Research Article

Subwavelength Grating Structures in Silicon-on-Insulator Waveguides

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First implementations of subwavelength gratings (SWGs) in silicon-on-insulator (SOI) 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. We demonstrate experimentally that by etching triangular SWGs into SOI waveguide facets, the facet power reflectivity can be reduced from 31% to <2.5%. Similar structures using square gratings can also be used to achieve high facet reflectivity. Finite difference time-domain simulations show that >94% facet reflectivity can be achieved with square SWGs for 5 μm thick SOI waveguides. Finally, SWG fiber-chip couplers for SOI photonic wire waveguides are introduced, including design, simulation, and first experimental results.

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1. INTRODUCTION

Subwavelength gratings (SWGs) have been known and used for many years [1], most commonly as an alternative to antireflective (AR) coatings on bulk optical surfaces. The defining property of an SWG is a pitch that is sufficiently small to suppress all but the 0th order diffraction, the latter referring to the light that is reflected or transmitted according to Snell's law. According to the grating equation for normally incident light ($\sin \theta = m\lambda/\Lambda$, where θ is the angle of diffraction, λ is the wavelength of light, Λ is the grating pitch, and m is the diffraction order) diffraction is suppressed for $\Lambda < \lambda$, as the diffraction angle becomes imaginary for all orders m . Conceptually, the light propagating through a SWG structure "senses" the average optical properties of the SWG medium. The SWG can thus be represented as a locally homogeneous effective medium with optical properties determined by the grating geometry. The effect of a specific optical coating can be mimicked by an SWG with an appropriate modulation depth and duty cycle. Effective multilayer and gradient-index (GRIN) structures can also be obtained with SWGs. Low reflectivities on optical surfaces have been demonstrated with SWGs both by a single-layer AR effect as well as by a GRIN effect [2]. More recently,

SWG surface structures that exhibit very high reflectivity over a broad wavelength band have also been demonstrated [3, 4]. In this paper we discuss the first implementations of SWG structures in silicon-on-insulator (SOI) integrated planar waveguide circuits.

Integrated planar waveguide circuits are widely used in optical telecommunication systems, with arrayed waveguide grating (AWG) multiplexers being one of the most complex of such circuits [5]. Currently, these commercial waveguide devices are typically made from doped silica glass with a low refractive index contrast. The high-index contrast (HIC) SOI material system offers the potential of a significant size and cost reduction of integrated planar waveguide devices, including AWGs [6, 7]. In addition, new applications are emerging for miniaturized SOI waveguide devices. For example, we have recently demonstrated a compact high resolution microspectrometer [8] and highly sensitive photonic wire evanescent field sensors (PWEF) with a detection limit of ~ 20 fg of organic molecules [9, 10]. However, there are also fundamental challenges of the SOI material system related to the fixed value of the refractive indices of the constituent materials (Si and SiO_2). Since the SWG effect allows one to engineer artificial materials with intermediate effective indices simply by lithographic patterning, it has

the potential to circumvent this limitation. We demonstrate this on two specific examples, namely, the control of the Fresnel reflectivity of the waveguide facets and the fiber-to-chip coupling, both relying on the SWG effect.

The Fresnel reflectivity of a cleaved SOI waveguide facet is typically $\sim 30\%$, which is the reflectivity of the Si-air interface. This comparatively high facet reflectivity causes Fabry-Pérot cavity effects in SOI planar waveguide devices and also increases the fiber-chip coupling loss. Thus antireflective facets are often desirable. For some devices, for example, optical cavities, a facet reflectivity larger than 30% is required. Both AR and highly reflective (HR) facets can be achieved by the use of thin-film coatings; however, the use of optical coatings on facets has various drawbacks. For example, film deposition has to be carried out at the chip level after cleaving, requiring additional processing and precluding device testing at the wafer level. Thin film deposition processes can be complex, may reduce yield, and may require the use of expensive deposition equipment. Furthermore, optical coatings may become mechanically unstable under thermal cycling, leading to restrictions on device power and limitation of device lifetime.

A major problem in the design and fabrication of silicon microphotonic devices is the limited efficiency of optical coupling to silicon waveguides at the input/output interfaces. Due to the large mode size disparities, the light coupling between an optical fiber and a silicon waveguide with a small cross section is largely inefficient. Various solutions to this problem have been suggested, for example, three-dimensional mode size transformers, edge [11] and off-plane [12–15] grating couplers, inversely tapered waveguides [16] and GRIN planar waveguide lenses [17], each having some advantages and drawbacks. A comparative review of various coupling schemes is contained in [18]. For submicron silicon wire waveguides, inverse tapers have emerged as a particularly efficient coupling method. Demonstrated coupling losses of inverse tapers with a minimum width of $0.1\ \mu\text{m}$ reported in [16] are 6 dB and 3.3 dB for TE and TM polarized light, respectively. While this is a remarkable achievement, a further improvement of the total coupling efficiency is desirable. Furthermore, the coupling efficiency of inverse tapers is strongly dependent on the minimum taper width, a fact that results in tight fabrication tolerances for the taper width.

We have recently proposed the use of the SWG effect as a general tool for waveguide mode modifications, including light coupling between an optical fiber and high index contrast waveguides of submicrometer dimensions [19] and modification of facet reflectivity [20]. In this paper, we review our work but also provide new experimental and modeling results on the use of SWGs in SOI waveguides. All SWG patterns discussed here, both for facet reflectivity modification and for fiber-to-chip coupling enhancement, can be fabricated by standard lithography and vertical etching processes. This has two obvious advantages. First, devices can be processed at the wafer level before dicing; and second, shape control of the SWG is limited only by the resolution of the lithography and pattern transfer. To demonstrate the effects, we have carried out experiments on

SOI waveguides and compared the experimental results with reflectivity calculations using effective medium theory and finite difference time-domain (FDTD) simulations.

2. ANTIREFLECTIVE WAVEGUIDE FACETS

The AR effect of specific SWG structures on waveguide facets is analogous to the same effect on bulk optical surfaces. It can be described using the effective medium theory (EMT) [21]. 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 (Λ/λ) , where Λ is the pitch of the SWG and λ is the wavelength of the light. For the case of a one-dimensional surface grating, the first-order expressions for the anisotropic refractive index are given by

$$n_{\parallel} = (fn_1^2 + (1-f)n_2^2)^{1/2}, \quad (1a)$$

$$n_{\perp} = \left(\frac{f}{n_1^2} + \frac{(1-f)}{n_2^2} \right)^{-1/2}. \quad (1b)$$

Equations (1a) and (1b) refer to the case of the electric field of the incident light being parallel or perpendicular to the grooves (see Figure 1), respectively. In these equations, n_1 and n_2 are the refractive indices of the two media comprising the SWG, and f is the filling factor, defined as the fraction of material with index n_1 in a thin slice parallel to the surface, as shown in Figure 1. The equations above are valid in the limit $(\Lambda/\lambda) \rightarrow 0$. Figure 1 shows the geometry of SWGs with square and triangular shapes at a silicon-air interface ($n_1 = 3.5$, $n_2 = 1$). For square gratings (top left), the filling factor profile is a step function (left center panel). Using (1a) and (1b), the refractive index profile, which is also a step function, is obtained (bottom left). The effective index in the grating region is polarization dependent, as per (1a) and (1b). The TM mode has the electric field parallel to the grating grooves, corresponding to (1a) whereas the electric field of the TE mode is perpendicular to the grooves, corresponding to (1b). For triangular gratings (top right in Figure 1), the filling factor profile is a linearly decreasing function along the depth of the grating (center right). The corresponding effective index profiles are continuously decreasing functions across the grating region for both polarizations as shown in the bottom right panel of Figure 1.

The step function effective index profile of a square grating is equivalent to that of a single-layer coating on a silicon surface. The thickness of this effective layer is given by the modulation depth of the grating and the effective refractive index can be adjusted between the values of silicon and air by changing the duty cycle of the SWG. From thin film theory, the requirements for a single-layer interference AR coating for light crossing the boundary between two materials of reflective indices n_1 and n_2 at normal incidence are $n_f^{\text{AR}} = \sqrt{n_1 n_2}$ and $t = m\lambda/(4n_f^{\text{AR}})$ where n_f^{AR} is the film refractive index, t is the film thickness, and $m = 1, 3, 5, \dots$ is an odd integer. Thus an AR surface with a square SWG can be designed by choosing the effective refractive index for

FIGURE 1: Effective medium theory applied to square and triangular SWGs on a Si-air interface. Top: schematic of the grating geometry. Center: filling factor corresponding to the square and triangular SWGs. Bottom: resulting effective refractive index profiles for light with the electric field along the grating grooves (TM, dashed curves) and perpendicular to the grating grooves (TE, solid curves).

a specific polarization in (1a) and (1b) equal to the required n_f^{AR} . This determines the filling factor and thus the duty cycle of the grating. The modulation depth is then determined by the condition above for the AR coating thickness t . In contrast to the square gratings, the antireflective properties of triangular gratings arise from the GRIN effect, as the effective refractive index varies continuously between the bulk values of the two media that comprise the grating, namely, Si and air.

Figure 2 shows the scanning electron microscope images of SOI ridge waveguide facets patterned with square and triangular SWGs. These structures were fabricated with a two-step patterning process on SOI substrates with a Si layer thickness of $1.5 \mu\text{m}$ and a buried oxide (BOX) layer thickness of $1 \mu\text{m}$, as described in [20]. Square and triangular facet patterns with various dimensions as well as flat reference facets were produced by electron beam lithography and reactive ion etching (RIE). The facet reflectivity was inferred from Fabry-Pérot (FP) transmission measurements on waveguides terminated with SWG facets, as shown schematically in Figure 3. The ridge waveguides have a width of $1.5 \mu\text{m}$, adiabatically tapered to a width of $4 \mu\text{m}$ near the facets. This increased waveguide width at the facet makes it possible to include 10 periods of the SWG with a pitch of $0.4 \mu\text{m}$. The etch depth for the shallow etch (defining the ridge waveguide) is $0.7 \mu\text{m}$, while the deep facet etch is terminated at the bottom oxide.

Transmittance of fabricated waveguides was measured as a function of wavelength near $\lambda = 1.55 \mu\text{m}$. Propagation

FIGURE 2: Scanning electron micrographs of SOI waveguide facets patterned with (a) square and (b) triangular SWGs.

FIGURE 3: Schematic top view of a SOI ridge waveguide terminated at both ends with a SWG (not to scale), as used for waveguide transmission measurements described in the text.

loss was determined from the reference waveguides with flat facets to be 1.7 dB/cm for TE and 5.2 dB/cm for TM polarized light, using the Fabry-Pérot method. The Fresnel reflectivity of a material with the mode effective index was used as an approximation for the reference waveguide facet reflectivity. This value differs from the reflectivity of a Si-air interface by less than 0.5% for either polarization. The polarization dependence of the propagation loss is believed to be due to scattering loss from the etched sidewalls of the waveguides. The reproducibility of the loss measurement was found to be good with waveguide-to-waveguide fluctuations of the loss less than 0.5 dB/cm . A comparison of transmission spectra of waveguides with flat facets and with triangular and square SWG patterned facets is shown in Figure 4 for TE polarized light. The peak-to-peak grating modulation depth is 720 nm for the triangular SWG pattern and 270 nm for the square pattern which has a duty ratio of 61%. The amplitude of the FP fringes is reduced from 4.5 dB for the flat facets to approximately 0.3 dB and 0.5 dB for the triangular and square SWGs, respectively. Assuming the same propagation loss for all waveguides as obtained from the reference measurement on waveguides with flat facets, the power reflectivities of the triangular and square SWG facets are calculated to be 2.1% and 3.6%, respectively, from the amplitude of the observed FP fringes shown in Figure 4.

For triangular gratings, the facet reflectivity was measured as a function of the modulation depth of the SWG for both polarizations and compared with EMT theory for the equivalent grating on a bulk silicon surface. The results are shown in Figure 5. The EMT calculation was carried out by discretizing the continuous effective index profiles shown in Figure 1 (bottom right) in steps of 1 nm . The resulting discrete index profile for each polarization is the same as

FIGURE 4: Fabry-Pérot fringes for the reference waveguide with flat facets and for the waveguides terminated with antireflective triangular or square SWG structures. The curves are offset for clarity.

that of a stack of 1 nm thick films. The reflectivity of the SWG is then calculated as the reflectivity of this equivalent thin film stack using standard thin film theory. There is good quantitative agreement of experiment and theory (see Figure 5). The reflectivity decreases substantially with the grating modulation depth, as the gradient-index section becomes more adiabatic. The minimum measured reflectivity of 2.0% for TE and 2.4% for TM polarization is obtained for a modulation depth of 720 nm, which is the maximum grating depth used in our experiments. The quoted values are an average over 4 measured samples. According to the EMT calculations, reflectivities below 1% can be achieved for SWG modulation depths of approximately 1 μm and 2.5 μm for TE and TM polarized light, respectively. Since the SWG profiles are defined lithographically, their shape and thus the effective index profile can be readily engineered for specific requirements (e.g., polarization properties), in a similar way as for bulk SWG surfaces [22].

For square SWGs (Figure 2, left), the lowest measured facet reflectivity was 3.6% for TE polarized light whereas the TM reflectivity of the same sample was 23%. Such a large polarization dependence is expected for square gratings. As discussed above, according to EMT, the square AR SWGs can be represented as a single-layer AR coating, the efficiency of which is known to be rather sensitive to the index of the layer. Since the effective index of the SWG is polarization dependent (Figure 1, bottom left), optimal AR performance can only be achieved for one polarization state for a particular SWG duty cycle. The strong polarization dependence of square SWG facets can potentially be exploited for making polarization selective waveguide elements.

3. WAVEGUIDE FACETS WITH HIGH REFLECTIVITY

Subwavelength gratings with high reflectivity have recently been demonstrated on optical surfaces as a replacement for the top distributed Bragg reflector in a vertical-cavity

surface emitting laser (VCSEL) [23]. In order to obtain the SWG effect, these gratings need to be separated from the substrate by a layer of low index material. This was achieved in a VCSEL device by fabricating a grating freely suspended above the substrate with an air gap of $\sim 1 \mu\text{m}$. A similar SWG structure can be envisioned for planar waveguide facets consisting of a row of vertical posts in front of a flat waveguide facet at a specific distance (equivalent to the air gap of the VCSEL structure). However, in such a structure there is no vertical mode confinement in the air gap, resulting in out-of-plane radiative loss as the light propagates in the air gap. For a SOI waveguide thickness of $\sim 1 \mu\text{m}$ or less, these radiative losses are prohibitive for practical devices, as we have found with three-dimensional FDTD simulations.

Interestingly though, FDTD simulations show that if a square grating is etched directly into the facet without a separating air gap, high reflectivities can also be obtained. The modeled structure is shown in Figure 6(a). It is a 7 μm wide Si slab waveguide ($n_{\text{Si}} = 3.476$) with SiO_2 lateral claddings ($n_{\text{SiO}_2} = 1.44$), 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 $\lambda = 1550 \text{ nm}$ propagating in the waveguide towards the facet was assumed. The mesh size used was 10 nm and the simulation was run for a total of 10 000 time steps of $\Delta t = 2.2 \times 10^{-17}$ seconds. The calculated TE electric field map is shown in Figure 6(b). 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, hence 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. The facet reflectivity is calculated as an overlap integral of the reflected intensity profile in the waveguide region to the left of the excitation plane with the fundamental TE mode. A reflectivity value of 97% was obtained for this 2D structure. Figure 6(c) 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 $1/e^2$ width of 10.4 μm (SMF-28 fiber mode), is located at the excitation plane (white line in Figure 6(c)). The calculated field in the waveguide reveals a strong transverse modulation with a period half of the grating pitch. This modulation persists almost unperturbed for several micrometers as the light propagates in the waveguide. Since the overlap integral of this modulated field with the fundamental mode of the waveguide is comparatively small, coupling from an external fiber to the waveguide is inefficient.

These markedly different grating properties for light propagating in opposite directions may seem surprising, but have a straightforward explanation. Obviously, diffraction is suppressed on the air side of the grating, since $\Lambda < \lambda_{\text{air}}$. However, the grating is not subwavelength for light coupled

FIGURE 5: Experimental and theoretical results from effective medium theory for the reflectivity of facets with triangular SWGs as a function of the length of the gradient-index section (i.e., the grating modulation depth).

FIGURE 6: FDTD simulations of HR SOI facets. (a) Layout used for a typical simulation. The light and dark blue regions are the silicon waveguide core and SiO₂ lateral cladding, respectively. (b) Simulated TE field map for a waveguide mode launched at the plane indicated in the figure. (c) TE field map for an external optical fiber mode coupling into the waveguide.

into the Si waveguide, where the first diffraction order is not evanescent, since $\Lambda > \lambda_{\text{Si}}$. In our case $\Lambda = 700$ nm, $\lambda_{\text{air}} = 1.55$ μm , and $\lambda_{\text{Si}} = \lambda_{\text{air}}/n_{\text{Si}} = 446$ nm. This is a fundamental difference between the HR gratings and the square AR gratings discussed in the previous section, which have a pitch of $\Lambda = 400$ nm and are thus subwavelength both in the Si and in air. It can be shown with rigorous coupled wave analysis (RCWA) that for a plane wave normally incident from inside the bulk Si on a surface grating with the same pitch and duty cycle as our HR facet gratings, both the diffraction efficiency and the transmittance are extremely small, while the specular (0th order) reflectivity is $>99.9\%$. Conversely, when the plane wave is incident on such a bulk

grating from the air to Si, the power diffracted into the $+1$ and -1 diffracted orders is approximately 98%, with $<2\%$ of light reflected or transmitted in 0th order. The intensity pattern in Figure 6(c) is thus a superposition of the -1 and $+1$ diffraction orders, while the 0th order is suppressed. This zero-order suppression effect is commonly employed in phase masks used in the fabrication of fiber-Bragg gratings [24].

The reflectance of HR gratings on waveguide facets can be estimated from measured FP fringes similar to the AR measurements discussed in the previous section. The most notable difference is that fiber-waveguide coupling is now largely inefficient due to the diffraction effect explained above. In fact, waveguides terminated with HR facets on both sides were found experimentally to have no measurable transmittance ($T < -60$ dB). To circumvent this problem and measure the internal (Si-air) facet reflectivity, we have used waveguides that are terminated with an HR grating on the output facet but with a regular flat facet having a Fresnel reflectivity of 31% on the input side. This way an asymmetric FP cavity is formed. As in the case of the AR facets, FP fringes can be observed in the transmission spectra of these waveguides. In Figure 7, the spectrum of such an asymmetric cavity waveguide is compared to that of a reference waveguide terminated on both ends with flat facets. The measured peak-to-peak fringe modulations are 6.4 dB and 4.2 dB for the respective waveguides. Using a simple Fabry-Pérot model for the asymmetric cavity, this corresponds to an HR facet reflectivity of 75%, clearly demonstrating the validity of the HR grating concept. However, since this reflectivity is significantly lower than the best results of our 2D FDTD simulations, full 3D FDTD simulations of the HR facet structures were carried out. These simulations

FIGURE 7: Measured Fabry-Pérot fringes in the transmission spectrum of a waveguide with an HR grating on the output facet. A reference waveguide with flat facets is also shown. The curves are offset for clarity.

reveal a strong dependence of the expected reflectivity on mode confinement. For the $1.5\text{ }\mu\text{m}$ thick SOI waveguides with the $0.7\text{ }\mu\text{m}$ pitch gratings used in our experiments, the highest reflectivity obtained in the 3D FDTD simulations is 80%, in good agreement with the measurement. For thicker waveguides with the same facet grating dimensions the achievable reflectivity increases significantly. For example, 94% reflectivity is expected for $5\text{ }\mu\text{m}$ thickness according to the 3D FDTD simulations. Physically, the reason for the mode size effect is the dependence of the grating reflectivity on the incident angle. With RCWA we find that the grating reflectivity for plane waves drops from $>99.9\%$ to 81% when the angle of incidence is increased from 0° to 10° . Therefore, the larger range of incident angles contained in a smaller, more localized mode, results in a lower reflectivity.

4. FIBER-TO-CHIP COUPLERS

An original application of SWGs for fiber-to-waveguide coupling and mitigating losses due to the mode size mismatch of optical fibers and submicron SOI waveguides has been proposed recently [19]. The principle of this fiber-chip coupler is based on a gradual modification of the waveguide mode effective index by the SWG effect. The idea is illustrated in a schematic side view of a coupler structure in Figure 8. The waveguide mode effective index is altered by chirping the SWG duty ratio $r(z) = a(z)/\Lambda$, where $a(z)$ is the length of the waveguide core segment. Unlike in the case of the AR and HR SWG structures discussed above, where the direction of light propagation is orthogonal to the grating vector, here they are colinear, that is, the light propagates along the grating. Nevertheless, EMT applies to these structures in a similar way. The effective index of the mode in the SWG coupling structure increases with the grating duty ratio. The duty ratio and hence the volume fraction of the Si waveguide core is modified such that at one end of the coupler the effective index is matched to the SOI waveguide while at the other

FIGURE 8: Schematic of an SWG fiber-to-waveguide coupler, side view.

end, near the chip facet, it matches that of the optical fiber. We have demonstrated the proposed principle on various SWG coupling structures [19], using two-dimensional FDTD calculations for an SOI waveguide with Si core thickness of $0.3\text{ }\mu\text{m}$ with SiO_2 cladding. Efficiencies as large as 76% (1.35 dB loss) and a negligible return loss (-35 dB , or 0.03%) were calculated for coupling from a standard optical fiber (SMF-28, mode field diameter $10.4\text{ }\mu\text{m}$) using a $50\text{-}\mu\text{m}$ -long SWG coupler. Further loss reduction can be expected by advanced design, including parabolic width tapering and chirping the SWG pitch. The coupling efficiency tolerance to misalignment is high. Transverse misalignment of $\pm 2\text{ }\mu\text{m}$ results in an excess coupling loss of only 0.5 dB. The angular misalignment tolerance is also large, with only 0.24 dB loss penalty for angular misalignment of ± 2 degrees. We have also demonstrated the reduction of the coupler length down to $10\text{ }\mu\text{m}$ and found an excess loss of 0.6 dB compared to the $50\text{ }\mu\text{m}$ long coupler discussed above. Unlike waveguide grating couplers based on diffraction, the SWG mechanism is nonresonant, and hence intrinsically wavelength insensitive.

First SWG waveguide couplers for SOI photonic wires (PWs) have recently been fabricated in our lab. The dimensions of the PWs are $0.45\text{ }\mu\text{m}$ (width) $\times$ $0.26\text{ }\mu\text{m}$ (height). Such thin PW waveguides have been shown to provide the maximum sensitivity for evanescent field waveguide-based biosensors [9]. The coupler structures were fabricated on SOI substrates from SOITEC with an Si layer and BOX thickness of $0.26\text{ }\mu\text{m}$ and $2\text{ }\mu\text{m}$, respectively. Electron beam lithography with a chemically amplified negative resist (NEB 22 A3) was used to define both waveguides and SWG couplers in a single step. The pattern was then etched through the Si layer to the BOX with inductively coupled plasma RIE. After the resist mask was stripped, a $2\text{ }\mu\text{m}$ thick upper cladding layer of SU-8 resist with a refractive index of $n = 1.58$ was deposited on the sample using a standard spin and bake procedure. The samples were then cleaved and polished as necessary to obtain good facet quality. The ideal SWG coupler structure described above requires a specific duty cycle at the facet; however, for cleaving and polishing the facet some tolerance in the exact position of the facet with respect to the pattern is required. Therefore, the SWG was extended with constant grating parameters for $400\text{ }\mu\text{m}$ beyond the ideal position of the facet. This allows the final position of the fabricated facet to be within this distance from the end of the coupler structure. SEM images of a fabricated coupler structure are shown in Figure 9. On the left side, the part of the SWG joining the PW waveguide is shown.

FIGURE 9: SEM micrographs of a fabricated SOI photonic wire waveguide with an SWG coupler (top view). (a) The SWG coupler joining the photonic wire waveguide. (b) Mid-section of the SWG coupler.

The pitch of the grating is $0.2\text{ }\mu\text{m}$ and the smallest gaps are nominally 50 nm . Due to the proximity effect in the e-beam lithography, the grating gaps become successively more closed as the waveguide, which is written with a higher e-beam dose, is approached. Within a distance of a few periods of the SWG from the waveguide, the grating is essentially a subwavelength sidewall grating. This gradual closing of the gaps may in fact be beneficial to the performance of the coupler, as it reduces the small discontinuity in the effective mode index as the waveguide transforms into an SWG, making the transition more adiabatic. Figure 9(b) shows the same coupler at a position closer to the facet. Here the fabricated structure shows little deviation from the design except for some corner rounding. To increase the effective index gradient along the SWG coupler, the width of the SWG segments is tapered from $0.45\text{ }\mu\text{m}$ at the waveguide to $0.2\text{ }\mu\text{m}$ at the facet.

Samples with SWG couplers of varying lengths and taper widths have been fabricated. Two identical couplers are connected via S-shaped PW waveguides for transmission measurements. The S-shape helps to reduce the amount of scattered light reaching the photodetector, as the latter is laterally offset from the light source. The SWG couplers are compared with inverse tapers of similar dimensions, as well as untapered waveguides. The inverse taper couplers are adiabatically tapered waveguides that reach a specific minimum width at the facet [16]. Coupling loss was inferred from measurements of the waveguide transmittance at a wavelength $\lambda = 1.55\text{ }\mu\text{m}$ using an erbium doped fiber amplified spontaneous emission (ASE) source with 50 mW output power. An indium gallium arsenide photo diode was used as a detector. Coupling loss values were estimated from the measured waveguide transmittance by correcting for the photonic wire propagation loss, which was determined using the cut back method on comparable samples to be 9.1 dB/cm and 6.5 dB/cm for TE and TM polarization, respectively. The lowest coupling loss for the SWG couplers of 6.5 dB and 4 dB for TE and TM polarization, respectively, was obtained for a width of $0.2\text{ }\mu\text{m}$. The corresponding values for straight waveguides with a width of $0.45\text{ }\mu\text{m}$ are 18 dB and 11 dB . The coupling loss of our first coupler is comparable to the loss of inverse couplers as reported in [16] (6.0 dB and 3.3 dB loss for TE and TM polarization, respectively), but is achieved for a two times larger width. A wider taper width implies improved fabrication tolerance to width

fluctuations. We expect the loss can be reduced by further improvements in our design and fabrication, using a thicker box and/or a wider taper width. Our experiments provide a first verification of the proposed SWG coupler concept. Also, the SWG principle experimentally demonstrated in this paper can be generalized to other types of waveguide modifications including effective index changes and mode transformations, opening new possibilities for engineering of waveguide properties at the subwavelength scale.

5. SUMMARY AND CONCLUSIONS

We have reviewed our work in implementing 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 GRIN effect from triangular SWGs or a single-layer AR effect from square SWGs. The GRIN AR structures were found to be particularly efficient, with measured facet reflectivities below 2.5% for both polarizations. These experimental results are in good agreement with EMT calculations. A minimum reflectivity of 3.6% for the TE mode is reported for square SWGs, including highly polarization selective properties. HR facets employ a very similar structure to that of square AR SWG waveguide facets but with different grating parameters. The $0.7\text{ }\mu\text{m}$ pitch of the HR grating is large enough that the ± 1 orders of diffraction are allowed in the Si, but are evanescent in air. For light incident from the air, such gratings act as a zero-order suppressed phase mask. In the opposite direction (light incident from the waveguide), high specular reflectivity is observed. We have measured up to 75% reflectivity for facets in $1.5\text{ }\mu\text{m}$ thick SOI waveguides, in good agreement with 3D FDTD simulations. The FDTD simulations predict that reflectivities in excess of 95% can be achieved for SOI waveguides with a thickness of $5\text{ }\mu\text{m}$ or more. Finally, the principle, design and first experimental results on SWG fiber-chip couplers were reviewed. Coupling losses on the order of $\sim 1\text{ dB}$ can be achieved with these structures according to FDTD simulations and losses of 6.5 dB and 4 dB for TE and TM polarized light, respectively, have been demonstrated experimentally. The first results suggest that the SWG couplers may outperform inverse taper fiber-chip couplers in terms of fabrication robustness, compactness, and tolerance to misalignment.

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