Resonant Coupling in Double-layer Monolithic Integration of Al_2O_3 and Si_3N_4

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Our double-layer Al_2O_3-Si_3N_4 platform by monolithic integration combines the outstanding optical features of LPCVD Si_3N_4 layer and properties of rare-earth ion doped Al_2O_3 layer, showing a promising way of realizing active-passive integration for various photonic functionalities. Here, a resonant coupling effect is investigated by introducing lateral misalignment to the width-tapered Al_2O_3 and thickness-tapered Si_3N_4 waveguides, which avoids submicron lithography process and yields good fabrication tolerances. Coupling loss <0.15 dB was experimentally achieved in the spectral window of 1460–1635 nm, for undoped-Al_2O_3-Si_3N_4 couplers at the lateral misalignment of 1.4 μm.

Introduction

Integration of low-cost, compact size and high efficiency laser sources on a single photonic chip remains an open problem. The Si_3N_4 platform shows very low propagation loss (<0.1 dB/cm) and a wide transparency window covering visible to near infrared wavelengths [1]. These features make Si_3N_4 a promising candidate for various applications in fields such as microwave photonics, non-linear optics, and bio-sensing [1]. Integrated lasers in the Si_3N_4 platform have been investigated by butt-coupling an InP-based semiconductor amplifier with Si_3N_4 external laser cavities [2]. However, cost-effective, tolerant and large-scale production is challenging for such integration. Monolithic integration of rare-earth-ion doped Al_2O_3 onto passive Si_3N_4 platforms [3] shows a great potential to overcome these challenges. In our previous work, a double-layer platform has been developed, where the Al_2O_3 and Si_3N_4 waveguides are monolithically integrated in two individual layers [4]. Adiabatic coupling is achieved by using a lateral Al_2O_3 taper and a vertical Si_3N_4 taper in the coupling region. To confirm the adiabaticity [5], long tapers (~800 μm) with small geometrical changes are employed to avoid coupling the fundamental mode to other unwanted higher order modes. The total loss of the coupler is mainly due to the mode mismatch losses at the taper tips. The mismatch can be reduced by either fabricating tiny (tens of nanometers) taper tips or increasing the lateral misalignment. The former requires high precision lithography tools such as stepper lithography or electron-beam lithography tools. For the latter method, the resonant coupling occurs when the lateral misalignment between two long tapers increases to certain values. This is because the effective refractive indices of the two waveguides matches at some point along the taper [6].

In this paper, we focus on the analysis of the influence of such resonant coupling in the taper region. A lateral misalignment range of 1.2–1.8 μm is selected for investigating the coupling losses at different wavelengths ranging from 1460 nm to 1640 nm with a step of 20 nm. The simulation results demonstrate how the lateral misalignment, wavelength and taper length affect the coupling losses. The fabricated Al_2O_3-Si_3N_4 couplers with lateral misalignment of 1.4±0.15 μm and 1.7±0.15 μm are characterized in the spectral window of 1460–1635 nm, which verifies the resonant coupling effect and shows further improvement on the coupler loss.

Simulation results

Figure 1(a) shows a 3D schematic of the Al_2O_3-Si_3N_4 coupler, where the Al_2O_3 waveguide on the upper layer is laterally misaligned to the Si_3N_4 waveguide on the bottom layer. They are separated by a thin LPCVD SiO_2 film with a thickness of 200 nm. The width of Si_3N_4 waveguide is 1.4 µm, and its thickness is vertically tapered from 200 nm down to 30 nm. The width of Al_2O_3 waveguide is tapered from 1 µm to 0.8 µm, and its thickness is fixed at 700 nm. The refractive indices of Al_2O_3 and Si_3N_4 at the wavelgnth of 1550 nm is 1.64 and 1.98 respectively. The coupling loss in the taper region is calculated by 3D eigenmode expansion (EME) method of Lumerical software. The fundamental modes at the taper tips are employed as input and output modes for the simulation. Figure 1(b) and Figure 1(c) show the top-view and side-view of the intensity fields during the coupling in the taper, respectively. The resonant coupling effect can be visibly seen from the field intensity pattern, which becomes weaker with light propagating along the vertical Si_3N_4 taper while more power is transferred to the Al_2O_3 waveguide core. Furthermore, mode mismatch losses at the taper tips are calculated by overlapping the modes at the taper tips [7] for different lateral misalignments of 1.2 µm, 1.4 µm, 1.6 µm and 1.8 µm, as shown in Figure 1(d), which is excluded from in the following EME simulation.

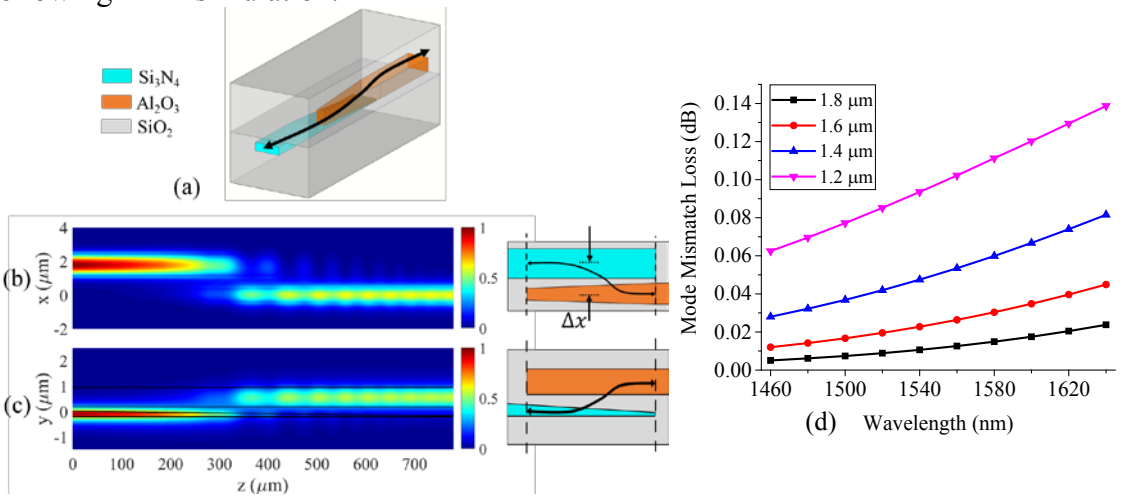

Figure 1. (a) 3D schematic of the Al_2O_3-Si_3N_4 coupler in a double-layer platform. Intensity fields of the coupler at the lateral misalignment of 1.8 µm at the wavelength of 1550 nm: (b) top-view, and (c) side-view. (d) Calculated mode mismatch losses at the taper tips

Figure 2(a) to 2(d) show the calculated coupling loss in the taper region as functions of the taper length and the wavelength. At the smallest investigated lateral misalignment, i.e. 1.2 µm, it can be seen in Figure 2(a) that the coupling loss remains less than 0.05 dB at all wavelengths for taper lengths larger than 150 nm, indicating good broadband adiabatic coupling. With the increase of lateral misalignment, as shown in Figure 2(b) to 2(d), the coupling region with less than 0.05 dB loss gets more confined to a reduced range of taper lengths and the coupler loss also becomes more sensitive to the operation wavelength. As the misalignment increases, the behavior of the coupler shifts from adiabatic to resonant, which relies on the phase match condition and coupling strength between two waveguides. A longer taper length does not always results into lower coupling loss, which is clearly demonstrated in the loss maps for lateral misalignments of 1.6 µm and 1.8 µm. The resonant coupling effect in the taper region makes the coupler loss wavelength dependent and disrupts the broadband performance of the coupler. Nevertheless, properly selected lateral misalignment and taper length can benefit from

the resonant coupling to further improve the coupler loss and avoid the mode mismatch losses caused at the taper tips. As can be seen in Figure 1(d) that increasing the misalignment reduces the mode mismatch losses reduces.

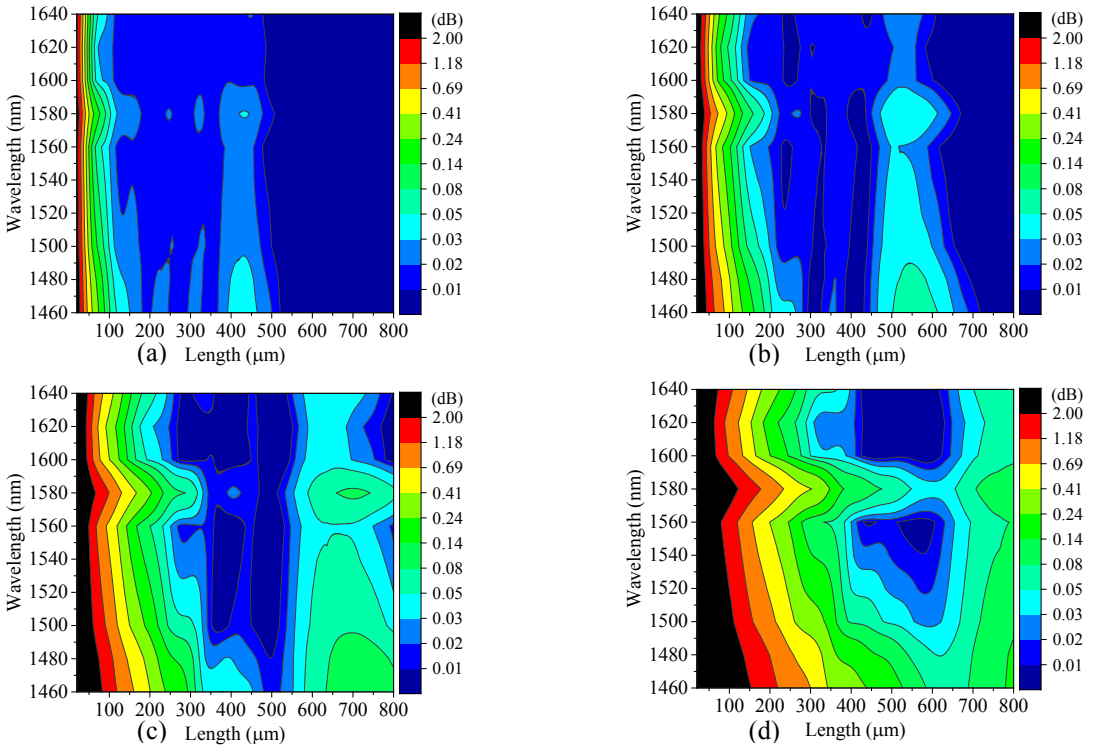

Figure 2. Loss of the coupling region calculated by 3D EME as a function of the taper length (x-axis) and wavelength (y-axis) at different lateral misalignments of (a) 1.2 μm, (b) 1.4 μm, (c) 1.6 μm and (d) 1.8 μm. The tip thickness of the Si_3N_4 waveguide is 30 nm.

Experimental results and discussions

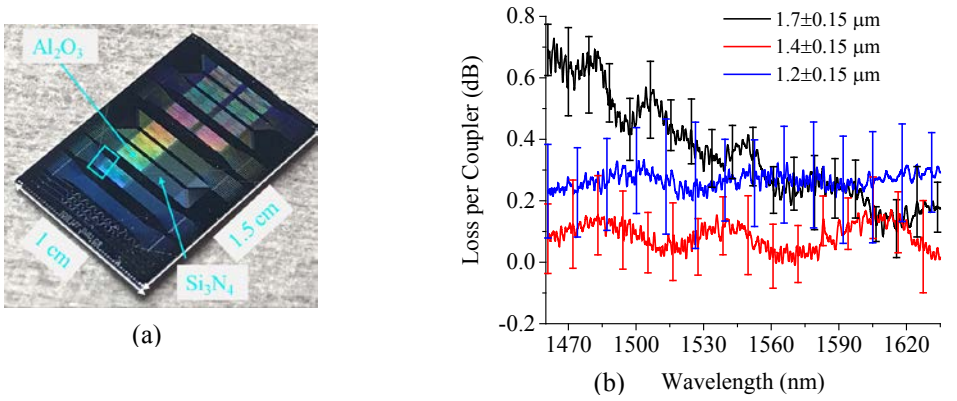

Figure 3. (a) Optical image of the fabricated coupler chip. (b) Measured loss per coupler of the fabricated couplers at lateral misalignments of 1.2 μm, 1.4 μm and 1.7 μm. The lateral misalignments are characterized by a calibrated microscope with a deviation of 0.15 μm. The taper length is 800 μm.

Since the work focuses on investigating the resonant coupling effect, Figure 3(a) shows the fabricated couplers. They are characterized with lateral misalignments of 1.1±0.15 μm, 1.4±0.15 μm and 1.7±0.15 μm determined by a calibrated optical microscope. In the spectral window of interest, namely 1460–1635 nm, the measured loss per coupler is plotted in Figure 3(b). The measured loss contains the mode mismatch

losses at the taper tips and the coupling loss from the taper region. The propagation losses originated from the Al_2O_3 waveguides, which ranges from 0.8 dB/cm at the wavelength of 1630 nm to 1.2 dB/cm at the wavelength of 1460 nm, are excluded in the measurement data. The resonant coupling effect becomes more obvious for the chips with larger lateral misalignment. Especially at the misalignment of 1.7±0.15 μm, the loss per coupler increases fast at a shorter wavelength, showing a good agreement with the expected tendency in Figure 2(d). At the lowest misalignment of 1.1±0.15 μm, the loss per coupler in the spectral window is larger than that at the misalignment of 1.4±0.15 μm. This increment is mainly due to the influence of the mode mismatch at the taper tips. A weak resonant coupling pattern can be observed in the coupler with lowest misalignment (1.2 μm). However, the simulation shows that there is almost no resonant coupling effect at such misalignment. We found that this resonant coupling at the nominal misalignment of 1.2 μm appears from the deviation of the fabricated value from the design value of the width of the Al_2O_3 waveguide tapers. Side-wall angle from the dry etching process makes the bottom width of the Al_2O_3 waveguide taper wider and increases the resonant coupling effect. Nevertheless, the measured data agrees with the tendency estimated from the simulation.

Conclusion

In this work, a resonant coupling effect of the Al_2O_3-Si_3N_4 coupler in our double-layer integrated platform is studied. Coupling loss <0.15 dB was experimentally achieved in the spectral window of 1460–1635 nm for the fabricated couplers with a lateral misalignment of 1.4±0.15 μm. It shows that the resonant coupling effect can further improve the coupler performance at a certain lateral misalignment and minimize the influence of mode mismatch losses at the taper tips, avoiding submicron lithography process and yielding good fabrication tolerances.

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