and low attenuation from 405 nm to 532 nm. The edge coupler is designed based on an alumina-on-insulator waveguide with a 100-nm-thick alumina core on a 3200-nm-thick silica box and a 3100-nm-thick silica top cladding. The three-dimensional finite-difference time-domain (3D-FDTD) method is used to analyze and optimize the two main parameters, i.e., the distance between the centers of the two tapers and the tip width (G and w_1 in Fig. 1). To relax the fabrication process, we choose w_1 =100 nm. It is viable to calculate the mode overlap by placing a mode monitor at the interface between the chip facet and the optical fiber. The distance between the centers of the two tapers (G in Fig. 1) is optimized to be 1260 nm by using particle swarm optimization (PSO) method to achieve a maximum overlap value. The length of the taper (L in Fig. 1) is 33 μm, as a compromise between the transition loss caused by sidewall roughness and taper length.

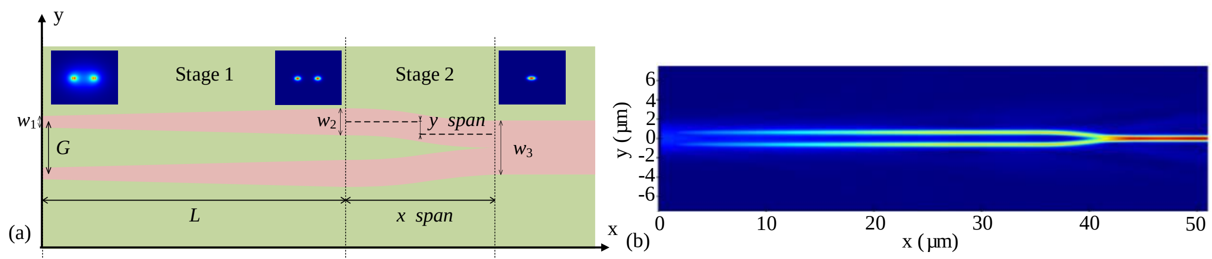

Fig. 1. (a) Schematic structure of the edge coupler. (b) Simulated electric field distribution in the coupler for the TE polarization input.

When the injected light beam enters the chip, the waveguides is tapered from w_1 =100 nm to w_2 =300 nm, which is half of the width of the strip waveguide w_3 =600 nm. The middle inset shows the final mode profile of the stage 1, in which a majority of optical power is located in the core area. In stage 2, two S-bend waveguides connect the end of the double-tip taper and the strip waveguide. A low insertion loss can be achieved with the parameters of *y-band* = 480 nm and *x-band* =10 μm. As all the waveguide widths in the stage 1 and stage 2 are narrower than 300 nm, any higher-order mode cannot be excited, leading to a low-loss transmission for fundamental modes [4]. Fig. 1 (b) shows electric field distribution (E_y) of the simulated TE mode propagation in the coupler.

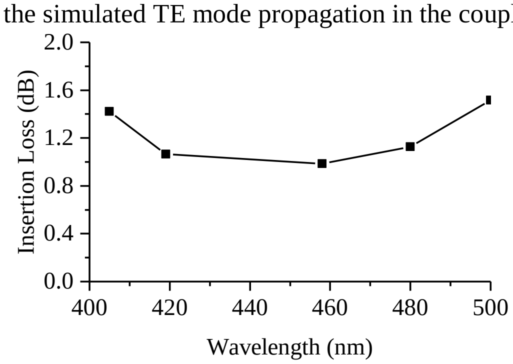

Fig. 2. Simulated coupling loss for the edge coupler for the TE polarization input.

Fig. 2 shows the simulated coupling loss for the edge coupler for the TE polarization input. The coupler exhibits an insertion loss ~ 1 dB per facet at 458 nm for TE polarization. In the wavelength range from 405 nm to 500 nm, the insertion loss is < 1.6 dB for the TE polarization.

3. Waveguide Fabrication

To initiate the experiment, the first step is to fabricate alumina waveguides. A 3.2-μm thick silica film is deposited via plasma-enhanced chemical vapor deposition (PECVD) (Oxford PECVD system) on a bare 200 mm silicon wafer. Then a 100 nm thick alumina waveguide film is deposited using ALD. Due to the challenges in etching the alumina materials, SiO_2 is used as a hard mask during the reactive ion etching (RIE) [4]. Thus another 200 nm thick film of PECVD SiO_2 is deposited after the alumina layer. A photoresist layer is then spin-coated onto the film, followed by baking on a hot plate at 150 ℃. The photoresist template is patterned using e-beam lithography (Vistec EBPG-5200+). After the development, RIE is used to transfer the pattern to the SiO_2 hard mask (NMC ICP Reactive Ion Etching System), followed by photoresist removal (PVA-Tepla Microwave Stripper /Plasma processing system). A second inductively coupled plasma (ICP) RIE is needed to transfer the pattern from the hard mask to the alumina, yielding waveguides with ~70 °sidewall angle profiles, as shown in Fig. 1 (a). After this etch, another 3.1-μm thick film of SiO_2 is deposited as cladding, and the wafer is annealed again. Finally, the facets used for the butt coupling are fabricated using deep etching process (NMC ICP Deep Silicon Etching System). The whole fabrication process is shown in Fig. 3 (b). Further optimization for the process will be taken in the next step. The schematic structure of the alumina optical waveguide is shown in Fig. 3 (c). Further experiments will be carried out to fabricate the proposed edge coupler and characterize the performance.

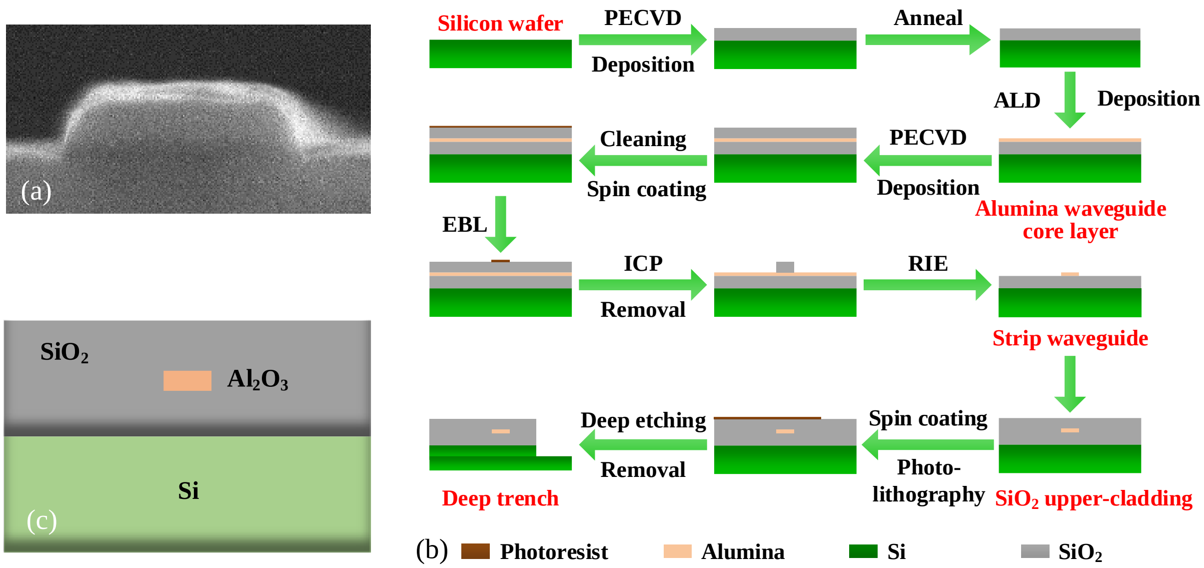

Fig. 3. (a) Cross-section of the fabricated waveguide after the ICP RIE without cladding. (b) Fabrication processes of alumina waveguides. (c) Schematic of the cross-section of an alumina waveguide.

4. Conclusion

In summary, we have proposed a fiber-chip edge coupler based on symmetric double-tip taper on the alumina-on-insulator. Our edge coupler has the highest simulated coupling efficiency for fiber-chip coupling for visible light based the alumina-on-insulator platform, to the best of our knowledge. The calculated results show that the insertion loss is ~ 1 dB at 458 nm for the TE polarized light and also maintains insertion loss < 1.6 dB within 405 nm to 500 nm window.

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