Tolerance Investigation of Low-loss Optical Couplers in Si_3N_4 technology

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A low-loss, broadband and high fabrication tolerant optical coupler is significantly required for the integration of various optical modules into a compact cost-effective device. However, its performance usually changes originating from fabrication uncertainties. Here, a tolerance investigation of various design parameters is carried out for the couplers between the Si_3N_4 *and various polymer materials. Low-loss operation is experimentally verified at both 976 nm and 1460–1635 nm wavelengths. Measured losses per coupler are found to be as low as 0.12 dB and 0.14 dB at 976 nm and 1550 nm respectively, paving the way for the integration of various active materials onto the* Si_3N_4 *platform.*

Introduction

The rapid development of integrated photonic technology increasingly demands to integrate various optical modules into compact cost-effective devices with high fabrication yield [1]. Optical coupling in these devices is among the most significant challenges for connecting information between the chips and the external world. Recently, numerous low-loss coupling have been extensively researched for fiber to chip coupling such as silicon to polymer [2] and silicon to silicon oxynitride [3] mode size converters. However, to obtain adiabatic coupling, their width is typically needed to be tapered down to tens of nm which requires high resolution patterning using electron-beam or stepper lithography. Or low-confinement waveguide core is requested to overcome the size limit and satisfy standard optical lithography [4]. Furthermore, the tolerance investigation mostly focuses on the lateral misalignment tolerance rather than quantitatively investigation of the tip dimensions [5]. Unlike lateral tapers, i.e. tapering the width, recent coupling based on vertical tapers, i.e. tapering the thickness, has achieved a good performance in on-chip coupling applications [6, 7]. Benefitting from isotropic etching process [8], the thickness can be vertically tapered thin enough to the cut-off condition of the modes, resulting in adiabatic coupling and broadband performance. In this work, design parameters such as the waveguide core dimensions, refractive index, and lateral misalignments are investigated, providing a further inspection about the influences of different parameters. An optimal case demonstrated shows the measured losses <0.2 dB at 976 nm wavelength and <0.25 dB in the spectrum range of 1460–1635 nm have been obtained within misalignment <1 μm.

Design and Simulation

Fig. 1 illustrates the cross-sections of the coupler and its 3D schematics. There is a layer of Norland Optical Adhesive (NOA-84) cladded on the top but it is not shown here. A 200 nm single-stripe Si_3N_4 layer is employed in this work, and SU-8 polymer is chosen. There are three losses. One is a mode mismatch loss at the tip of Si_3N_4 taper (α_{ab}).

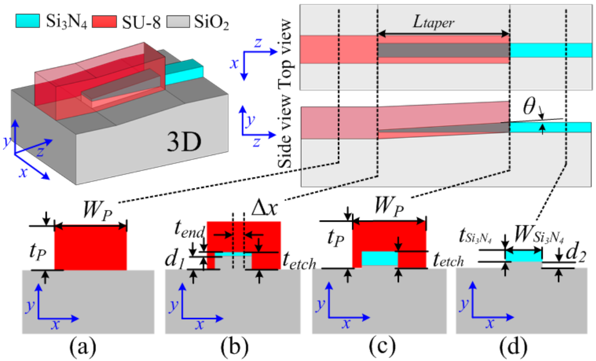

Fig. 1. Schematics of the coupler based on vertically tapered Si_3N_4 waveguide. (a) CS-a, (b) CS-b, (c) CS-c, and (d) CS-d. Refractive indices can be referred to the work of [7].

Another mode mismatch loss is from the facet of the polymer waveguide (α_{cd}). α_{ab} and α_{cd} can be calculated by overlapping the modes at the corresponding cross-sections, i.e. CS-a and CS-b, CS-c and CS-d. The third loss is from the coupling region between the CS-b and CS-c where the Si_3N_4 waveguide is vertically tapered. Fully etching the Si_3N_4 layer to create waveguides by rare-ion etching (RIE) inevitably causes the etching of SiO_2 underneath.

Mode mismatch losses α_{ab} are shown in Fig. 2(a)-(d) as functions of the Si_3N_4 waveguide thickness and the polymer waveguide width (W_p) at the wavelength of 980 nm (λ_p) and 1550 nm (λ_s). The etched depth of SiO_2 substrate are denoted as d_1 and d_2 for α_{ab} and α_{cd}. d_1 of 200 nm and 400 nm are investigated for the CS-b. The regions where $\alpha_{ab} <$ 0.1 dB and < 0.02 dB at λ_p and λ_s shifts along the increasing direction of the Si_3N_4 thickness with d_1 rises. α_{ab} is not sensitive to the variation of W_P for both cases of d_1, but it is generally larger at λ_p than that at λ_s. Seen from the figures, $t_{Si_3N_4}$ in the range of 30–50 nm is recommended. For the mode mismatch loss α_{cd}, d_2 of 40 nm and 400 nm is studied. The low-loss regions in Fig. 2(e)-(h) where α_{cd} is <0.05 dB at λ_p and <0.1 dB at λ_s moves along the reducing direction of $t_{Si_3N_4}$ with the increase of d_2, α_{cd} only significantly increases when $t_{Si_3N_4}$ is <150 nm at λ_p and <200 nm at λ_s, and becomes very sensitive to the variation of the Si_3N_4 width. Considering single-mode operation at λ_s, $W_{Si_3N_4}$ has to be below 1.5 µm at $t_{Si_3N_4}$ = 200 nm. Therefore, the thickness of Si_3N_4 waveguide is proposed to be ⩾200 nm so that the low-loss regions can be achieved for all d ranging from 40–400 nm.

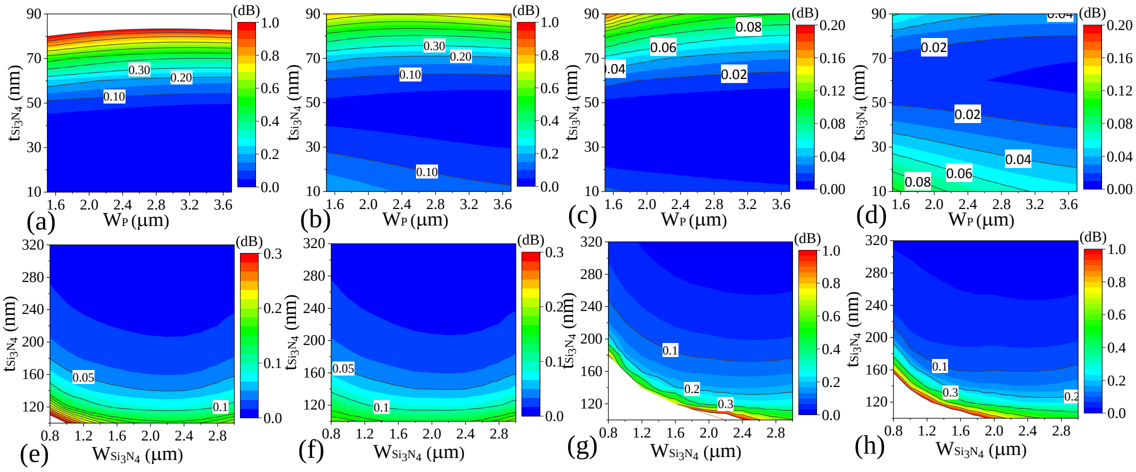

Fig. 2. Top row: α_{ab} as functions of $t_{Si_3N_4}$ and W_p: at d_1 of (a) 200 nm and (b) 400 nm at λ_p; (c) and (d) are those at λ_s for cases of d_1 of 200 nm and 400 nm respectively. The thickness of the polymer (t_P) is 1.8 µm, and $W_{Si_3N_4}$ = 1.3 µm. Bottom low: α_{cd} as functions of Si_3N_4 waveguide dimensions: at d_2 of (e) 40 nm and (f) 400 nm at λ_p; (g) and (h) are these values at λ_s for cases of d of 40 nm and 400 nm respectively. W_p is 2 µm and t_p is 1.8 µm.

Since the etching rates of Si_3N_4 and SiO_2 are observed to be very similar (30–35 nm/min), t_{etch} at the CS-b, CS-c and CS-d are regarded as the same. Fig. 3(a) shows the total mode mismatch loss (α_{c1}) as a function of t_{etch}. At λ_p, the loss for the case with t_{end} of 50 nm is higher than others and it reduces when the t_{etch} increases because of better center-center mode matching with CS-b. However, its α_{c1} at t_{end} = 20 nm rises reversely with the increase of t_{etch} though the mode is cut-off in the taper core because of additional mode mismatch loss from the etched SiO_2. Such patterns are not obvious for the mode at λ_s due to its less confinement. The variation of α_{c1} < 0.02 dB is regarded as tolerant to change of t_{etch}. Therefore, a tip thickness of 30–40 nm is suggested. Since α_{c1} curves at both wavelengths varies more in parallel at t_{end} = 40 nm than others, this value is eventually selected for the further demonstration. In addition, α_{c1} are investigated for various polymer materials with refractive index (n_p) of 1.54–1.7. A variation of n_p within 0.005 around the nominal value (1.574) increases α_{c1} below 0.016 dB at λ_s but almost negligible at λ_p, which is acceptable because n_p of SU-8 polymer varies much less than 0.005. Nevertheless, by giving any polymer, the most optimal range of n_p can be extracted by recalculating the parameters of the cross-sections.

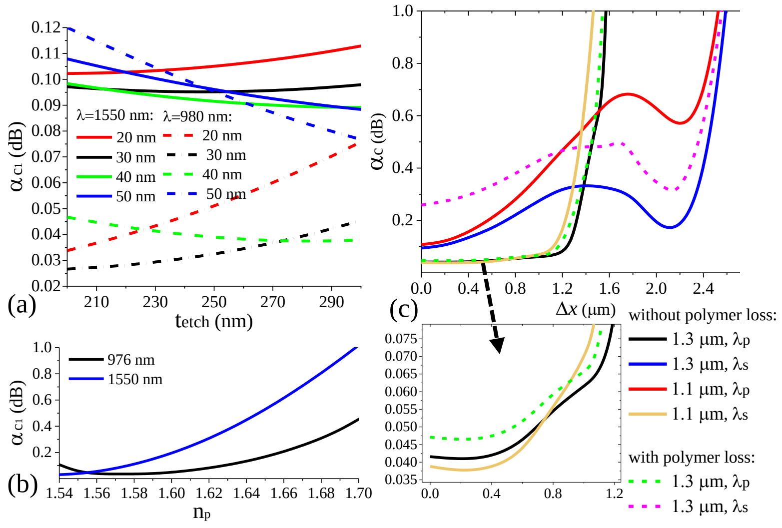

Fig. 3. (a) α_{c1} for the cases with different t_{end} as a function of total etched depth (i.e. t_{etch}). (b) α_{c1} as a function of the refractive index of the polymer. (c) α_c as a function of Δx. In (a), the widths of Si_3N_4 waveguide and polymer waveguide are 1.3 μm and 2 μm respectively.

Fig. 3(c) shows the total coupler loss (α_c) which includes two mode mismatch losses and the coupling loss in the vertical taper region as a function of lateral misalignment between the Si_3N_4 and polymer waveguide (Δx). Without considering the propagation loss of polymer waveguide, the coupler losses are calculated as 0.042 dB at λ_p and 0.095 dB at λ_s at Δx = 0 μm, showing good agreement with α_{c1}, which further confirms the adiabaticity of the vertical Si_3N_4 taper. α_c at $W_{Si_3N_4}$ = 1.1 μm is also presented and it is less tolerant to the variation of Δx as compared to the one at $W_{Si_3N_4}$ = 1.3 μm. Appling the measured propagation loss of polymer [Fig. 4(a)] to the EME simulation model, α_c at λ_s rises immediately because of additional loss in coupling region. Furthermore, a valley in α_c curve occurs at Δx ~2.1 μm. This is mainly because of tapered directional coupling after Δx of 1.7 μm but it is beyond the scope of this work.

Experimental Results

The measured tip thickness is ~52±10 nm which is much larger than expected, the rest parameters are within uncertainty range. Similar setup in the work of [4] was employed and the measurement data from cascaded couplers were processed following the method reported in our recent work of [7]. Fig. 4(a) demonstrates the measured loss per coupler versus the calculated one, and the propagation loss of SU-8 polymer. The coupler shows lower loss for a short wavelength because of its smaller mismatch loss at the facet of the polymer waveguide. More complete measurement for the couplers at different misalignment is shown in Fig. 4(b). The lowest loss is extracted to be 0.14 ± 0.02 dB at 1550 nm. Furthermore, at 976 nm, the lowest loss of 0.12 ± 0.04 dB is obtained. The measured losses are still below 0.2 dB at λ_p and below 0.25 dB in the spectrum range for misalignment <1 μm.

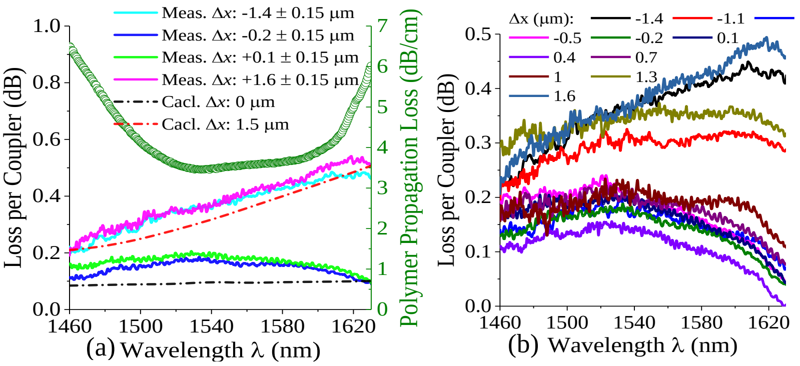

Fig. 4. (a) Measured propagation-n loss of the SU-8 polymer waveguide and loss per coupler after eliminating the loss of polymer waveguide. (b) Measured loss per coupler at various misalignment values.

Conclusion

Tolerance to various design parameter is investigated for the couplers between monolithically integrated Si_3N_4 and polymer waveguides. Low-loss and broadband operation is experimentally demonstrated using SU-8 polymer at 976 nm and 1460–1635 nm wavelengths. Measured losses per coupler are found to be as low as 0.12 dB and 0.14 dB at 976 nm and 1550 nm respectively, and paving the way for the integration of various active materials onto the Si_3N_4 platform.

Acknowledgements

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