Low-loss, broadband and high fabrication tolerant vertically tapered optical couplers for monolithic integration of Si$_3$N$_4$ and polymer waveguides

JINFENG MU,$^{1,*}$ MEINERT DIJKSTRA,$^1$ YEAN-SHENG YONG,$^1$ FRANS B. SEGEBINK,$^1$ KERSTIN WÖRHOF$^2$, MARCEL HOEKMAN,$^2$ ARNE LEINSE,$^2$ AND SONIA M. GARCÍA-BLANCO$^1$

$^1$Optical Sciences Group, MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands
$^2$LioniX International, P.O. Box 456, 7500 AL Enschede, The Netherlands

*Corresponding author: j.mu@utwente.nl

Received 6 July 2017; revised 24 August 2017; accepted 28 August 2017; posted 30 August 2017 (Doc. ID 296275); published 21 September 2017

The rapid development of integrated photonic technology increasingly demands reliable methods to integrate various optical modules into a compact cost-effective device with a high fabrication yield [1]. With an ultra-low propagation loss down to 0.1 dB/m, a large transparency window covering the 400–2350 nm wavelength range and a highly reproducible fabrication process [2], stoichiometric silicon nitride (Si$_3$N$_4$) deposited with low-pressure chemical vapor deposition (LPCVD), appear as one of the most versatile commercially available integrated photonic platforms. Benefiting from the abovementioned advantages, the TriPleX platform has been widely employed in diverse fields such as telecommunications [3], bio-sensing [4], and nonlinear optics [5].

Many active devices have been realized in polymers such as efficient tunable filters [6], high-speed modulators [7], lasers [8], and amplifiers [9], owing to their low-cost, ease of fabrication, and fairly high thermo-optic and electro-optic (EO) coefficients. Particularly, the integration of an EO polymer with low-loss silicon nitride and oxynitride waveguides has increased the tunability [6] and decreased the attenuation of all-polymer modulators [7].

In recent years, numerous low-loss coupling solutions have been demonstrated on a silicon-on-insulator platform. Examples include silicon to polymer [10,11] and silicon to silicon oxynitride [12] waveguide mode size converters for optical interconnects or fiber-to-chip coupling. These converters are typically based on narrow silicon inverse lateral tapers (<50 nm tip width) fabricated by electron-beam or stepper lithography. Adiabatic width-tapered Si$_3$N$_4$ waveguides have been utilized for fiber-to-chip coupling on Si$_3$N$_4$ platform, resulting in >90% coupling efficiency within 1450–1650 nm wavelength range [13]. On-chip coupling of a single-stripe Si$_3$N$_4$ waveguide to a dual-stripe Si$_3$N$_4$ waveguide by tapering the thickness of the top Si$_3$N$_4$ layer of the dual-stripe waveguide has been demonstrated with ~0.5 dB loss [14], while recently optimized mode size converters show negligible loss. Si$_3$N$_4$-polymer flip-chip couplers for the hybrid integration of Si$_3$N$_4$ and polymer waveguides by tapering the widths of the Si$_3$N$_4$ and polymer waveguides have shown <0.8 dB loss per coupler [15].

In this Letter, a low-loss, broadband and high fabrication tolerant coupler for interconnecting polymer and Si$_3$N$_4$ waveguides based on a Si$_3$N$_4$ adiabatic vertically tapered coupler is presented. Since the target application is the development of erbium-doped waveguide amplifiers and lasers, the couplers are optimized to operate at both 980 and 1460–1635 nm wavelengths. Losses per coupler as low as 0.12 dB at 976 nm and 0.14 dB at 1550 nm are measured. The couplers are highly tolerant to the lateral misalignment between the Si$_3$N$_4$ and polymer waveguides.

Figure 1 shows the 3D schematic, as well as the top and side views, of the coupler and its cross sections (CSS) at different locations along the coupler. A layer of Norland Optical Adhesive (NOA-84) is deposited as cladding in the final chip to prevent damage to the waveguides (not shown in Fig. 1). SU-8 is the polymer employed for this demonstration. The refractive indices of Si$_3$N$_4$, polymer, NOA-84, and SiO$_2$ are characterized using a prism coupler (Metricon 2010/M) and by ellipsometry (Woollam M-2000UI) at the two wavelength regions of interest (see Table 1).
The adiabatic vertical Si$_3$N$_4$ taper plays an essential role in the performance of the optical coupler. The thickness of the Si$_3$N$_4$ layer can be gradually tapered down to the desired value with a vertical taper angle $\theta$ of $\sim 0.013^\circ$, which is defined by the optimized wet etching process used to realize the vertical tapers. Therefore, tapers with tip height in the nanometer range can be fabricated using an ultraviolet (UV) contact lithography tool. Adiabatic coupling between the confined modes of the polymer waveguide (CS-a) and the Si$_3$N$_4$ waveguide (CS-d) takes place in the region between the Si$_3$N$_4$ taper tip (CS-b) and the polymer waveguide facet (CS-c).

The total losses of the optical couplers are given by the loss in the coupling region which, under adiabatic conditions, is mainly due to the mismatch losses at the abrupt interfaces at the polymer waveguide facet (CS-c) and at the Si$_3$N$_4$ vertical taper tip (CS-b), plus the propagation losses caused by material absorption and fabrication errors. The mismatch losses originate from mode and effective refractive index differences between the modes at the sides of the discontinuity. The total mode mismatch loss, $\alpha_{\text{total}}$, is calculated as $\alpha_{\text{total}} = \alpha_{\text{ab}} + \alpha_{\text{cd}}$, where $\alpha_{\text{ab}}$ and $\alpha_{\text{cd}}$ are mode mismatch losses at the tip of the Si$_3$N$_4$ taper and at the facet of the polymer waveguide. The same methodology used for the design of optimal flip-chip couplers [15] is used here. First, the mode mismatch losses are calculated by means of a 2D mode solver, and the optimal waveguide CS parameters are selected. Then, the 3D eigenmode expansion (EME) method simulations are carried out to calculate the losses induced in the coupler region (between CS-c and CS-b), as well as the misalignment tolerance. The propagation loss of the different materials was not included in the calculation model, as the objective of this Letter is to minimize the losses originating from the coupler itself. The couplers are designed for TE polarization.

Table 1. Refractive Indices of the Materials Employed

<table>
<thead>
<tr>
<th>$\lambda$ (nm)</th>
<th>Si$_3$N$_4$</th>
<th>Polymer</th>
<th>NOA-84</th>
<th>SiO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>980</td>
<td>1.994</td>
<td>1.581</td>
<td>1.52</td>
<td>1.449</td>
</tr>
<tr>
<td>1550</td>
<td>1.984</td>
<td>1.574</td>
<td>1.51</td>
<td>1.446</td>
</tr>
</tbody>
</table>

Figures 2(a) and 2(b) show the mode mismatch losses, $\alpha_{\text{ab}}$, at the wavelengths of 980 and 1550 nm. In these simulations, the thickness of the polymer waveguide $L_w$ is 1.8 $\mu$m. The etched depth into the SiO$_2$ under-cladding at the Si$_3$N$_4$ taper tip [Fig. 1(b) CS-b] is 200 nm, and the width of the Si$_3$N$_4$ waveguide $W_{\text{SiN}_4}$ is 1.3 $\mu$m. As can be seen in Fig. 2, the design is very tolerant to the variations of the width of both polymer and Si$_3$N$_4$ waveguides. The polymer width $W_p$ of 2 $\mu$m is selected to ensure single-mode (SM) operation at 1550 nm. The width of the Si$_3$N$_4$ waveguide was selected to be 1.3 $\mu$m for the same consideration, as well as to increase the tolerance to the lateral misalignment, defined as $\Delta x$, as it will be discussed below. At the polymer facet (CS-c), the thicker the Si$_3$N$_4$ core, the more confined the mode is in the Si$_3$N$_4$ waveguide, reducing the mode mismatch losses $\alpha_{\text{cd}}$ as shown in Figs. 2(c) and 2(d). A thickness of 200 nm was chosen for the Si$_3$N$_4$ waveguide at the CS-c. At the Si$_3$N$_4$ taper tip (CS-b), the mode mismatch losses are very sensitive to the thickness of the Si$_3$N$_4$ taper $t_{\text{end}}$. Therefore, the thickness of the Si$_3$N$_4$ taper tip at the CS-b is one of the most critical parameters in the coupler design. 3D EME simulations showed negligible intermodal coupling losses at 980 nm, provided that adiabaticity is preserved.

Figure 3(a) shows the simulated total mode mismatch losses $\alpha_{\text{ab}}$ as a function of the thickness of the Si$_3$N$_4$ taper $t_{\text{end}}$. It can be seen that $\alpha_{\text{ab}}$ is much more tolerant to the variation of $t_{\text{end}}$ ranging from 20 to 60 nm at 1550 nm than that at 980 nm. Nevertheless, as compared to $\alpha_{\text{cd}}$, at 1550 nm, $\alpha_{\text{cd}}$ at 980 nm is significantly lower for $t_{\text{end}}$ values ranging within 30–40 nm, where the change of $\alpha_{\text{cd}}$ with tip thickness is also very small. The influence of total etched depth $t_{\text{etch}}$ on $\alpha_{\text{ab}}$ is demonstrated in Fig. 3(b). The same $t_{\text{etch}}$ value is considered for both CS-b and CS-c, since the etch rates of Si$_3$N$_4$ and SiO$_2$ are similar in our fabrication process. For a nominal value of $t_{\text{etch}} = 40$ nm, $\alpha_{\text{ab}}$ slightly decreases/increases at both wavelengths with the increase/decrease of $t_{\text{etch}}$. The changes are $<0.01$ dB. The design is also very tolerant to the variation of the refractive index of the SU-8 polymer. A variation of the refractive index within 0.005 around the nominal value increases $\alpha_{\text{ab}}$ below 0.016 dB at 1550 nm. The increase is negligible at 980 nm.

![Fig. 1. Top: 3D schematic, top and side views of the optical coupler with an adiabatic Si$_3$N$_4$ vertical taper. Bottom: CSs at (a) the polymer waveguide core (CS-a), (b) the tip of vertical Si$_3$N$_4$ taper (CS-b), (c) the facet of a polymer waveguide (CS-c), and (d) the Si$_3$N$_4$ waveguide core (CS-d). Note: the devices have an upper-cladding of NOA-84 (not shown).](image-url)

![Fig. 2. $\alpha_{\text{ab}}$ at wavelengths of (a) 980 and (b) 1550 nm with $W_{\text{SiN}_4} = 1.3$ $\mu$m. $\alpha_{\text{cd}}$ at (c) 980 and (d) 1550 nm with $W_p = 2$ $\mu$m. Other parameters: $t_p = 1.8$ $\mu$m and $t_{\text{etch}} = 240$ nm.](image-url)
This is because the coupler losses are dominated by lateral misalignments at 980 nm. Fig. 3 shows the total coupler losses $\alpha$ as a function of lateral misalignment $\Delta x$ between the Si$_3$N$_4$ and polymer waveguides calculated by a combination of 2D mode solver and 3D EME simulations applied between CS-b and CS-c. At the Si$_3$N$_4$ taper tip thickness of 40 nm, the losses of a perfectly aligned coupler are calculated as 0.042 dB at 980 nm and 0.092 dB at 980 and 1550 nm.

Figure 4 shows the total coupler losses $\alpha$ as a function of lateral misalignment $\Delta x$ between the Si$_3$N$_4$ and polymer waveguides calculated by a combination of 2D mode solver and 3D EME simulations applied between CS-b and CS-c. At the Si$_3$N$_4$ taper tip thickness of 40 nm, the losses of a perfectly aligned coupler are calculated as 0.042 dB at 980 nm and 0.092 dB at 980 and 1550 nm. The results have good agreement with the total mismatch loss computed by a 2D mode solver, confirming the adiabaticity of the vertical Si$_3$N$_4$ taper. The coupler losses are more tolerant to lateral misalignments at 980 nm. This is because the coupler losses are dominated by $\alpha_{cd}$ (i.e., mismatch losses at the polymer waveguide facet). The higher confinement of the mode to the Si$_3$N$_4$ core at 980 nm makes $\alpha_{cd}$ more tolerant to lateral misalignments at this wavelength. At 1550 nm, the higher confinement of the mode in the 1.3 μm wide Si$_3$N$_4$ waveguide core, with respect to the one with $W_{Si3N4} = 1.1 \mu m$, makes this dimension more tolerant to the lateral misalignment. Alignment accuracies below 1 μm are easily attainable with the lithography machine (EVG620) utilized in this Letter.

The Si$_3$N$_4$ waveguides with adiabatic vertical Si$_3$N$_4$ tapers were fabricated by Lionix B. V. [2]. A 200 nm thick Si$_3$N$_4$ layer was deposited by LPCVD at 750–800°C. The vertical tapers were fabricated by UV lithography and isotropic wet etching of the Si$_3$N$_4$ layers [16]. The Si$_3$N$_4$ waveguide cores were patterned by UV lithography and reactive ion etching. The measured dimensions of the fabricated waveguides are shown in Table 2, line B. Figure 5 shows a focused ion beam image of the CS of one of the fabricated waveguides at two locations along the taper separated by 300 μm, confirming the constant $t_{etch}$ along the taper, as well as a taper angle of 0.013°.

In the chip layout, groups of waveguides with different numbers of cascaded couplers $N$, with $N = 6, 18, \text{and } 30$, were included. Within each group, different misalignments between the Si$_3$N$_4$ and polymer waveguide cores were introduced “by design.” Straight waveguides (i.e., without couplers) were introduced as a reference. An optical measurement setup similar to that reported in Ref. [15] was used, in which a polarization maintaining fiber (PM980-XP) and an SM fiber (SM-1550) were used for input and output, respectively, at 1550 nm, and high numerical aperture fibers (UHNA3) were used for both input and output at 976 nm. The total insertion loss ($\alpha_{tot}$) is measured for the waveguides with cascaded couplers. The fiber-to-chip edge coupling losses, as well as the propagation losses accumulated in the Si$_3$N$_4$ waveguide section outside the couplers, are almost completely factored out by subtracting the insertion loss of a reference Si$_3$N$_4$ straight waveguide on the same chip ($\alpha_{ref}$), which is measured as 9.7 dB at 976 nm and 16.9 dB at 1550 nm, and assuming identical fiber-to-chip coupling coefficients for each waveguide. An average loss per coupler $\bar{\alpha}$ is obtained from the fitted slope of $\alpha_{w} - \alpha_{ref}$ over the number of cascaded couplers. The average loss contains the propagation loss of the polymer waveguide sections, which includes the 700 μm long polymer taper, plus half of the 300 μm long section connecting adjacent couplers. The propagation losses of the SU-8 polymer waveguides used in this Letter are measured using the cutback method as 0.32 and 3.53 dB/cm at 976 and 1550 nm, respectively. The loss per coupler is obtained by subtracting the total propagation loss of the polymer from the average measured coupler loss.

The propagation loss induced by the Si$_3$N$_4$ waveguide in the coupler section was considered negligible, due to the low
The measured coupler losses as a function of the lateral misalignment are shown in Fig. 6(a). The lowest losses are measured at 976 nm and 1550 nm wavelengths. The solid lines are calculated for the nominal parameters and dotted lines for the fabricated parameters (Table 2). (b) measured loss per coupler in the spectral window of 1460–1635 nm. The dotted lines are for calculated losses for the nominal structure.

The measured coupler losses as a function of the lateral misalignment are shown in Fig. 6(a). The lowest losses are measured to be 0.12 ± 0.04 dB at a 976 nm wavelength and 0.14 ± 0.02 dB at a 1550 nm wavelength. At 976 nm, average measured coupler losses are between 0.12 and 0.2 dB for misalignments <1 μm and are still below 0.32 dB for misalignments up to 1.6 μm. The insensitive response to the misalignment variation agrees with the simulation shown in Fig. 4. At 1550 nm, average losses of 0.14–0.19 dB are obtained for misalignments below 1 μm. As clearly seen in Fig. 6(a), a deviation between the calculated and measured results of ∼0.08–0.15 dB occurs at 976 nm for misalignments below 1 μm. The origin of such a deviation is probably caused by the thicker Si3N4 taper tip obtained after fabrication (i.e., 52 ± 10 nm versus the 40 nm target), which results in the higher mode mismatch loss $\alpha_{ab}$. As expected from Fig. 2(a), a thicker Si3N4 taper tip can account for this difference. At 976 nm, the total mode mismatch loss increases by 0.07–0.13 dB for taper tip thicknesses ranging between 52 and 56 nm, which is within the thickness uncertainty of the measured individual Si3N4 taper tips. A smaller effect is expected at 1550 nm, which is confirmed by the experimental data. Additionally, the propagation loss of a vertically tapered Si3N4 waveguide is potentially larger than the straight Si3N4 waveguide due to the extra surface roughness that can lead to increased scattering loss, especially at 976 nm. Figure 6(b) shows the measured average losses of mode converters in the 1460–1635 nm wavelength range for different misalignments. For large misalignments, e.g., $\Delta x$ of 1.4 and 1.6 μm, the mode at shorter wavelengths experiences lower loss due to its smaller mismatch loss at the tip of the polymer waveguide.

In summary, a low-loss, broadband and highly tolerant vertical coupler based on an adiabatic vertical Si3N4 taper is presented for the monolithic integration of Si3N4 and polymer waveguides. The influence of the different design parameters on the loss of the couplers was reported. The fabricated couplers exhibit losses as low as 0.12 and 0.14 dB at 976 and 1550 nm wavelengths, respectively. For lateral Si3N4-polymer misalignments <1 μm, average losses less than 0.2 dB are achieved at both wavelengths. The measured losses are still below 0.27 and 0.38 dB for a misalignment <1.6 μm. The performance of the couplers in the spectral range of 1460–1635 nm agrees with the design. Further performance improvement could be achieved by choosing the optimal value of $t_{ch}$ after the measurement of the obtained $e_{end}$ and tapering in both lateral and vertical directions. This robust optical coupling solution potentially paves the way for the integration of various active materials onto the Si3N4 platform.

**Funding.** Stichting voor de Technische Wetenschappen (STW) (STW-13536).

**Acknowledgment.** The authors thank S. A. Vázquez-Córdova, L. Chang, M. de Goede, and C. I. van Emmerik for useful discussions.

**REFERENCES**