L-shaped grating couplers engineered with subwavelength metamaterial for sub-decibel coupling loss

D. Benedikovic[1], C. Alonso-Ramos[1], S. Guerber[1,2], V. Vakarin[1], G. Marcaud[1], X. Le Roux[1], P. Cheben[3], É. Cassan[1], D. Marris-Morini[1], F. Boeuf[2], C. Baudot[2], and L. Vivien[1]

[1]Centre de Nanosciences et de Nanotechnologies, CNRS, Univ. Paris-Sud, Université Paris-Saclay, C2N – Palaiseau, 91120 Palaiseau, France

[2]Technology R&D, STMicroelectronics, SAS, 850 rue Jean Monnet – 38920 Crolles, France

[3]National Research Council Canada, 1200 Montreal Road, Ottawa, Ontario, K1A0R6, Canada

e-mail: daniel.benedikovic@c2n.upsaclay.fr

ABSTRACT

Practically attractive nanophotonic technologies, mostly realized on mature silicon-on-insulator (SOI) substrates, call upon availability of efficient input/output grating-coupled optical interfaces. In this work, we demonstrate, both theoretically and experimentally, ultra-directional *L*-shaped grating couplers for low-loss light coupling between standard optical fibres and SOI chips. Experimentally, we show grating couplers without and with subwavelength (SWG) transition, seamlessly fabricated with a 193-nm deep-ultraviolet lithography. Coupling loss of -2.7 dB is measured with a low return loss as low as -20 dB. In addition, we propose an apodized *L*-shaped grating coupler layouts with coupling loss below 1 dB. Apodized fiber-chip grating couplers are designed with a sub-decibel coupling performance, together with substantially relaxed requirements in terms of minimum feature dimensions.

Keywords: fibre-chip grating couplers, deep-ultraviolet technology, subwavelength gratings, metamaterials, silicon-on-insulator platform, silicon photonics

1. INTRODUCTION

The use of surface grating couplers instead of edge couplers to couple the light between integrated circuits and optical fibres is of particular practical interest. Indeed, grating couplers enable flexible placement on the chip, wafer-scale device testing, and relaxed tolerances in fibre attachments [1,2]. More recently, several outstanding implementations of surface grating couplers were reported [3-14]. Several decisive aspects contribute to the overall coupling performance [2], however, the grating directionality is recognized as a key enabler towards development of high-efficiency surface grating couplers. More specifically, improved diffraction performance in grating couplers with additional overlayers [4], metal mirrors [5] or Bragg reflectors [6] underneath, and multi-layer [7] or multi-level device arrangements [8] have been proposed and demonstrated over years. However, such design strategies call upon additional technological steps with added fabrication complexity, which in turn, increases the overall cost. On one side, this includes precise top layer depositions or backside wafer processings. Other approaches are typically founded by custom-designed guiding layers, etching depths, and fabrications that differ considerably from those used in established photonic foundries or even mandate subsidiary frontend / backend silicon nitride layers. Alternatively, efficient surface grating couplers that advantageously exploit the unique blazing effect using only a two set of etching depths were demonstrated [9-14]. Fibre-chip grating couplers with interleaved [9-11] or *L*-shaped waveguide arrangements [12-14] were reported to demonstrate the imminent promise of such solution. Conceptual design simplicity [9,12], versatility [10,11], as well as waveguide platform portability [14] are essential ingredients for straightforward fabrication and advanced integration.

2. *L*-SHAPED GRATING COUPLERS: DESIGN, FABRICATION, AND OPTICAL TESTING

In this work, surface grating couplers were designed for a silicon-on-insulator (SOI) platform with 300-nm-thick Si waveguide and 720-nm-thick BOX, covered by silicon dioxide (SiO_2). Grating couplers were optimized for transverse electrical (TE) light injection and operation at a wavelength of 1.55 μm. As shown in the inset of Fig. 1(a), diffraction grating is formed by two-etching (full and partial) depths, with levels of 300 nm and 150 nm, respectively. The judiciously designed grating period consists of deep- and shallow-etched trenches and unetched Si slab. This geometry forms an *L*-shaped waveguide with an asymmetric radiation profile that maximizes the light diffraction towards a specific direction (here, towards an optical fibre situated above the chip). As a result, near-unity diffraction efficiency, as shown in Fig. 1(a), can be readily achieved for a wide range of geometries and wavelength span wider than 100 nm [12]. Albeit superior directionality is afforded by the *L*-shaped grating couplers, the overall performance is far beyond the desired sub-decibel coupling levels. The performance is strongly limited by the excessively large return loss (back-reflections of 20%) and grating-fibre field profile mismatch up to 80%.

In this work, surface grating couplers were fabricated using foundry-enabled production flow in STMicroelectronics cleanroom facilities using 300 mm SOI photonic platform with 193-nm deep-ultraviolet lithography, followed by dual-level dry etching and plasma enhanced chemical vapour deposition to form a SiO_2 cladding. Devices were characterized using back-to-back measurements with cleaved standard single-mode optical fibres (SMF-28). Detailed information about grating coupler dimensions can be found in Ref. [12].

Coupling performance of two types of *L*-shaped grating couplers is shown in Figs. 1(b) and (c). In particular, a peak coupling loss of -3.4 dB at 1.56 µm was measured for a coupler without the subwavelength grating (SWG) metamaterial transition (inset of Fig. 1(b)). As compared to the nominal design, with a coupling loss of -2.2 dB, the measured device yielded a 1.2 dB loss penalty, most likely attributed to the presence of fabrication imperfections such as variations in the partial etching depth and changes in the lengths of grating trenches and tooth. The 3-dB coupling bandwidth is 46 nm. The spectral response exhibits noticeable Fabry-Perot fringes, with a magnitude up 0.85 dB, resulting in a return loss of 8%. The grating coupler with an SWG transition (inset of Fig. 1(b)) yielded a coupling loss of only -2.7 dB at 1.565 µm with a 3-dB coupling bandwidth of 62 nm and a substantially reduced magnitude of Fabry-Perot ripples down to 0.1 dB. This results in a reflectivity of around 1%. This corresponds to an eight-fold return loss reduction as compared to a grating coupler design without the use of SWG metamaterial transition.

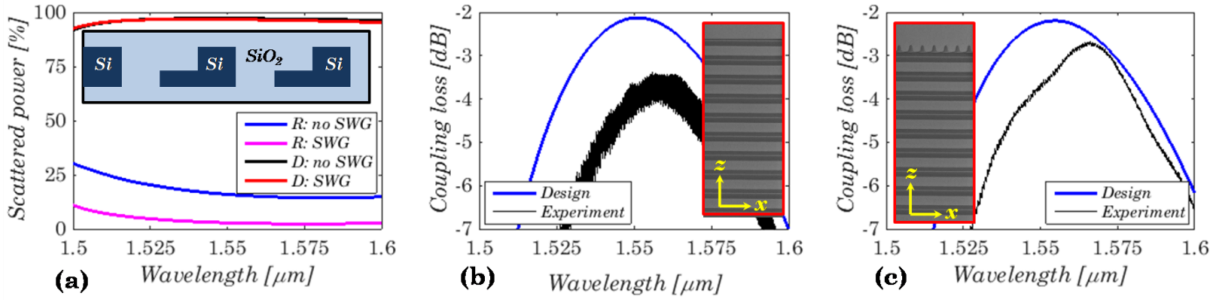

Figure 1. (a) Diffracted power from an L-shaped grating coupler as a function of wavelength. Inset: Vertical schematic of the L-shaped grating coupler. Calculated and measured coupling loss as a function of wavelength of the L-shaped grating couplers (b) without and (c) with sub-wavelength-engineered metamaterial transition. Insets of (b) and (c): Scanning electron microscopy images.

3. APODIZED *L*-SHAPED GRATING COUPLERS: TOWARDS SUB-DECIBEL COUPLING LOSS

Figure 2(a) shows a side view schematics of the proposed apodized *L*-shaped surface grating coupler. The grating coupler comprises apodized and uniform grating sections. The apodization of an *L*-shaped grating coupler was carried out by varying the effective refractive index of the SWG metamaterial in the etched grating trenches, both deep- and shallow-etch trenches, along the propagation direction to match the near-field profile of the radiated grating beam to the mode of SMF-28 optical fibre, i.e. to a Gaussian-like fibre mode profile of a 10.4 µm mode field diameter (MFD) at a wavelength of 1.55 µm. By implementing the SWG metamaterial within the etched grating trenches, the coupling strength of the grating can be properly controlled, yet without sacrificing the outstanding near-unity directionality of *L*-shaped grating couplers. This brings an additional degree of freedom to tailor the coupler performance.

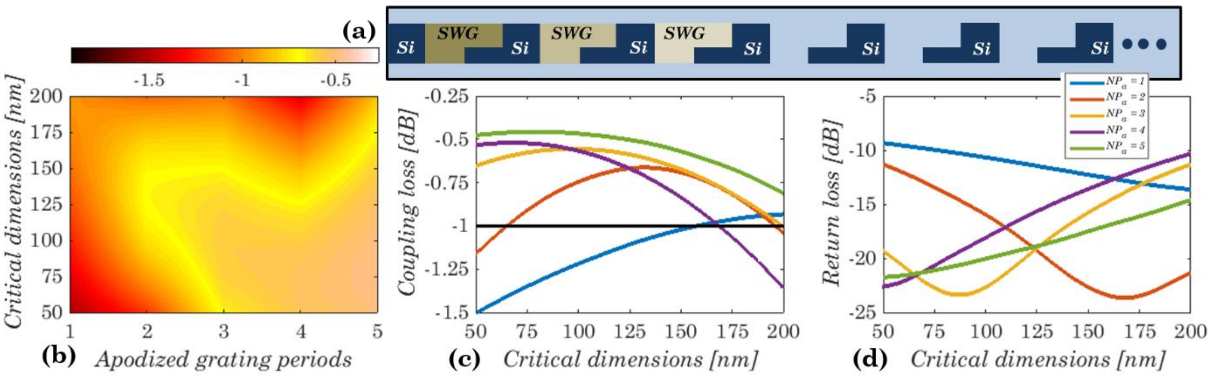

Figure 2. (a) Vertical schematics of an apodized L-shaped grating coupler with sub-wavelength-engineered trenches. (b) Colour map showing coupling loss of the L-shaped grating coupler as a function of the number of apodized periods and critical dimensions. (c) Coupling loss and (d) reflectivity of the L-shaped grating coupler as a function of critical dimensions for different numbers of apodized periods.

Figure 2(b) shows a colour map of the fiber-chip coupling losses of an apodized *L*-shaped grating coupler with an SWG metamaterial trenches as a function of the number of apodized grating periods and SWG critical dimensions. It can be observed that a wide range of device designs is suitable to provide a sub-decibel coupling losses. In particular, as shown in more detail in Fig. 2(c), grating coupler design with only 1 period engineered with SWG metamaterial yields a coupling loss of -0.95 dB for a SWG minimum feature size of 195 nm, while for 2 apodized periods of the *L*-shaped grating coupler, the coupling of -0.65 dB is predicted for a minimum dimensions of 140 nm. Furthermore, for a 5 apodized periods, the sub-decibel fiber-chip coupling performance is readily achieved for all minimum feature size criteria, with a coupling loss as small as -0.46 dB for a 100 nm feature size restrictions. The corresponding evolution of the grating coupler reflectivity as a function of the SWG critical dimensions is shown in Fig. 2(d). The reflectivity down to -23 dB is suggested by numerical simulations.

4. CONCLUSIONS

We demonstrated, both theoretically and experimentally, a set of *L*-shaped surface grating couplers engineered with sub-wavelength grating metamaterial to afford a low-loss coupling between SOI waveguides and standard single-mode fibres. Our couplers yield directionality close to the theoretical limit of 100% with a comparatively easy to fabricate geometry. Devices were fabricated with a 193-nm deep-ultraviolet lithography at STMicroelectronics. Fiber-chip coupling loss of -2.7 dB was experimentally measured with a low return loss down to -20 dB. In addition, we designed an advanced apodized low-period-count *L*-shaped grating couplers with a sub-decibel coupling performance, providing substantially relaxed requirements for minimum feature sizes up to 200 nm. These results open up a way towards deployment of low-cost and high-performance fiber-chip optical interfaces in large-volume nanophotonic applications.

ACKNOWLEDGEMENTS

This work has received the funding from the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation Program (ERC POPSTAR – grant agreement No 647342).

REFERENCES

[1] P. Cheben, *et al.*: Subwavelength integrated photonics, *Nature*, vol.560, pp. 565 – 572 (2018).
[2] R. Halir, *et al.*: Subwavelength-Grating Metamaterial Structures for Silicon Photonic Devices, *P IEEE*, vol.106, pp. 2144 – 2157 (2018).
[3] D. Taillaert, *et al.*: Compact efficient broadband grating coupler for silicon-on-insulator waveguides, *Opt. Letters*, vol. 29, pp. 2749 – 2751 (2004).
[4] G. Roelkens, *et al.*: High efficiency silicon-on-insulator grating coupler based on a poly-silicon overlay, *Opt. Express*, vol. 14, pp. 11622–11630 (2006).
[5] D. Benedikovic, *et al.*: Subwavelength index engineered surface grating coupler with sub-decibel efficiency for 220-nm silicon-on-insulator waveguides," *Opt. Express*, vol. 23, pp. 22628–22635 (2015).
[6] C. Baudot, *et al.*: Low Cost 300 mm double-SOI substrate for low insertion loss 1D & 2D grating couplers, in IEEE Group IV Photonics, pp. 137–138 (2014).
[7] W. S. Sacher, *et al.*: Monolithically Integrated Multilayer Silicon Nitride-on-Silicon Waveguide Platforms for 3-D Photonic Circuits and Devices," *P IEEE*, vol. 106, pp. 2232 – 2245 (2018).
[8] J. Notaros, *et al.*: Ultra-Efficient CMOS Fiber-to-Chip Grating Couplers, in Optical Fiber Communication Conference, paper M2I.5 (2016).
[9] C. Alonso-Ramos, *et al.*: Fiber-chip grating coupler based on interleaved trenches with directionality exceeding 95%, *Opt. Letters*, vol. 39, pp. 5351-5354 (2014).
[10] D. Benedikovic, *et al.*: High-directionality fiber-chip grating coupler with interleaved trenches and subwavelength index-matching structure, *Opt. Letters*, vol. 40, pp. 4190-4193 (2015).
[11] Xia Chen, *et al.*: Dual-etch apodised grating couplers for efficient fibre-chip coupling near 1310 nm wavelength,*Opt. Express*,vol. 25, pp. 17864-17871 (2017).
[12] D. Benedikovic, *et al.*: L-shaped fiber-chip grating couplers with high directionality and low reflectivity fabricated with deep-UV lithography, *Opt. Letters*, vol. 42, pp. 3439-3442 (2017).
[13] T. Watanabe, *et al.*: Perpendicular Grating Coupler Based on a Blazed Antiback-Reflection Structure, *J. Lightw. Technol.*, vol. 35, pp. 4663-4669 (2017).
[14] Y. Chen, *et al.*: Experimental demonstration of an apodized-imaging chip-fiber grating coupler for Si_3N_4 waveguides," *Opt. Letters*, vol. 42, pp. 3566-3569 (2017).