# Subwavelength metamaterial grating couplers on silicon nitride platform

*Student paper*

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**We present design and experimental results of single-etch silicon nitride grating couplers engineered with sub-wavelength grating metamaterials. For fabricated devices, we measured coupling loss of -3.9 dB and -4.4 dB at *C*-band wavelength range. Moreover, by judiciously designing the apodized-imaging grating coupler topology, fibre-to-chip coupling loss of -1.6 dB loss is predicted by finite difference time domain simulations.**

***Keywords***: *Surface grating couplers, Subwavelength metamaterials, Silicon Nitride platform*

## INTRODUCTION

Near-infrared (NIR) wavebands, ranging from 1260 nm to 1675 nm, are particularly interesting for communication applications, including short-reach data communications and long-distance telecommunications. Such applications call upon integrated platforms for developing low-cost and high-yield systems on a photonic chip. Among others, silicon nitride (SiN) is a compelling platform for photonic integration due to its wide transparency, low waveguide losses, and compatibility with complementary metal-oxide-semiconductor (CMOS) fabrication processes [1]. Waveguide dimensions in high-index contrast integrated photonics are typically in the sub-micrometric range, making the interconnection between the chip and external ports particularly challenging. Even though compared to silicon-on-insulator (SOI) waveguides [2], the index contrast (of about1 to 0.5) between the SiN waveguide core and its air/silicon dioxide ($SiO_2$) cladding is more moderate, it is still challenging to obtain low coupling loss, when the integrated SiN chips are interfaced with standard optical fibres [1,2]. Surface grating couplers are an attractive solution for coupling light in and out from photonic waveguides. Grating couplers are compliant with planar manufacturing and wafer-level testing, allow flexible placement on a chip surface, and have comparatively large alignment tolerances to fibre attachments. However, SiN waveguide couplers have higher losses due to the reduced the grating strength. To date, a number of approaches have been explored [3-8], with a steady progress in increasing the coupling efficiency. This includes SiN couplers with Bragg and metal mirror underneath [3,4], stair-like gratings [5], bi-layer topologies [6] and top overlays [7], or SiN-on-SOI platforms [8]. However, such approaches are comparatively complex to fabricate and require dedicated processing steps, which indeed comes with additional expenses. To keep the process cost low, single-etch grating couplers appear as optimal choice. Nevertheless, the limited degree of design freedom in single-etch devices has so far been the limiting factor to boost their coupling performances.

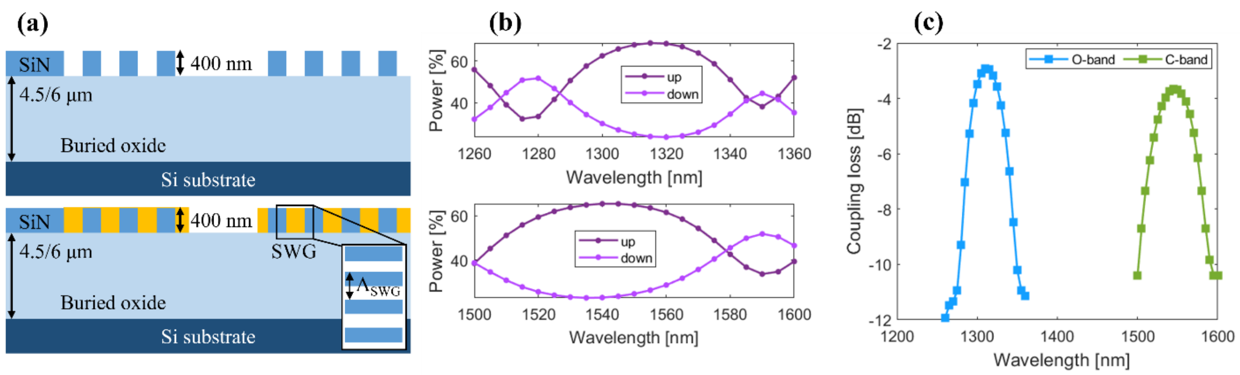


*Fig. 1: (a) Vertical schematics of the single-etch grating couplers, without and with SWG-index-engineered grooves. (b) Power radiated upwards and downwards and (c) coupling loss as a function of wavelength for O- and C-band device designs.*

In this work, we report on design and experiments of single-etch-step surface grating couplers realized on the SiN photonic platform, with and without a subwavelength grating (SWG) engineered medium. Since their first demonstration in silicon photonics [10,11], SWG metamaterials [12-14] have been used as a powerful engineering tool for overcoming performance limitations of conventional silicon photonic devices. Grating couplers are designed for central wavelengths of 1.31 µm (*O*-band) and 1.55 µm (*C*-band), respectively, both harnessed by mainstream fibre-optic communication systems.

**UNIFORM GRATING COUPLERS**

Figure 1(a) shows a side view schematics of the single-etch SiN surface grating couplers, without and with SWG-engineered grooves. Couplers are made in a 400 nm SiN platform, with either 4.5 µm or 6 µm thick buried oxides (BOX). The air serves as upper cladding. The light from standard optical fibers, with mode field diameters (MFDs) of 9.2 µm (at 1.31 µm) and 10.4 µm (at 1.55 µm), is coupled into a SiN chip to the in-plane transverse electric (TE) fundamental mode of the waveguide. Grating couplers were designed and analyzed by using Lumerical finite difference time (FDTD) tool from the Ansys, Inc [9].

Figures 1(b) shows the powers radiated towards an optical fiber and a bottom Si substrate as a function of the wavelength for *O*-band and *C*-band couplers, respectively. In both coupler designs, the power up and the power down reach their maxima and minima of about 68% and 23%, respectively, yielding a peak grating directionality up to 70%. The directionality of the coupler is governed by the effect of thin-film interference at the substrate-to-BOX interface. The maximum directionality can be obtained by optimizing the BOX thickness or by judiciously adjusting the grating radiation angle [15-17]. With designed coupling angles of -36° and 4.5 µm BOX (*O*-band) and -15° and 6 µm BOX (*C*-band), the peak coupling losses of -2.8 dB and -3.7 dB are predicted by FDTD calculations. In both designs, negative coupling angles are chosen to favor single-beam operation, while avoiding higher-order radiation. Figure 1(c) shows the spectral performance of designed *O*-band and *C*-band fiber-chip grating couplers. The 1-dB coupler bandwidths are 33 nm and 41 nm, respectively.

Grating couplers were fabricated on a SiN platform with 400 nm core and 6 µm BOX and connected in a back-to-back configuration using adiabatic tapers and interconnection single-mode strip waveguides. The couplers and interconnecting waveguides were defined in the same step by electron beam lithography. The device patterns were transferred into the SiN waveguide layer by reactive ion etching. Figure 2(a) show a fiber-chip coupling loss as a function of the wavelength for a uniform *C*-band-operated grating couplers, with air and SWG fully etched grooves. The back-to-back tested peak coupling losses are -3.9 dB and -4.4 dB, respectively.

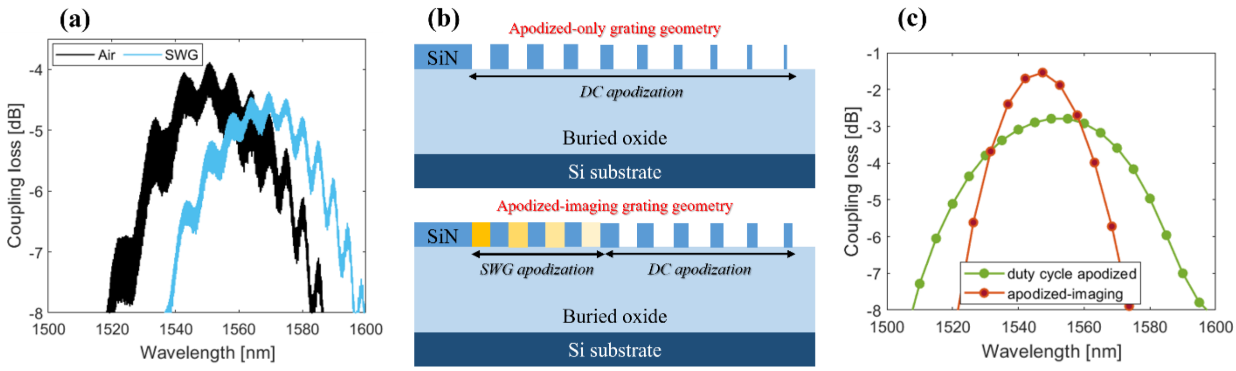


*Fig. 2: (a) Measured coupling loss as a function of wavelength for fabricated SiN surface grating couplers. (b) Vertical schematics and (c) calculated coupling loss of the apodized and apodized-imaging surface grating couplers.*

**APODIZED GRATING COUPLERS**

Due to the lower index contrast in SiN waveguides, grating couplers are too weak, which makes it difficult to design gratings that radiate all the power within a length that matches the MFD of conventional optical fibers. Further improvement of grating coupler performance was obtained through grating apodization.

Here, grating couplers were apodized by exploiting two apodization schemes: (i.) single duty cycle apodization and (ii.) combined apodization via duty cycle and SWG refractive index engineering, while leveraging a self-imaging effect. In both schemes, the grating strength is varied along the direction of mode propagation by either changing the duty cycle or by changing the duty cycle and synthesizing different SWG metamaterials in fully etched grating grooves. Both apodization approaches are schematically shown in Fig. 2(b). In the first case, the grating radiation angle is kept constant for all grating radiation units and the grating period was appropriately chirped , thus satisfying the phase matching condition. In the second case, besides the grating strength adjustment, the coupling angle and the period are not constant, yet they are allowed to vary along the mode propagation to facilitate the imaging effect

Figure 2(c) shows the coupling loss as a function of the wavelength for grating coupler designs at telecom spectral range, with duty cycle and self-imaging-assisted apodizations. The peak coupling loss for a duty cycle apodized design was estimated to be -2.9 dB, while apodized-imaging design improved the fiber-chip coupling loss up to -1.6 dB. Compared to the uniform grating coupler, the enhancement in coupling loss is directly linked to the improved modal overlaps between the profile of the out-radiated grating mode and Gaussian-like optical fiber mode.

**CONCLUSION**

In this work, we reported on low-loss surface grating couplers with engineered SWG metamaterials on a SiN waveguide platform and single-etch step fabrication. Measured devices yielded coupling loss of -3.9 dB and -4.4 dB near 1.55 µm wavelength range. Furthermore, optimized fiber-chip couplers with apodized-imaging grating geometry yielded coupling loss of -1.6 dB. These results are promising for the development of low-cost and efficient fiber-coupled surface grating interfaces as required by SiN-founded applications, including interconnects, communications, and quantum science.

**Acknowledgements**

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**References**

[1] C. Xiang, W. Jin, and J. E. Bowers, *Silicon nitride passive and active photonic integrated circuits: trends and prospects*, Photonics Research, vol. 10, no 6, pp. A82-A96, 2022

[2] Roel Baets, et al., *Silicon Photonics: silicon nitride versus silicon-on-insulator*, In Proc. of Optical Fiber Communication Conference, pp. Th3J.1, 2016

[3] S. Nambiar, A. Chatterjee, and S. K. Selvaraja, *Comprehensive grating enabled silicon nitride fiber-chip couplers in the SNIR wavelength band*, Optics Express, vol. 30, no. 3, pp. 4327-4341, 2022

[4] S. Romero-García, F. Merget, F. Zhong, H. Finkelstein, and J. Witzens, *Visible wavelength silicon nitride focusing grating coupler with AlCu/TiN reflector*, Optics Letters, vol. 38, no 14, pp. 2521-2523, 2013

[5] Y. Chen, T. Domínguez Bucio, A. Z. Khokhar, M. Banakar, K. Grabska, F. Y. Gardes, R. Halir, Í. Molina-Fernández, P. Cheben, and J.-J. He, *Experimental demonstration of an apodized-imaging chip-fiber grating coupler for Si3N4 waveguides*, Optics Letters, vol. 42, no. 18, pp. 3566-3569, 2017

[6] E. W. Ong, N. M. Fahrenkopf, and D. D. Coolbaugh, *SiNx bilayer grating coupler for photonic systems*, OSA Continuum, vol. 1, no. 1, pp. 13-25, 2018

[7] B. Chmielak, S. Suckow, J. Parra, V. C. Duarte, T. Mengual, M. A. Piqueras, A. L. Giesecke, M. C. Lemme, and P. Sanchis, *High-efficiency grating coupler for an ultralow-loss Si3N4-based platform*, Optics Letters, vol. 47, no. 10, pp. 2498-2501, 2022

[8] S. Guerber, C. Alonso-Ramos, D. Benedikovic, D. Pérez-Galacho, X. Le Roux, N. Vulliet, S. Crémer, L. Babaud, J. Planchot, D. Benoit, P. Chantraine, F. Leverd, D. Ristoiu, P. Grosse, D. Marris-Morini, L. Vivien, C. Baudot, and F. Boeuf, *Integrated SiN on SOI dual photonic devices for advanced datacom solutions*, In Proc. SPIE Photonics Europe, pp. 106860W, 2018

[9] Ansys Lumerical FDTD. Available: http://ansys.com

[10] P. Cheben, D-X. Xu, S. Janz, and A. Densmore, *Subwavelength waveguide grating for mode conversion and light coupling in integrated optics*, Optics Express, vol. 14, no. 11, pp. 4695-4702, 2006.

[11] P. Cheben, P. J. Bock, J. H. Schmid, J. Lapointe, S. Janz, D.-X. Xu, A. Densmore, A. Delâge, B. Lamontagne, and T. J. Hall, *Refractive index engineering with subwavelength gratings for efficient microphotonic couplers and planar waveguide multiplexers*, Optics Letters, vol. 35, no 15, pp. 2526-2528, 2010

[12] P. Cheben, R. Halir, J. Schmid, H. Atwater, D. Smith, *Subwavelength integrated photonics*, Nature, vol. 560, no. 7720, pp. 565-572, 2018

[13] R. Halir, A. Ortega-Moñux, D. Benedikovic, G. Z. Mashanovich, J. G. Wangüemert-Pérez, J. H. Schmid, Í. Molina-Fernández, and P. Cheben, *Subwavelength-Grating Metamaterial Structures for Silicon Photonic Devices*, Proceedings of the IEEE, vol. 106, no. 12, pp. 2144-2157, 2018

[14] J. M. Luque-González, A. Sánchez-Postigo, A. Hadij-ElHouati, A. Ortega-Moñux, J. G. Wangüemert-Pérez, J. H. Schmid, P. Cheben, Í. Molina-Fernández, and R. Halir, *A review of silicon subwavelength gratings: building break-through devices with anisotropic metamaterials*, Nanophotonics, vol. 10, no.11, pp. 2765-2797, 2021

[15] D. Benedikovic, P. Cheben, J. H. Schmid, D.-X. Xu, J. Lapointe, S. Wang, R. Halir, A. Ortega-Moñux, S. Janz, and M. Dado, *High-efficiency single etch step apodized surface grating coupler using subwavelength structure*, Laser and Photonics Reviews, vol. 8, no. 6, pp. 93-97, 2014

[16] D. Benedikovic, P. Cheben, J. H. Schmid, D.-X. Xu, B. Lamontagne, S. Wang, J. Lapointe, R. Halir, A. Ortega-Moñux, S. Janz, and M. Dado, *Subwavelength index engineered surface grating coupler with sub-decibel efficiency for 220-nm silicon-on-insulator waveguides*, Optics Express, vol. 23, no. 17, pp. 22628-22635, 2015

[17] D. Benedikovic, C. Alonso-Ramos, P. Cheben, J. H. Schmid, S. Wang, R. Halir, A. Ortega-Moñux, D.-X. Xu, L. Vivien, J. Lapointe, S. Janz, and M. Dado, *Single-etch subwavelength engineered fiber-chip grating couplers for 1.3 µm datacom wavelength band*, Optics Express, vol. 24, no. 12, pp. 12893-12904, 2016