Low-loss multimode flip-chip couplers for the hybrid integration of Si_3N_4 and polymer waveguides

Jinfeng Mu, Meindert Dijkstra, Yean-Sheng Yong, Sergio A. Vázquez-Córdova and Sonia M. García-Blanco, *Member, IEEE*
Optical Sciences Group, MESA+ Institute for Nanotechnology, University of Twente
P.O. Box 217, 7500 AE Enschede, The Netherlands, e-mail: j.mu@utwente.nl

In this paper, low-loss vertical couplers under multimode condition are presented for the integration of polymer waveguides onto Si_3N_4/SiO_2 platform. Lateral misalignment between polymer and Si_3N_4 waveguides is within 1.25 μm. For Si_3N_4 taper angles larger than 0.8°, the coupler losses are measured to be below 0.8 dB, which are in good agreement with the calculation. Furthermore, thermal shock test results show less than 0.1 dB degradation, indicating a robust coupling performance.

Introduction

Recent years, due to its ultra-low propagation loss of <1 dB/m in the C-band [1] and large transparency window, i.e. 0.4-2.35 μm [2], the passive Si_3N_4 platform integrated with other materials such as polymer [3], InGaAs [4] and rare-earth-ion-doped Al_2O_3 [5] has attracted significant interest. Especially the integration with cost-effective polymer materials has led to the demonstration of power-efficient thermally tunable filters [3] and fast modulators [6] (>100 GHz) because of their electro-optic effect as well as good efficiency for heat insulation.

Still, the low-loss optical coupling between chips remains one of the biggest challenges. In hybrid integration, adiabatic vertical coupler gradually varies the effective refractive index of the propagating mode by changing the waveguide dimension to achieve high coupling efficiency and tolerance to fabrication errors. Mode mismatch losses caused by the abrupt geometry changes at the taper tips are not further investigated [7], [8]. One reason is that the tip of the SOI taper is always made to reach the cut-off condition by means of electron-beam or stepper lithography. The other is that the highly confined mode in the SOI core is hardly interrupted by the taper tips of other materials. However, the mode mismatches at the taper tips in the Si_3N_4 platform with ultra-low propagation loss play a predominant role in the overall losses of the device and an optimal design is required. This is especially significant when using contact optical lithography with a relatively large resolution limit (>0.8 μm).

In this paper, low-loss flip-chip couplers under the MM condition for hybrid integration in Si_3N_4/SiO_2 technology are presented. The vertical couplers are designed by combining two-dimensional (2D) film mode matching (FMM) method and three-dimensional (3D) eigenmode expansion method (EME). The couplers are fabricated and experimentally verified in the spectral window of 1.48-1.56 μm both before and after thermal shock tests.

Chip Design

Fig. 1 shows a 3D schematic of the vertical coupler and the corresponding cross-sections (CS) at different locations along the propagation direction. To transfer the mode field vertically between the Si_3N_4 and polymer waveguides, both the Si_3N_4 and polymer waveguides are linearly tapered in the coupling region, i.e., between the CS at (b) and (d). The device is designed to work for the transverse-electric (TE) polarization. The refractive indices of the SiO_2, NOA adhesive, SU-8, and the Si_3N_4 layers at a

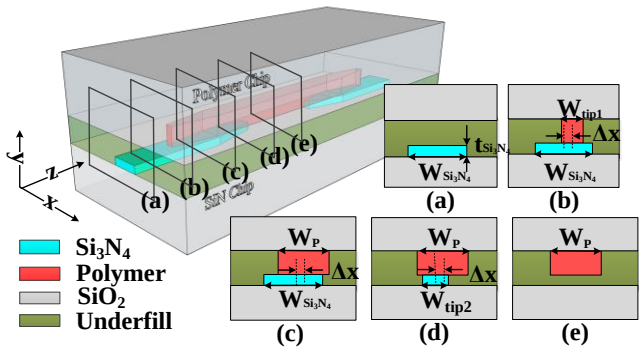

Fig. 1. 3D schematic of vertical coupler at the cross-sections: (a) Si_3N_4 waveguide input/output, (b) the polymer taper tip, (c) the start of polymer/Si_3N_4 taper, (d) the Si_3N_4 taper tip, and (e) polymer waveguide input/output.

wavelength of 1.55 μm are 1.4491, 1.509, 1.574 and 1.9835 respectively for TE polarization, as determined experimentally (Metricon 2010/M and Woollam M-2000UI).

To obtain optimal parameters, the design hybrids 2D mode solver and 3D EME solver. In the mode calculation, the mode mismatch losses between the CS (a) and (b), α_1 and between the CS (d) and (e), α_2, are computed from the mode overlap coefficient Γ of the fundamental TE modes at both CSs as $-10\,log_{10}\Gamma$. Under the adiabatic condition, the coupler loss (α_c) can be estimated by the sum of α_1 and α_2 (in dB) if the propagation losses can be considered negligible. Fig. 2(a) shows the values of α_1, in which the smaller the thickness of the polymer (t_P), the lower the mismatch loss α_1. The opposite occurs at the tip of the Si_3N_4 taper tip, where lower α_2 requires the bigger t_P, as shown in Fig. 2(b). In order to achieve high tolerance to the lateral Si_3N_4-polymer misalignment, the mode should be designed to be less confined with a large mode diameter. Thus thicknesses for the Si_3N_4 and polymer layers of 90 nm and 0.5 μm are selected. The calculated coupler total losses are shown in Fig. 2(c). A minimum coupler loss of 0.4 dB is found at W_{Si3N4} = 2.9 μm and W_P = 2.5 μm respectively. A case in the MM region that supports 3 TE modes in both polymer and Si_3N_4 waveguide cores, i.e. $W_{Si_3N_4}$ = 3 μm and W_P = 3.5 μm, is selected.

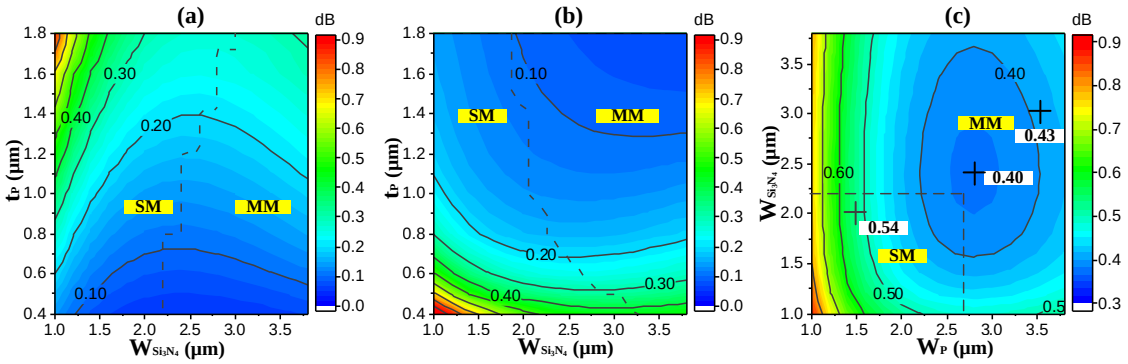

Fig. 2. (a) Mode mismatch loss, α_1; (b) mode mismatch loss, α_2; (c) total loss, α_c. At the polymer thickness of 0.5 μm. The tip widths of both polymer and Si_3N_4 tapers are 0.8 μm. The thickness of the Si_3N_4 layer is 90 nm. Single-mode and multimode conditions of the device are separated by the dashed lines.

3D structures are then constructed with the selected values of Si_3N_4 and polymer thicknesses and widths to perform EME simulations to determine the propagation losses neglected by the 2D FMM method, namely the taper loss due to conversion to radiation modes and reflections at the taper tip cross-sections. The verification is implemented by comparing the 2D and 3D results to further determine the optimal parameters. Length optimization is not illustrated in this work. The 3D EME results at different lateral misalignments (Δx) are shown in Fig. 3, in which a small value of 0.25° is chosen for the polymer taper angle. The Si_3N_4 taper angles are varied from 0.1° to 3.0°. At Δx

smaller than 0.8 μm, the coupler losses converge when the Si_3N_4 taper angle is below 1.2°. This value is regarded as the adiabatic angle of the Si_3N_4 taper. The coupler losses significantly depend on the lateral misalignment, which vary from 0.43 dB at Δx =0 up to 0.92 dB at Δx = 0.8 μm.

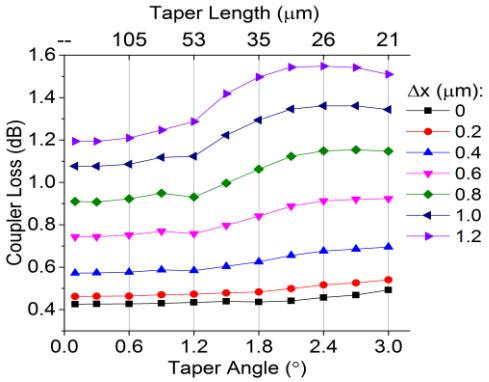

Fig. 3. Coupler losses calculated by EME for different lateral misalignments as a function of Si_3N_4 taper angle. The Si_3N_4 taper lengths are shown in the top axis. The angle and length of the polymer taper are 0.25° and 310 μm.

Characterization Results

The two chips are assembled by flip-chip bonding with controlled <1 μm accuracy (Finetech Lambda). The propagation loss of the straight Si_3N_4 waveguides is <0.1 dB/cm, whereas the loss of the SU-8 waveguides is 3.5-5.5 dB/cm in the spectral window of interest. The total loss of the waveguide with N cascaded vertical couplers, $\alpha_{c,total}$, can be calculated by subtracting the loss of the reference waveguide loss without converters, α_{ref}. The straight polymer waveguide connecting two converters is 500 μm, therefore, the measured loss is dominated by the coupling loss of the vertical couplers. For each coupler, its average loss is extracted by $\bar{\alpha}_c = (\alpha_{c,total}/N)$, which represents performance metric of the fabricated couplers rather than the loss at a specific misalignment. The fabricated chip is characterized both before and after thermal shocks according to according to the standard from the International Electrotechnical Commission (IEC), IEC 60512-11-4: 2002, as shown in Fig. 5.

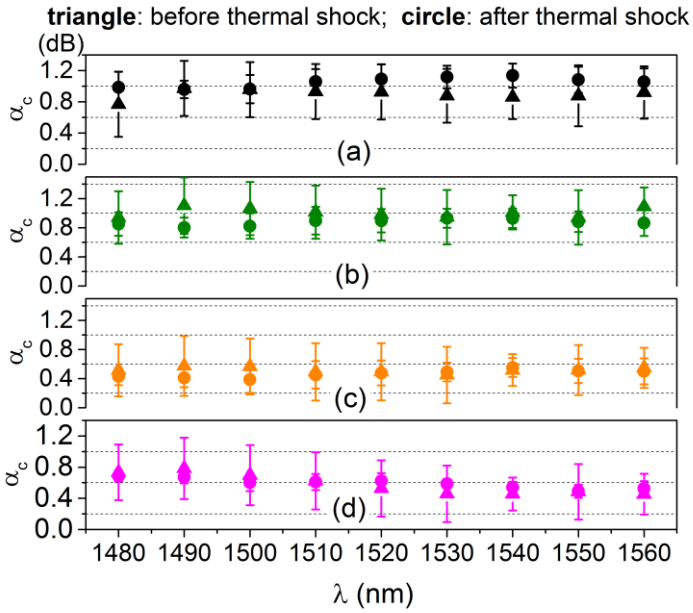

Fig. 4. Average coupler losses ($\bar{\alpha}_c$) of the chip 2 before and after thermal shock test at different Si_3N_4 taper angles and corresponding lengths: (a) 0.1° (630 μm), (b) 0.3° (210 μm), (c) 0.5° (126 μm), (d) 0.7° (90 μm) and (e) 0.9° (70 μm). The angle and the length of the polymer taper are 0.25° and 310 μm.

Before the thermal shock test, the average loss for the couplers with Si_3N_4 taper angles larger than 0.3° are below 0.8 dB in the spectral window of interest. Especially, the losses of the couplers with the Si_3N_4 taper angle of 0.1° are ~0.6 dB, which has good

agreement with the calculated results. After thermal shocks, the losses of the couplers with smaller Si_3N_4 taper angles have more significant increase. This is because the straight polymer waveguides on the top of the Si_3N_4 tapers produce more absorption and propagation losses due to the degradation of polymer. Nevertheless, the losses of the couplers with the Si_3N_4 taper angles larger than 0.3° are still below 1 dB.

Conclusion

The optimized design of vertical couplers under multimode condition for hybrid integration of Si_3N_4 with polymer waveguides based on flip-chip bonding has been presented. To demonstrate the proof-of-concept, the fabricated couplers are characterized in the spectral window of 1.48-1.56 μm both before and after thermal shock tests (IEC 60512-11-4: 2002). Less than 1 dB average losses have been obtained by the couplers with lateral misalignments below 0.8 μm and the Si_3N_4 taper angles larger than 0.3°.

Acknowledgements

This work was financially supported from the “Stichting voor de Technisch Wetenschappen” (STW) under the project number STW-13536. Y. Yong, S. A. Vázquez-Córdova, M. Hoekman, K. Wörhoff, J. Duis and A. Leinse are thanked for useful discussions.

Reference

[1] J. F. Bauters, M. J. R. Heck, D. John, D. Dai, M.-C. Tien, J. S. Barton, et al., "Ultra-low-loss high-aspect-ratio Si3N4 waveguides," Opt. Express, vol. 19, pp. 3163-3174, Feb. 2011.

[2] K. Wörhoff, R. G. Heideman, A. Leinse, and M. Hoekman, "TriPleX: a versatile dielectric photonic platform," Advanced Optical Technologies, vol. 4, pp. 189-207, Apr. 2015.

[3] Z. Zhang, G. Genrich, N. Keil, and N. Grote, "Widely tunable grating-assisted heterogeneous silicon nitride/polymer waveguide coupler," Opt. Lett., vol. 39, pp. 162-165, 2014/01/01 2014.

[4] M. Piels, J. F. Bauters, M. L. Davenport, M. J. R. Heck, and J. E. Bowers, "Low-Loss Silicon Nitride AWG Demultiplexer Heterogeneously Integrated With Hybrid III-V/Silicon Photodetectors," J. Lightwave Technol., vol. 32, pp. 817-823, Feb. 2014.

[5] J. D. B. Bradley, E. S. Hosseini, Purnawirman, Z. Su, T. N. Adam, G. Leake, et al., "Monolithic erbium- and ytterbium-doped microring lasers on silicon chips," Opt. Express, vol. 22, pp. 12226-12237, 2014/05/19 2014.

[6] P. Groumas, V. Katopodis, J. H. Choi, H. G. Bach, J. Y. Dupuy, A. Konczykowska, et al., "Multi-100 GbE and 400 GbE Interfaces for Intra-Data Center Networks Based on Arrayed Transceivers With Serial 100 Gb/s Operation," J. Lightwave Technol., vol. 33, pp. 943-954, 2015.

[7] J. Shu, C. Qiu, X. Zhang, and Q. Xu, "Efficient coupler between chip-level and board-level optical waveguides," Opt. Lett., vol. 36, pp. 3614-3616, 2011/09/15 2011.

[8] I. M. Soganci, A. La Porta, and B. J. Offrein, "Flip-chip optical couplers with scalable I/O count for silicon photonics," Opt. Express, vol. 21, pp. 16075-16085, 2013/07/01 2013.