# Subwavelength Structures in Silicon-on-Insulator Waveguides for Modification of Facet Reflectivity and Efficient Fiber-Chip Coupling

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***Abstract.*** *First implementations of subwavelength gratings in silicon-on-insulator waveguides are discussed and demonstrated by experiment and simulations. The subwavelength effect is exploited for making antireflective and highly reflective waveguide facets as well as efficient fiber-chip coupling structures for photonic wire waveguides.*

## Introduction

Subwavelength gratings (SWGs), i.e. gratings with a pitch that is sufficiently small to suppress all but the 0$^{th}$ order diffraction, have been known and used for many years [1], most commonly as an alternative to antireflective (AR) coatings on bulk optical surfaces. Since diffraction is suppressed, the light propagating through a SWG structure is influenced by the average optical properties of the SWG medium. This SWG effect allows one to engineer artificial materials with refractive indices that are intermediate to those of the constituent materials of the SWG. In the context of high index contrast (HIC) integrated planar waveguide circuits, SWG patterns can be used to alleviate some of the fundamental problems intrinsic to HIC waveguides. Here, we demonstrate by experiment and simulation the first implementations of SWG structures in silicon-on-insulator (SOI) waveguides. We show that both AR and highly reflective (HR) waveguide facets as well as highly efficient fiber-chip couplers for photonic wire waveguides can be made using SWGs fabricated by standard lithography and etching processes.

## Modification of Facet Reflectivity by SWGs

The AR effect of SWG structures formed on waveguide facets, such as those shown in Fig. 1, is analogous to the same effect on bulk optical surfaces and can be described using the effective medium theory (EMT) [2]. According to EMT, a composite medium comprising two different materials interleaved at the subwavelength scale can be approximated as a homogeneous medium with a refractive index expressed as a power series in ($\Lambda/\lambda$), where $\Lambda$ is the pitch of the SWG and $\lambda$ is the wavelength of the light. From this theory a gradient-index AR effect is expected for gratings with a triangular shape while square SWGs can be used to mimic the effect of a single layer AR coating. The duty cycle of the grating controls the effective index and the modulation depth corresponds to the thickness of the equivalent thin film. Examples of square and triangular SWG patterns on ridge waveguide facets in 1.5 μm thick SOI are shown in Fig. 1. In both cases, samples are fabricated with a two-step patterning process. The facets are formed by electron beam lithography and reactive ion etching.

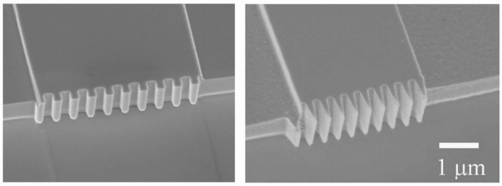


Fig. 1: Scanning electron micrographs of SOI waveguide facets patterned with square (left) and triangular (right) SWGs.

To measure the facet reflectivity, transmittance of fabricated waveguides was measured as a function of wavelength near λ=1.55 μm and the reflectivity was inferred from the depth of the Fabry-Pérot fringes observed in the transmission spectrum. Results of these measurements for triangular SWGs are shown in Fig. 2 as a function of the grating modulation depth. An efficient AR effect is observed, with facet power reflectivities as low as 2.0% for transverse electric (TE) and 2.4% for transverse magnetic (TM) polarization for a modulation depth of 0.7 μm [3]. The single layer AR effect of square SWGs is also demonstrated experimentally. Unlike the case of the triangular SWGs, the reflectivity of square SWGs is strongly polarization dependent. For example, the lowest experimental facet reflectivity for a square SWG obtained is 3.6% for TE polarized light; however, the same facet has a reflectivity of 23% for TM polarization. The experimental results for both triangular and square SWG facets are in good agreement with EMT.

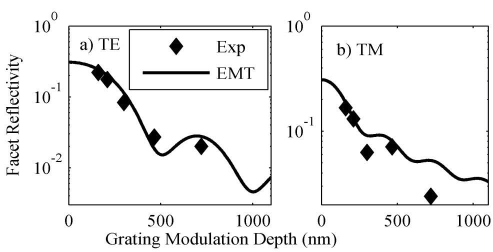


Fig. 2: Experimental data and theoretical results from EMT for the reflectivity of facets with triangular SWGs as a function of the grating modulation depth (corresponding to the length of the gradient-index section).

When the pitch of a square SWG is increased to the point where diffraction becomes possible on the silicon side, but is still suppressed on the air side of the grating, i.e. $\lambda/n_{Si} < \Lambda < \lambda$, an interesting effect is observed. The grating parameters can be chosen such that a waveguide mode incident on the patterned facet from the silicon side experiences a high reflectivity, whereas light incident from the air is almost completely diffracted into the +1 and -1 diffraction orders inside the silicon, with the $0^{th}$ order transmission and reflection being suppressed. Finite-difference time domain (FDTD) modeling is used to demonstrate this effect. The layout of a 2D FDTD simulation is shown in Fig. 3a. It is a 7 μm wide Si waveguide ($n_{Si}$ = 3.476) with $SiO_2$ lateral claddings ($n_{SiO2}$ = 1.44), terminated at the facet with a square grating. The grating period is 0.7 µm, the duty cycle is 54% and the grating modulation depth is 485 nm. The external medium is air (n = 1). A continuous-wave field excitation of a TE (electric field in the plane of the drawing) waveguide fundamental mode of free space wavelength λ = 1.55 µm propagating in the waveguide towards the facet was assumed. The mesh size used was 10×10 $nm^2$ and the simulation was run for a total of 10,000 time steps of $\Delta t=2.2\times10^{-17}$ s. The calculated TE electric field map is shown in Fig. 3b. The excitation plane for the waveguide mode source is indicated in the figure by a blue line, including the mode propagation direction (arrow). It can be seen that the transmittance through the grating structure is efficiently suppressed, creating the mirror effect. Between the excitation plane and the facet, the forward propagating and the reflected light form a standing wave interference pattern. To the left of the excitation plane, the reflected mode propagates unperturbed in the waveguide. A reflectivity value of 97% is obtained for this 2D structure. Figure 3c shows the simulation of light coupling from an external optical fiber to the Si waveguide. In this case, a light source with Gaussian intensity profile with a $1/e^2$ full width of 10.4 µm (SMF-28 fiber mode), is located at the excitation plane (white line in Fig. 3c). The calculated field in the waveguide reveals a strong transverse modulation with a period half of the grating pitch, which persists almost unperturbed for several micrometers as the light propagates in the waveguide. This intensity pattern stems from the superposition of the -1 and +1 diffraction orders, while the $0^{th}$ order is suppressed. Rigorous coupled wave theory (RCWT) of plane waves incident on silicon surface gratings corroborates the FDTD results described above. For example, reflectivities >99% for light incident from the silicon side are calculated from RCWT.

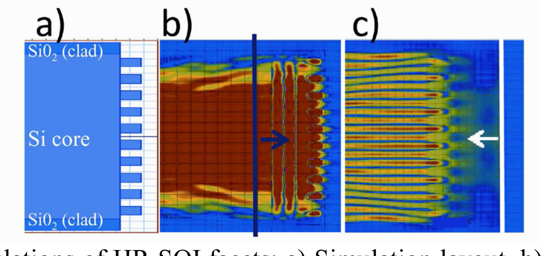


Fig. 3: FDTD simulations of HR SOI facets: a) Simulation layout. b) FDTD simulation for a TE waveguide mode launched at the plane indicated in the figure. c) TE field map for an external optical fiber mode coupling into the waveguide.

Waveguide transmission measurements similar to the ones we have discussed for the AR facets have been carried out for the HR structures. The results confirm the HR subwavelength grating concept; however, it is found that the reflectivity depends strongly on mode confinement. This was confirmed by 3D FDTD simulations, which showed that the maximum facet reflectivity for a 1.5 µm thick SOI waveguide is 80%, whereas 94% reflectivity can be achieved for a waveguide thickness of 5 µm.

## Fiber-Chip SWG Couplers

An original application of SWGs for fiber-to-waveguide coupling and mitigating losses due to the mode size mismatch of optical fibers and SOI waveguides of submicrometer dimensions has been proposed recently [4]. The principle of this fiber-chip coupler is based on a gradual modification of the waveguide mode effective index by the SWG effect. In this scheme the waveguide is transformed into a longitudinal subwavelength waveguide grating, as shown in the scanning electron micrographs of a fabricated coupler structure in Fig. 4a. As the mode travels along the SWG, the waveguide mode effective index is altered by chirping the SWG duty ratio $r(z) = a(z)/\Lambda(z)$, where $a(z)$ is the length of the waveguide core segment and $\Lambda(z)$ is the pitch. Figure 4b depicts the same coupler structure closer to edge of the chip, where the fiber is coupled to the SWG. Both the duty ratio and the width of the segments are reduced to optimize the overlap of the fiber mode with the mode of the segmented waveguide. Coupling efficiencies as large as 76% (1.35 dB loss) were calculated for coupling from a standard SMF-28 optical fiber using 2D FDTD simulations of SOI waveguides with a Si core thickness of 0.3 μm. The first fabricated SWG waveguide couplers shown in Fig. 4 are for SOI photonic wire waveguides with dimensions of 0.45 μm (width) × 0.26 μm (height). The minimum pitch of the grating is 0.2 μm and the smallest gaps are nominally 50 nm. In first experiments, the lowest coupling loss of approximately 4 dB was achieved for a coupler length of 50 μm, compared to 11 dB loss for photonic wires without couplers. Preliminary experimental results indicate that the coupling loss can be further improved by optimization of the SWG parameters, in particular by tapering the width.

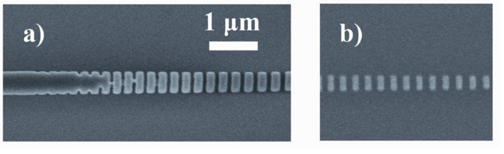


Fig. 4: Scanning electron micrographs of a fabricated SOI photonic wire waveguide with a SWG coupler (top view): a) The SWG coupler joining the photonic wire waveguide. b) Mid-section of the SWG coupler.

## Conclusions

We have presented results of experiments and simulations of first SWG structures in SOI waveguides. Three types of structures have been discussed, namely AR and HR waveguide facets and fiber-chip couplers, all fabricated using standard fabrication techniques. The AR facets were demonstrated exploiting either a single layer AR effect from square SWGs or a GRIN effect from triangular SWGs with a minimum measured reflectivity of 2%. HR SWG facets employ a similar structure to that of square AR SWG waveguide facets but with different grating parameters, namely pitch, modulation depth and duty ratio. Finally, the principle, design and first experimental results on SWG fiber-chip couplers were reviewed, demonstrating a fiber-to-photonic wire coupling loss of ~4 dB.

## References

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