Subwavelength metamaterials structures for applications in silicon photonics

(Invited paper)

J. H. Schmid,[1] P. Cheben,[1] D. Melati,[1] D.-X. Xu,[1] S. Janz,[1] J. Lapointe,[1] S. Wang,[1] M. Vachon,[1] R. Halir,[2] A. Ortega-Moñux,[2] G. Wangüemert-Pérez,[2] I. Molina-Fernández,[2] A. Sánchez-Postigo,[2] J.M. Luque-Gonzalez,[2] J.D. Sarmiento-Merenguel,[2] Jiří Čtyroký[3]

[1] Advanced Electronics and Photonics Research Centre, National Research Council Canada,
1200 Montreal Road, Ottawa, Ontario, Canada
e-mail: jens.schmid@nrc-cnrc.gc.ca
[2] Universidad de Málaga, Dpto. de Ingeniería Comunicaciones, ETSI Telecomunicación,
Campus de Teatinos s/n, 29071 Málaga, Spain
[3] Institute of Photonics and Electronics, CAS,
Chaberská 57, 182 51 Prague, Czech Republic

ABSTRACT

Subwavelength engineering in silicon photonic integrated circuits is a powerful design tool that allows one to adjust the waveguide core effective refractive index by periodically patterning the silicon waveguide layer at the subwavelength scale. This creates a new degree of freedom in photonic circuit design. In recent years, the subwavelength metamaterial concept has been demonstrated and applied to many silicon photonic devices such as fiber-chip couplers, waveguide crossings, microspectrometers, ultra-fast optical switches, athermal waveguides, evanescent field sensors, polarization rotators and colorless interference couplers. Here we report our advances in the development of subwavelength engineered dielectric metamaterial structures for silicon photonic devices with a special emphasis on the practical performance of fiber-chip coupling structures and the possibility to affect the spectral bandwidth of silicon photonic devices by subwavelength engineering. In particular, we will present our results in developing highly efficient and broadband fiber-chip and laser-chip couplers for silicon photonic wire waveguides using subwavelength engineered structures, a broadband prism assisted grating coupler, an ultra-broadband multi-mode interference (MMI) coupler device and narrow-band Bragg spectral filters in subwavelength grating (SWG) waveguides.

Keywords: Silicon photonics, subwavelength structures, metamaterials, Bragg gratings

1. INTRODUCTION

In recent years, the research field of subwavelength photonics has seen tremendous progress, particularly in nanostructured engineered materials: metamaterials, metallic and dielectric subwavelength structures and subwavelength engineered waveguides. The novel optical properties found in these structures, along with the capability, through advanced fabrication techniques, to control their optical responses with unprecedented accuracy, has opened new prospects for controlling and manipulating light in planar waveguide circuits at the subwavelength scale. Since the first demonstrations of an optical waveguide with a periodic subwavelength grating metamaterial core [1-3], metamaterial SWG waveguides have attracted a strong research interest in academia and industry because of their unique potential to control light propagation in planar waveguides [4] and subwavelength engineered structures are likely to become key building blocks for the next generation of integrated photonic circuits.

2. FIBER-CHIP COUPLING

Efficient input and output coupling interfaces between silicon photonic chip and optical fiber or lasers are a fundamental prerequisite for successful implementations of such photonic chips for processing, modulating and detecting light. Here we demonstrate that tapered SWG edge couplers, as shown in the SEM micrograph in Fig. 1, can outperform inverse taper couplers in efficiency and polarization dependent loss. Specifically, as we have previously reported in [5], by optimizing the coupler design, we experimentally demonstrated an SWG coupler with a loss of 0.4 dB and negligible polarization dependence fabricated on a silicon-on-insulator chip with a standard 220 nm silicon thickness and silicon dioxide cladding. In this work we used lensed optical fiber tips with a mode field diameter of 3 µm.

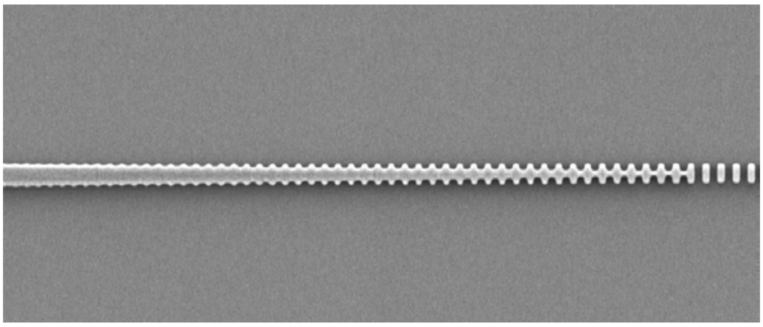

Figure 1. SEM micrograph of SWG fiber-chip edge coupling structure.

It is highly desirable to increase the mode size at the interface between SWG coupling structure and the optical fiber to improve alignment tolerance of the fiber to the chip. However, for large mode sizes, optical loss of the waveguide mode through the buried oxide (BOX) layer to the substrate becomes a serious limitation to the coupling efficiency. Minimizing the SWG taper length helps alleviate this source of optical loss. In Fig. 2 we show an example eigenmode expansion propagation calculation of the effect of substrate loss as a function of length of an optimized taper shape for a facet mode size diameter of 6 µm. It can be seen that even for this relatively large mode size and standard BOX thickness of 2 µm coupling efficiencies >90% are feasible.

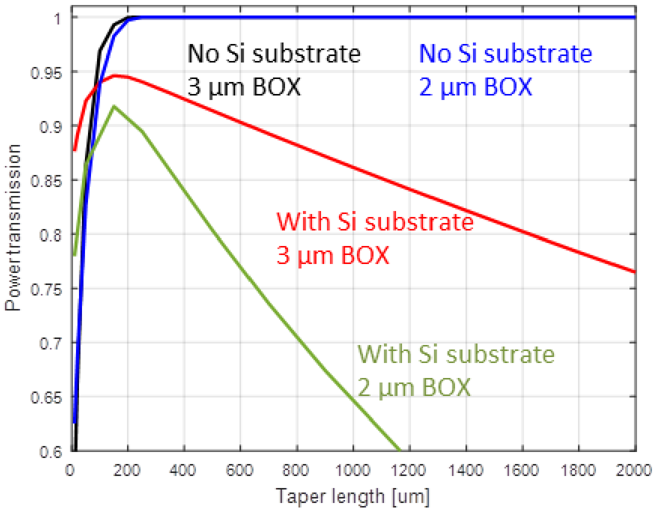

Figure 2. Eigenmode expansion propagation calculation of power transmission through an optimized SWG taper structure as a function of length in the presence of substrate leakage losses for a facet mode size diameter of 6 µm.

3. NARROWBAND BRAGG FILTERS

We have recently presented the first systematic theoretical and numerical study of narrowband reflection and transmission spectral filters in silicon-on-insulator SWG waveguides comprising Bragg gratings with lateral loading segments [6]. Such narrowband reflection filters can potentially find applications as components providing wavelength selective feedback for a narrow linewidth hybrid III-V-silicon laser system or as sensing elements. The combination of waveguide core refractive index engineering and evanescent coupling of the waveguide mode with the Bragg grating loading segments makes it possible to design long and weakly coupled grating structures as required for narrowband operation, which is otherwise hard to achieve in the silicon-on-insulator high-index contrast material system. The results of the theoretical study indicated a narrow Bragg reflection bandwidth of 50 pm is attainable for realistic grating parameters with critical dimensions larger than 100 nm. An example of a fabricated structure is shown in Fig. 3. In optical transmission measurements we have found Bragg peaks as narrow as 50 pm with an extinction ratio of 10 dB or 250 pm with an extinction ratio of 30 dB.

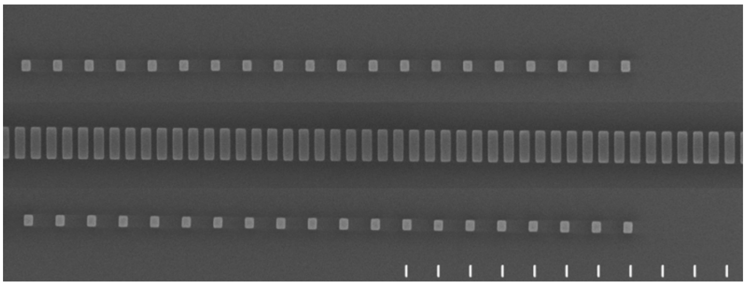

Figure 3. SEM micrograph of a fabricated SWG Bragg grating structure with lateral loading segments.

4. CONCLUSIONS

Subwavelength engineering provides a new degree of freedom in the design of silicon photonic components. We have provided examples of the application of this powerful technique in two areas that are of particular practical importance, namely fiber-chip coupling and bandwidth engineering of components. We presented an optimized fiber-chip coupler with broadband and polarization-independent coupling with high efficiency and discussed design strategies for increasing the mode size while minimizing substrate leakage loss. We also showed the design of narrowband Bragg filters including first experimental results demonstrating a 3-dB reflection bandwidth of 50 pm.

REFERENCES

[1] P. Cheben, *et al.*, Subwavelength waveguide grating for mode conversion and light coupling in integrated optics, *Opt. Express* **14,** 4695–4702 (2006).

[2] J. H. Schmid, *et al.* Gradient-index antireflective subwavelength structures for planar waveguide facets. *Opt. Lett.* **32,** 1794–1796 (2007).

[3] P. Cheben, *et al.*, Refractive index engineering with subwavelength gratings for efficient microphotonic couplers and planar waveguide multiplexers, *Opt. Lett.* **35,** 2526–2528 (2010).

[4] R. Halir, *et al.*, Waveguide sub-wavelength structures: a review of principles and applications, *Laser Photonics Rev.* **9**, 25–49 (2015).

[5] P. Cheben, *et al.* Broadband polarization independent nanophotonic coupler for silicon waveguides with ultra-high efficiency, *Opt. Express* **23,** 22553–22563 (2015).

[6] J. Čtyroký, *et al.*, Design of narrowband Bragg spectral filters in subwavelength grating metamaterial waveguides, *Opt. Express* **26,** 171-194 (2018).