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$_3$N$_4$ 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$_3$N$_4$ 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$_3$N$_4$ 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$_3$N$_4$ taper ($\alpha_{ab}$).
Another mode mismatch loss is from the facet of the polymer waveguide ($\alpha_{cd}$). $\alpha_{ab}$ and $\alpha_{cd}$ 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$_3$N$_4$ waveguide is vertically tapered. Fully etching the Si$_3$N$_4$ layer to create waveguides by rare-ion etching (RIE) inevitably causes the etching of SiO$_2$ underneath.

Mode mismatch losses $\alpha_{ab}$ are shown in Fig. 2(a)-(d) as functions of the Si$_3$N$_4$ waveguide thickness and the polymer waveguide width ($W_p$) at the wavelength of 980 nm ($\lambda_p$) and 1550 nm ($\lambda_s$). The etched depth of SiO$_2$ substrate are denoted as $d_1$ and $d_2$ for $\alpha_{ab}$ and $\alpha_{cd}$. $d_1$ 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 $\lambda_p$ and $\lambda_s$ shifts along the increasing direction of the Si$_3$N$_4$ thickness with $d_1$ rises. $\alpha_{ab}$ is not sensitive to the variation of $W_p$ for both cases of $d_1$, but it is generally larger at $\lambda_p$ than at $\lambda_s$. Seen from the figures, $t_{Si_3N_4}$ in the range of 30–50 nm is recommended. For the mode mismatch loss $\alpha_{cd}$, $d_2$ of 40 nm and 400 nm is studied. The low-loss regions in Fig. 2(e)-(h) where $\alpha_{cd}$ is $< 0.05$ dB at $\lambda_p$ and $< 0.1$ dB at $\lambda_s$ moves along the reducing direction of $t_{Si_3N_4}$ with the increase of $d_2$. $\alpha_{cd}$ only significantly increases when $t_{Si_3N_4}$ is $< 150$ nm at $\lambda_p$ and $< 200$ nm at $\lambda_s$, and becomes very sensitive to the variation of the Si$_3$N$_4$ width. Considering single-mode operation at $\lambda_s$, $W_{Si_3N_4}$ has to be below 1.5 $\mu$m at $t_{Si_3N_4} = 200$ nm. Therefore, the thickness of Si$_3$N$_4$ waveguide is proposed to be $\geq 200$ nm so that the low-loss regions can be achieved for all $d$ ranging from 40–400 nm.

![Fig. 2](image-url)
Since the etching rates of Si3N4 and SiO2 are observed to be very similar (30–35 nm/min), $t_{\text{etch}}$ at the CS-b, CS-c and CS-d are regarded as the same. Fig. 3(a) shows the total mode mismatch loss ($\alpha_{c1}$) as a function of $t_{\text{etch}}$. At $\lambda_p$, the loss for the case with $t_{\text{end}}$ of 50 nm is higher than others and it reduces when the $t_{\text{etch}}$ increases because of better center-center mode matching with CS-b. However, its $\alpha_{c1}$ at $t_{\text{end}} = 20$ nm rises reversely with the increase of $t_{\text{etch}}$ though the mode is cut-off in the taper core because of additional mode mismatch loss from the etched SiO2. Such patterns are not obvious for the mode at $\lambda_s$ due to its less confinement. The variation of $\alpha_{c1} < 0.02$ dB is regarded as tolerant to change of $t_{\text{etch}}$. Therefore, a tip thickness of 30–40 nm is suggested. Since $\alpha_{c1}$ curves at both wavelengths varies more in parallel at $t_{\text{end}} = 40$ nm than others, this value is eventually selected for the further demonstration. In addition, $\alpha_{c1}$ 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 $\alpha_{c1}$ below 0.016 dB at $\lambda_s$ but almost negligible at $\lambda_p$, 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](image)

Fig. 3. (a) $\alpha_{c1}$ for the cases with different $t_{\text{end}}$ as a function of total etched depth (i.e. $t_{\text{etch}}$). (b) $\alpha_{c1}$ as a function of the refractive index of the polymer. (c) $\alpha_c$ as a function of $\Delta x$. In (a), the widths of Si3N4 waveguide and polymer waveguide are 1.3 μm and 2 μm respectively.

the adiabaticity of the vertical Si3N4 taper. $\alpha_c$ at $W_{\text{Si3N4}} = 1.1$ μm is also presented and it is less tolerant to the variation of $\Delta x$ as compared to the one at $W_{\text{Si3N4}} = 1.3$ μm. Applying the measured propagation loss of polymer [Fig. 4(a)] to the EME simulation model, $\alpha_c$ at $\lambda_s$ rises immediately because of additional loss in coupling region. Furthermore, a valley in $\alpha_c$ curve occurs at $\Delta x \approx 2.1$ μm. This is mainly because of tapered directional coupling after $\Delta x$ 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 \( \lambda_p \) and below 0.25 dB in the spectrum range for misalignment <1 \( \mu m \).

Conclusion
Tolerance to various design parameter is investigated for the couplers between monolithically integrated Si3N4 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 Si3N4 platform.

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References