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ABSTRACT

We demonstrate a new post-processing approach to efficiently couple light in silicon nitride (Si_3N_4) photonic integrated circuits (PIC) via grating couplers. Thin-film coupons of apodised Si_3N_4 grating couplers functionalized with metallic bottom reflectors and adiabatic couplers are micro-transfer printed onto the input and output of Si_3N_4 waveguides, providing efficient coupling without jeopardizing the rest of the PIC. Two-dimensional FDTD simulations predict coupling efficiencies as large as 78% (-1.1 dB) at a wavelength of 785nm. As a proof-of-concept, we report an experimental coupling efficiency above -4.6 dB, which is almost 3 dB better than the values obtained with standard designs of grating couplers.

Keywords: Micro-transfer printing, grating coupler, silicon nitride

1. INTRODUCTION

Silicon nitride (Si_3N_4) waveguides are widely used for photonic integrated circuits (PICs) for various applications.[1–3] To enable convenient fiber-to-chip coupling, grating couplers are commonly employed for their flexible position on the wafer and better alignment tolerance. However, the on-chip light coupling with grating couplers in a Si_3N_4 PIC is often rather lossy. On one hand, the coupling efficiency is reduced by mode mismatch between the grating and the optical fiber. On the other hand, a considerable fraction of power is diffracted towards the substrate.

It has been demonstrated that the coupling efficiency on a Si_3N_4 PIC can be boosted with single-layer bottom reflectors[4,5] or distributed Bragg reflectors.[6,7] But it is not compatible with standard waveguide platforms which are commonly used in large-scale processing. Chip-scale integration of such components and platforms can be realized through micro-transfer printing. With this technique, grating couplers with bottom reflectors are prefabricated on a source substrate and later released from it by etching a sacrificial layer. The tethered coupons are then picked up with a polymer stamp and printed onto a target substrate. This wafer-scale compatible technique offers high throughput and efficient use of source material, comparing to wafer-bonding and others.

In this work, we present a novel Si_3N_4 fiber-to-chip coupler, which is micro-transfer printed onto the input and output of Si_3N_4 photonic waveguides. The apodised Si_3N_4 grating couplers on thin-film coupons are functionalized with metallic bottom reflectors and adiabatic couplers. With micro-transfer printing technology, the coupons are fabricated separately and then printed onto the waveguides on a standard Si_3N_4 platform. Efficient coupling can be achieved without jeopardizing the rest of the PIC. Moreover, it creates more diverse options for the supply chain of PICs by enabling the addition of grating couplers in a late stage of the fabrication flow.

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2. DESIGN AND SIMULATION

The structure of the micro-transfer printed grating coupler is shown in Figure 1. In the cross-section sketched in Figure 1(a), light is coupled from a tilted optical fiber to the top Si_3N_4 layer through a grating coupler. The coupling efficiency is boosted by the metallic bottom reflector separated from the Si_3N_4 layer by a thin layer of silicon oxide (SiO_2) with a specific thickness that ensures constructive interference. Moreover, the grating is apodized to reduce mode mismatch between the fiber and the grating, as demonstrated by Marchetti *et al.*.[8] The fill factor of each pitch is varied linearly from 0.5 to 0.9 towards the waveguide. Then the light is transferred to the bottom Si_3N_4 layer through adiabatic couplers as shown in Figure 1(b), which consists of two 150 μm-long tapers in opposite directions. Compared to directional couplers, the adiabatic couplers are much less sensitive to coupler length and waveguide spacing.

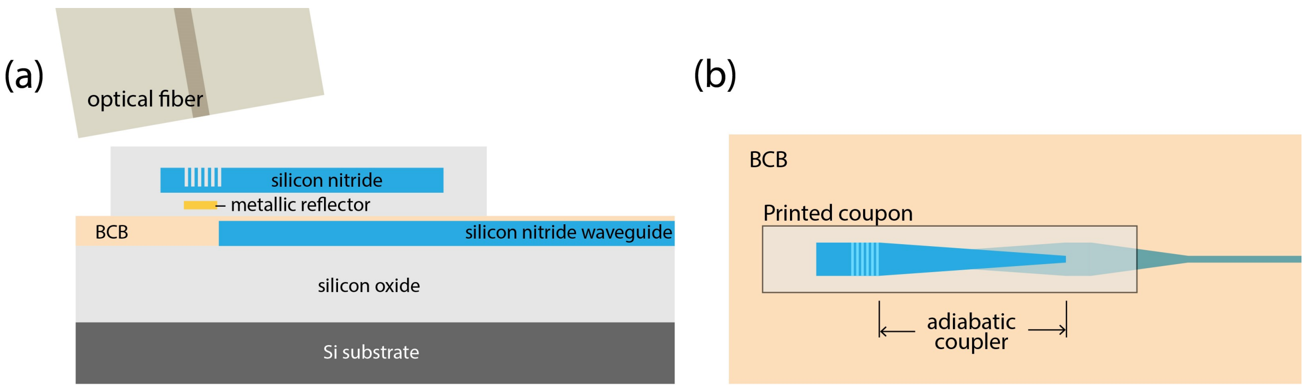

Figure 1. Schematics of a micro-transfer pritned grating coupler on a Si_3N_4 waveguide. (a) Cross-section with an tilted optical fiber. (b) Top-down view showing the adiabatic coupler between the two Si_3N_4 layers.

We numerically examined the performance of such grating couplers with two-dimensional (2D) FDTD simulations around a wavelength of 785 nm. Figure 2(a) shows the electric field distribution on the cross-section with light injected from the optical fiber. It can be seen that most power is coupled to the silicon nitride waveguide on the right. Figure 2(b) and 2(c) shows the simulated coupling efficiencies for a range of parameters, including etch depth, linear fill factor, and fiber tilting angle. The optimal coupling efficiency reaches 65% (-1.9 dB) and 78% (-1.1 dB) for optical fibers tilted at 10° and 5°, respectively.

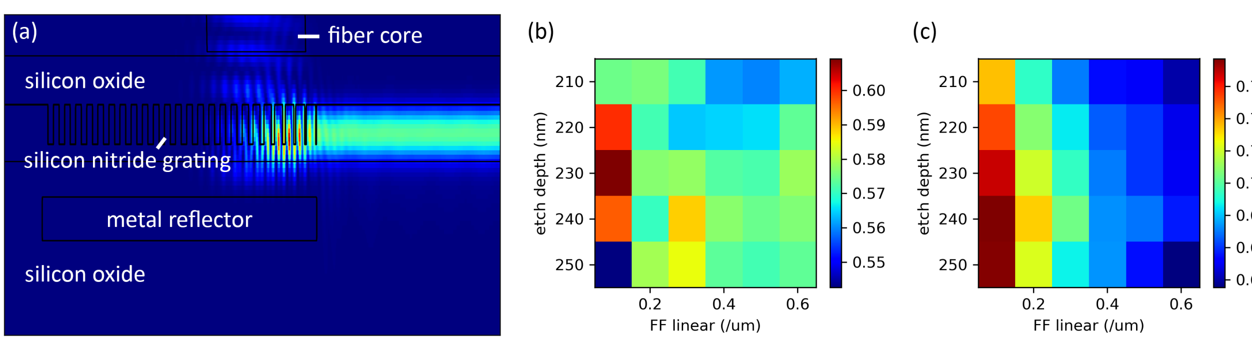

Figure 2. Simulation results of the grating couplers. (a)Electric field distribution on the cross-section, generated from the 2D FDTD simulations. Light is injected from the optical fiber. (b) Estimated coupling efficiencies over a range of etch depth and linearly varied fill factor, with fiber tilted at 10°, and (c) with fiber tilted at 5°.

3. FABRICATION AND MEASUREMENTS

The processing starts from depositing a thin layer of silicon oxide on a silicon substrate by plasma enhanced chemical vapor deposition (PECVD). Then the gold reflectors are defined through metal evaporation and lift-off. After the deposition of an 110 nm-thick layer of silicon oxide and 300 nm Si_3N_4, the grating couplers and adiabatic couplers are defined via electron beam (e-beam) lithography and reactive ion etching (RIE) with an etch depth of 230 nm. Another thin layer of silicon oxide is then deposited as top cladding. Once the coupons are defined via UV lithography and RIE, they are released from the substrate by under-etching the silicon substrate using tetramethylammonium hydroxide (TMAH) solution. Finally, the coupons are picked up and printed onto fully etched waveguides in 300nm thick PECVD Si_3N_4, assisted by a thin layer of benzocyclobutene (BCB) in between.

Figure 3(a) shows the released coupons on the source substrate before micro-transfer printing. It can be seen that the etching of silicon substrate with TMAH solution is rather anisotropic. Hence the direction of the coupons must be carefully chosen. In Figure 3(b), the coupons are already micro-transfer printed onto Si_3N_4 waveguides. The tethers are formed by pairs of triangle-like shapes. Some of them did not break at the narrowest position, causing some pieces of thin-films ripped off from the source substrate. Although it did not affect the adhesion of the coupons, it might be prevented by optimizing the tether design.

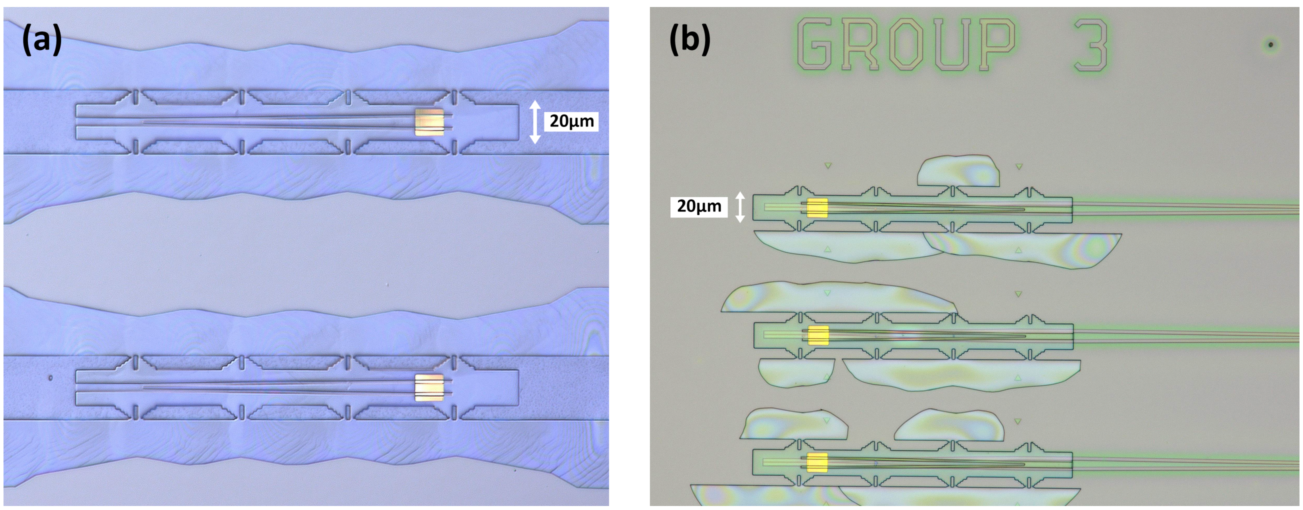

Figure 3. Fabricated devices observed under an optical microscope. (a) Coupons with grating couplers before micro-transfer printing, held on source substrate by tethers (b) Coupons with grating couplers printed onto Si_3N_4 waveguides.

We characterized the coupling efficiency of the grating couplers by evaluating the insertion loss of Si_3N_4 strip waveguides with micro-transfer printed grating couplers on the input and output. Light with wavelength from 780 nm to 900 nm is coupled to and from the waveguide through optical fibers tilted at 10° with a mode field diameter of 5 μm. Coupling efficiencies are estimated by subtracting the average propagation loss of the strip waveguide (3-7 dB/cm) from the insertion loss.

Figure 4 shows the coupling efficiency measured with standard and micro-transfer printed grating couplers, assuming 3 dB/cm propagation loss of the 300 nm-thick, 800 nm-wide Si_3N_4 strip waveguides. The micro-transfer printed grating couplers have an etch depth of 230 nm and a fill factor linearly varied at 0.11/μm. Six of them are printed onto three identical waveguides. The colored dots in Figure 4 show the average coupling efficiency of the two ports on each waveguide. As a comparison, we include the measured coupling efficiency of standard grating couplers (black dots in Figure 4), which are fully etched on the input and output of the waveguides with a pitch of 610 nm and fill factor of 0.5. The highest coupling efficiency of the micro-transfer printed grating couplers is found around the wavelength of 840 nm as -4.6 dB, while the average efficiency is -6.2 dB. The maximum and average coupling efficiency are both 3 dB better than the efficiencies measured with the standard grating couplers, which complies with the simulation.

It needs to be noted that the propagation loss of 3 dB/cm is only a rough estimation due to the lack of sufficient difference in waveguide lengths on the sample. We then fabricated another sample with longer, spiraled Si_3N_4 strip waveguides under similar conditions, on which the propagation loss is measured to be 7 dB/cm. If the two samples would have similar propagation losses, the maximum and average coupling efficiency can be estimated to be -2.5 dB and -4.4 dB, respectively. The coupling efficiencies are still 3 dB higher than the efficiencies measured with the standard grating couplers.

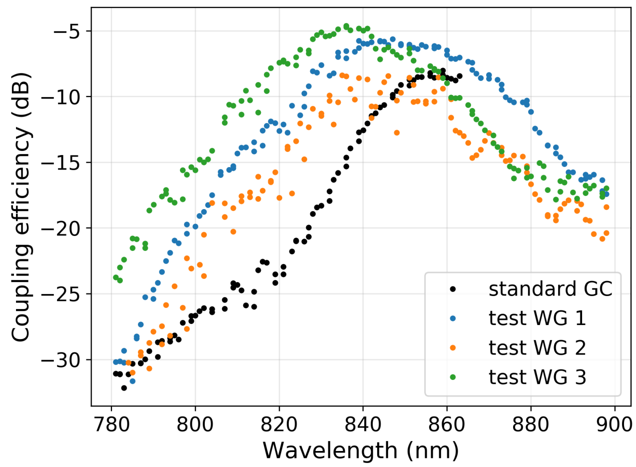

Figure 4. Coupling efficiency of micro-transfer printed and standard grating couplers in the wavelength range from 780 nm to 900 nm, estimated by assuming 3 dB/cm propagation loss. The black dots are measured on a Si_3N_4 strip waveguide with standard grating couplers on input and output. The colored dots are measured on three Si_3N_4 strip waveguides with identical micro-transfer printed grating couplers on input and output.

4. CONCLUSIONS

In this manuscript, we present micro-transfer printed silicon nitride (Si_3N_4) grating couplers that enable efficient fiber-to-chip coupling to Si_3N_4 photonic integrated circuits. Thin-film coupons with grating couplers and adiabatic couplers are micro-transfer printed onto the input and output of Si_3N_4 strip waveguides. The coupling efficiency is boosted by functionalizing the apodised grating couplers with metallic bottom reflectors. Two-dimensional FDTD simulation of the grating couplers shows that the coupling efficiency can reach 78% (-1.1 dB) around the wavelength of 785 nm. The fabricated devices give maximum and average coupling efficiencies above -4.6 dB and -6.2 dB, respectively. An additional measurement of waveguide propagation loss indicates that the maximum estimated coupling efficiency could reach -2.5 dB. In either case, the coupling efficiency is 3 dB higher than that measured with standard grating couplers.

This proof-of-concept demonstration shows that this approach can provide more efficient coupling on standard waveguide platforms without jeopardizing the rest of the PIC. Furthermore, the results show that grating couplers can be added in a late stage of the fabrication flow, thereby creating more diverse options for the supply chain of PICs.

REFERENCES

[1] Rahim, A., Ryckeboer, E., Subramanian, A. Z., Clemmen, S., Kuyken, B., Dhakal, A., Raza, A., Hermans, A., Muneeb, M., Dhoore, S., Li, Y., Dave, U., Bienstman, P., Le Thomas, N., Roelkens, G., Van Thourhout, D., Helin, P., Severi, S., Rottenberg, X., and Baets, R., "Expanding the silicon photonics portfolio with silicon nitride photonic integrated circuits," *J. Lightwave Technol.* **35**, 639–649 (2017).

[2] Blumenthal, D. J., Heideman, R., Geuzebroek, D., Leinse, A., and Roeloffzen, C., "Silicon nitride in silicon photonics," in [*Proceedings of the IEEE*], **106**(12), 2209–2231 (2018).

[3] Muñoz, P., Micó, G., Bru, L., Pastor, D., Pérez, D., Doménech, J., Fernández, J., Baños, R., Gargallo, B., Alemany, R., Sánchez, A., Cirera, J., Mas, R., and Domínguez, C., "Silicon nitride photonic integration platforms for visible, near-infrared and mid-infrared applications," *Sensors* **17**, 2088 (2017).

[4] Romero-García, S., Merget, F., Zhong, F., Finkelstein, H., and Witzens, J., "Visible wavelength silicon nitride focusing grating coupler with alcu/tin reflector," *Opt. Lett.* **38**, 2521–2523 (2013).

[5] Zou, J., Yu, Y., Ye, M., Liu, L., Deng, S., and Zhang, X., "Ultra efficient silicon nitride grating coupler with bottom grating reflector," *Opt. Express* **23**(20), 26305 (2015).

[6] Zhang, H., Li, C., Tu, X., Song, J., Zhou, H., Luo, X., Huang, Y., Yu, M., , and Lo, G. Q., "Efficient silicon nitride grating coupler with distributed bragg reflectors," *Opt. Express* **22**, 21800–21805 (2014).

[7] Hong, J., Spring, A. M., Qiu, F., and Yokoyama, S., "A high efficiency silicon nitride waveguide grating coupler with a multilayer bottom reflector," *Sci. Rep.* **9**, 12988 (2019).

[8] Marchetti, R., Lacava, C., Khokhar, A., Chen, X., Cristiani, I., Richardson, D. J., Reed, G. T., Petropoulos, P., and Minzioni, P., "High-efficiency grating-couplers: demonstration of a new design strategy," *Sci. Rep.* **7**, 16670 (2017).