A high efficiency input/output coupler for small silicon photonic devices

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Abstract: Coupling light from an optical fibre to small optical waveguides is particularly problematic in semiconductors, since the refractive index of the silica fibre is very different from that of a semiconductor waveguide. There have been several published methods of achieving such coupling, but none are sufficiently efficient whilst being robust enough for commercial applications. In this paper experimental results of our approach called a Dual-Grating Assisted Directional Coupler, are presented. The principle of coupling by this novel method has been successfully demonstrated, and a coupling efficiency of 55% measured.

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OCIS codes: (050.2770) Gratings; (060.1810) Couplers; (160.6000) Semiconductors

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References and links

1. A. Liu, R. Jones, L. Liao, D. Samara-Rubio, D. Rubin, O. Cohen, R. Nicolaescu, and M. Paniccia, "A high-speed silicon optical modulator based on a metal-oxide-semiconductor capacitor," Nature **427**, 615-618 (2004).
2. A. Liu, H. Rong, M. Paniccia, O. Cohen, and D. Hak, "Net optical gain in a low loss silicon-on-insulator waveguide by stimulated Raman scattering," Opt. Express **12**, 4261–4267 (2004), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-18-4261.
3. O. Boyraz and B. Jalali, "Demonstration of 11dB fiber-to-fiber gain in a silicon Raman amplifier," IEICE Elect. Express **1**, 429-434 (2004).
4. O. Boyraz and B. Jalali, "Demonstration of a silicon Raman laser," Opt. Express **12**, 5269-5273 (2004), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-21-5269.
5. H. Rong, R. Jones, A. Liu, O. Cohen, D. Hak, A. Fang, and M. Paniccia, "A continuous-wave Raman silicon laser," Nature **433**, 725-728 (2005).
6. V. R. Almeida, C. A. Barrios, R. R. Panepucci, and M. Lipson, "All-optical control of light on a silicon chip," Nature **431**, 1081-1084 (2004).
7. C. E. Png, S. P. Chan, S. T. Lim, and G. T. Reed, "Optical phase modulators for MHz and GHz modulation in silicon-on-insulator (SOI)," J. Lightwave Technol. **22,** 1573-82 (2004).
8. J. J. Fijol, E. E. Fike, P. B. Keating, D. Gilbody, J. J. LeBlanc, S. A. Jacobson, W. J. Kessler, and M. B. Frish, "Fabrication of silicon-on-insulator adiabatic tapers for low-loss optical interconnection of photonic devices," in *Photonics Packaging and Integration III*, R. A. Heyler, D. J. Robbins, and G. E. Jabbour, eds., Proc. SPIE **4997**, 157-170 (2003).
9. A. Sure, T. Dillon, J. Murakowski, C. Lin, D. Pustai, and D. W. Prather, "Fabrication and characterization of three-dimensional silicon tapers," Opt. Express **11**, 3555-3561 (2003), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-11-26-3555.
10. V. R. Almeida, R. R. Panepucci, and M. Lipson, "Nanotaper for compact mode conversion," Opt. Lett. **28**, 1302-1304 (2003).

11. K. Yamada, M. Notomi, I. Yokohama, T. Shoji, T. Tsuchizawa, T. Watanabe, J. Takahashi, E. Tamechika, and H. Morita, "SOI-based photonic crystal line defect waveguides," in Proc. SPIE **4870**, 324–338 (2002).

12. Z. Lu and D. W. Prather, "TIR-Evanescent coupler for fiber to waveguide integration of planar optoelectronic devices," Opt. Lett. **29**, 1784-1750 (2004).

13. G. Z. Masanovic, V. M. N. Passaro, and G. T. Reed, "Dual grating-assisted directional coupling between fibres and thin semiconductor waveguides," IEEE Photonics Technol. Lett. **15**, 1395-1397 (2003).

14. G. Z. Masanovic, V. M. N. Passaro, and G. T. Reed, "Coupling to nanophotonic waveguides using a dual grating-assisted directional coupler," IEE Proc. Optoelectron. **152**, 41-48 (2005).

15. S. J. McNab, N. Moll, and Y. A. Vlasov," Ultra-low loss photonic integrated circuit with membrane-type photonic crystal waveguides," Opt. Express **11**, 2927-2939 (2003), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-11-22-2927.

16. J. K. Butler, N.-H. Sun, G. A. Evans, L. Pang, and P. Congdon, "Grating-assisted coupling of light between semiconductor and glass waveguides," J. Lightwave Technol. **16**, 1038-1048 (1998).

17. R. Orobtchouk, N. Schnell, T. Benyattou, J. Gregoire, S. Lardenois, M. Heitzmann, and J. M. Fedeli, "New ARROW optical coupler for optical interconnect," in *Proceedings of IEEE International Conference on Interconnect Technology* (2003), pp 233-235.

18. W. Huang and J. Hong, "Transfer matrix approach based on local normal modes for coupled waveguides with periodic perturbation," J. Lightwave Technol. **10**, 1367-1375 (1992).

19. V. M. N. Passaro, "Optimal Design of grating-assisted directional couplers," J. Lightwave Technol. **18**, 973-984 (2000).

20. V. S. Nguyen, S. Burton, and P. Pan, "The variation of physical properties of plasma-deposited silicon nitride and oxynitride with their compositions," J. Electrochem. Soc. **131**, 2348-2353 (1984).

1. Introduction

Silicon Photonics has recently received considerable interest for low cost applications in communications and interconnect, becoming significantly more interesting with the report of a fast silicon modulator [1], optical gain [2,3] and silicon lasers [4,5]. There is also a trend to reduce the dimensions of silicon devices to improve the packing density [6], and to enhance the performance of silicon photonic circuits [7]. Cross sectional dimensions of silicon waveguide-based devices reported recently are ~ 1 µm or less. Whilst this reduction enhances the performance of the photonic circuit, it makes coupling of light to/from the circuit very difficult, particularly to/from standard optical fibres that typically have a core dimension of ~ 9 µm. Consequently several devices have been proposed for efficient coupling to/from the silicon photonic circuit [8-12] but none have yet produced satisfactory performance. We have previously presented theoretical work of an alternative device entitled the Dual Grating Assisted Directional Coupler (DGADC) [13,14] that predicted efficiencies as high as 97%. Whilst this was very promising, other methods also have high efficiencies in theory. It is when these devices are measured experimentally that they fail to fulfill their promise. Here we present experimental results of the DGADC, and we show that the experimental coupling efficiency is within a few percent of the theoretical value.

The importance of an efficient input/output coupler for silicon photonic circuits should not be underestimated. Many of the advantages of moving to small device dimensions will be nullified if a suitable CMOS compatible coupler cannot be fabricated reliably. Among several methods proposed for coupling to small silicon waveguides, tapers have been the most popular approach in recent years and are intuitively the most obvious. A three dimensional taper from the fibre dimensions to the waveguide dimensions in SOI has been demonstrated with loss as low as 0.7 dB per fibre-interface, when coupling to large silicon waveguides (> 3 µm in cross sectional dimensions) [8]. However, for waveguide dimensions smaller than 3 µm, the insertion loss (IL) increases rapidly reaching up to 2.5 dB for a width of 2 µm. Sure et al. [9] fabricated more efficient 3D adiabatic tapers using a gray scale mask. The theoretical coupling efficiency to a 0.25 µm thick silicon waveguide was 82%, while the value measured was 45%. It must be noted that these couplers also need anti-reflection (AR) coatings to reduce strong back-reflection at the facet, complicating fabrication. The surface roughness of such tapers can cause significant scattering when the taper is reduced to very small dimensions as fabrication of a sufficiently smooth taper is extremely difficult. Inverted tapers have also been popular [10,11], in which the waveguide is tapered down at the output rather

than up to the fibre dimension. This means that the mode becomes less well confined in the core of the waveguide and exists substantially in the cladding (typically silica or polymer). Therefore the effective index of the mode is reduced as the mode size increases, and matches well to an optical fibre. Despite the elegance of the approach the demonstrated loss has also been high, typically greater than 3 dB [10]. When scattering loss is excluded from the calculation these devices appear much more promising, having a conversion loss of less than 1 dB [11] although the total loss is higher.

In reference [15], which reports a loss of 0.5 dB per interface, the total insertion loss was measured, and the waveguide loss subtracted, leaving the coupling loss. However, the waveguide loss was measured by a rather inaccurate technique, the authors quoting an uncertainty of ±70%, although the data suggests perhaps even more. Furthermore, subtraction of waveguide loss implies removal of scattering loss, which is compounded in the taper section. Taking these issues together, this means that the quoted loss of 0.5 dB per interface could easily be substantially higher, but the accuracy of the data makes it impossible to say definitively.

Another promising approach for coupling to ~ 1/4 µm silicon waveguide is the inverted prism [12] producing an experimental efficiency of 45% as compared to 87% theoretically, but this requires external affixing of the prism to the waveguide.

To date, very few investigations have considered grating-based solutions for the problem. Prior to our work the most successful paper on grating-assisted coupling between a large glass waveguide and a thin semiconductor waveguide was that of Butler et al. [16], in which the maximum theoretical coupling efficiency for TE polarisation, was only 40% for optimised waveguide and grating parameters. For a change in the grating period of just 0.3 nm, the coupling efficiency dropped to only 20%, making the fabrication of this device impractical for commercial applications. Recently, experimental coupling efficiency of 50% has been reported using an AntiResonant Reflection Optical Waveguide (ARROW) incorporating a grating-assisted optical coupler [17]. However, the waveguide dimensions presented were 3 µm and 0.3 µm respectively for a wavelength of 1.3 µm, all much more restricted than presented here. Generally, the main disadvantages of grating-assisted couplers are relatively narrow bandwidth and significant polarisation dependence. We have already proposed a polarisation independent device [14] and work is underway to broaden spectrum of the device.

2. Dual Grating-Assisted Directional Coupling

We have developed the Dual Grating-Assisted Directional Coupler (DGADC) [13,14] that offers highly efficient coupling between a fibre and a thin Silicon on Insulator (SOI) waveguide. A schematic of an example design is shown in Fig. 1. The top layer is 5 µm thick with refractive index close to the refractive index of optical fibre, resulting in insertion loss ≤ 0.05 dB from the fibre to this waveguide. Therefore a fibre could be butt coupled to the thick SiON waveguide and subsequently the light coupled to the Si_3N_4 waveguide using the first grating, and to the thin SOI waveguide via the second grating. The silicon nitride waveguide is crucial for the operation of the device, because it enables highly efficient coupling at both gratings, consequently forming an efficient DGADC. This waveguide bridges the gap between SiON and Si layers in both refractive index and thickness. The buried oxide layer serves as the lower cladding layer, for isolation from the substrate, hence removing any leakage loss.

We have analysed the design in Fig. 1 using the Transfer Matrix Method (TMM) [18] and Floquet-Bloch Theory (FBT) [19] to ensure accuracy. For shallow gratings ($\approx$ 20 nm) such as those in our design, both methods agree well. It has been shown [14] that for the following design parameters: surface SiON waveguide thickness = 5 µm, refractive index = 1.478; upper SiON layer thickness = 0.15 µm, refractive index = 1.467; Si_3N_4 waveguide thickness = 0.5 µm, refractive index = 1.97; lower SiON layer thickness = 0.2 µm, refractive index = 1.467; silicon waveguide thickness = 230 nm, refractive index = 3.476, maximum coupling efficiency can reach ~93%. Whilst this is very encouraging, other approaches have also resulted in high theoretical efficiency but have produced inferior experimental results. Hence we have attempted to fabricate the device in Fig. 1 and measure it experimentally.
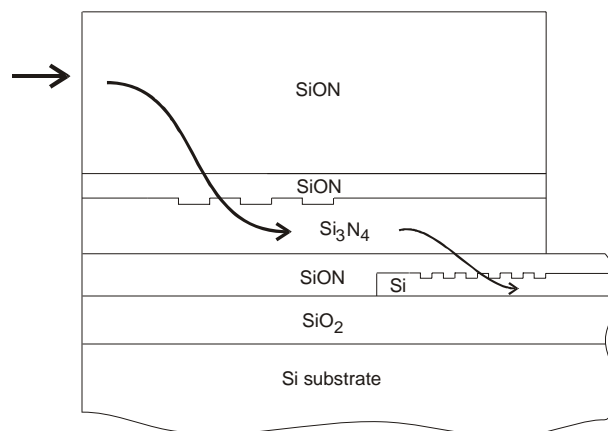
Fig. 1. Dual grating-assisted directional coupler in SOI [13]

3. Fabrication and experimental results

Unibond four inch wafers with 3 μm buried oxide layer and a 230 nm silicon overlayer were used for the fabrication of our devices. Both 'single' (Fig. 1) and 'double' DGADCs (Fig. 2) were fabricated. Obviously, the former was less convenient for measurement of the coupling efficiency than the latter because of a highly divergent beam coming out from the thin silicon waveguide. ICP etching was used to define the silicon waveguide. Gratings with a period of 1.3 - 1.4 μm and 10 nm height were then patterned by plasma etching on the top of this waveguide. Plasma Enhanced Chemical Vapour Deposition (PECVD) was used for the fabrication of SiON layers. The films were deposited at 300°C with varying flow of nitrous oxide, and constant flows of 50 sccm (standard cubic centimeters) of ammonia and 155 sccm of 5% silane in nitrogen. Silane and ammonia were used as reactants for the Si_3N_4 deposition process; ammonia instead of nitrogen was chosen as a reactant gas because it provides better thickness and refractive index uniformity [20]. The pressure was 0.5 Torr, and silane gas flow five times as large as that in the SiON deposition. The grating on this layer has a larger period (≈ 5 μm) and height of 20 nm. The top three layers were then etched in CHF_3 plasma down to the second gap layer.

Figure 3 shows a typical scanning electron micrograph of the resultant device. The most striking thing about the figure is that the total height of SiON and Si_3N_4 layers is 4.4 μm instead of 6 μm which means that the surface SiON waveguide has been significantly over-etched and is only up to 3.8 μm in height, as opposed to 5μm in the design of Fig. 1. The width of the waveguides is also reduced to 8-9 μm compared to 10 μm which has been used in the design. Wider waveguides have been chosen to minimize scattering caused by the side-wall roughness, similarly to [9]. Therefore we have recalculated the efficiency of the device as fabricated, and whilst the generic behaviour of the device remains the same, the maximum theoretical efficiency falls from 93% in the original design to 60% for the device as fabricated.

We have measured the efficiency of the device experimentally by fabricating the test structure in Fig. 2, which we refer to as the 'double DGADC' configuration. This enables light to be coupled into the thin silicon waveguide via the input SiON waveguide, and collected at the output via the output SiON waveguide, and the efficiency of two DGADCs evaluated. We assume that the efficiencies of each DGADC (at input and output) are equal. The efficiency was determined by normalising to the light transmitted through a straight surface SiON waveguide, which is almost identical to the 'double' DGADC structure, on the same chip. It is, however, continuous, unlike the 'double' DGADC which has an 800 μm long

silicon waveguide in the central region, and it does not have gratings so no coupling occurs. This approach was adopted because this excludes the reduced input coupling efficiency to the surface SiON waveguide, due to the over-etched waveguide, but still demonstrates the enhancement due to the DGADC. This approach has been also used extensively by other authors (e.g. in [8,9]). The total coupling loss from a fibre to silicon waveguide comprises the fibre to SiON waveguide loss (~ 0.7 dB) plus SiON to silicon waveguide loss (2.6 dB). However, if the surface SiON waveguide is 5 μm thick, the coupling loss from the fibre to SiON falls to ~ 0.1 dB and we expect the total coupling loss to be ~ 0.8 dB.
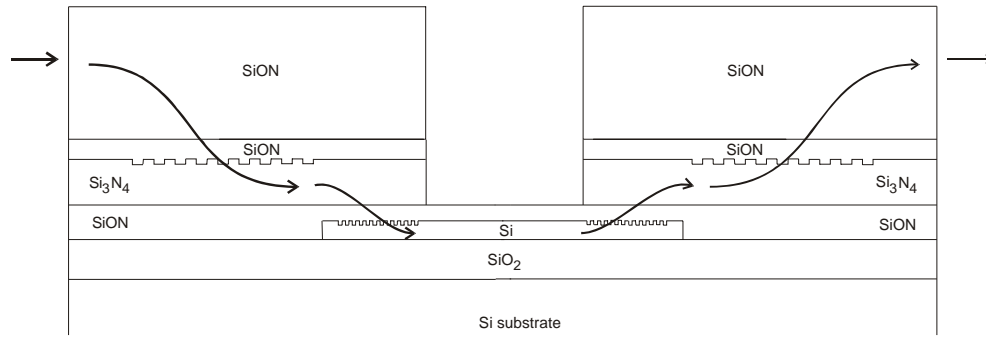

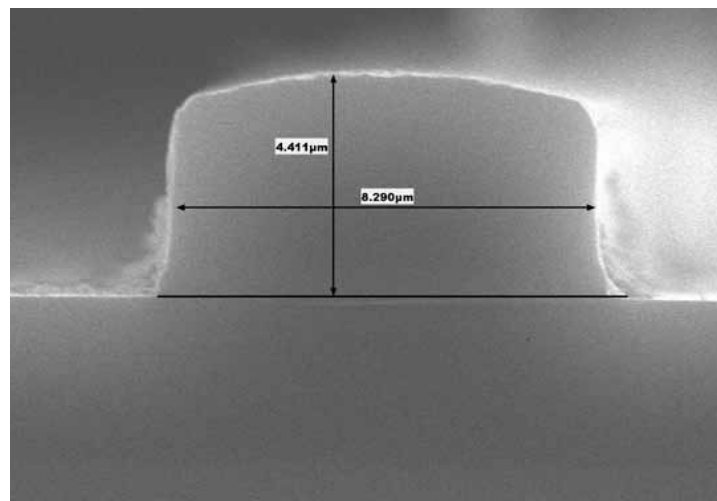Fig. 2. 'Double' DGADC configuration.

Fig. 3. Typical SEM micrograph of a fabricated DGADC.

Figure 4 shows a typical experimental spectra of the coupler. It can be seen that the resonant peak is well defined with typical side lobe suppression of 9-15 dB (theoretical value is ~ 14 dB). Higher values of mark to space ratio of the gratings (0.6-0.65) give higher coupling efficiency and bandwidth of ~ 4 nm (Fig. 4). The maximum measured efficiency is 55% (Fig. 5), within 5% of the theoretical value for this coupler design. For different grating periods, the resonant peak can be shifted towards longer or shorter wavelengths still achieving high coupling efficiency (Fig. 5). If the experimental to theoretical coupling efficiency ratio translates pro-rata to our original design, we can expect to achieve a coupling efficiency in excess of 80% (<1 dB loss) per interface for a correctly fabricated device. This makes the DGADC arguably the most promising method of coupling to small silicon waveguides and

devices, and is one of the only approaches that achieves an experimental efficiency close to the theoretical value.
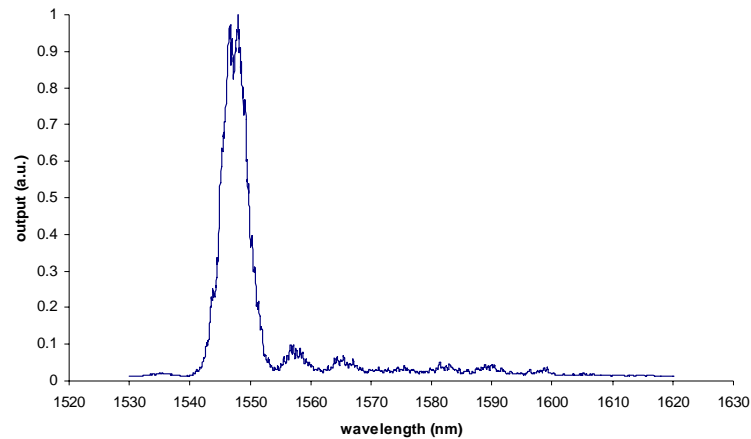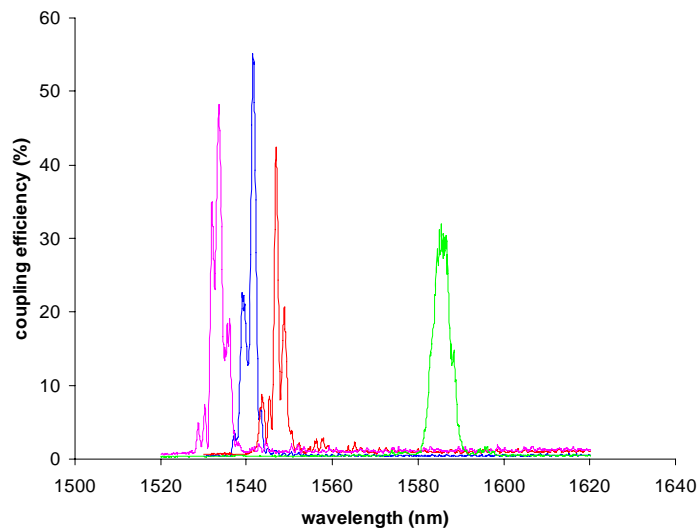

Fig. 4. Typical output from a 'double' DGADC.

Fig. 5. Coupling efficiency of DGADC can be as high as 55% and resonant peak position can be changed for different grating periods still achieving high efficiency.

4. Conclusion

We have presented experimental results for the DGADC approach. With the coupling efficiency of 55%, the DGADC is the most efficient grating-assisted directional coupling method for coupling to small semiconductor waveguides reported to date. The DGADC has a range of applications. It will be useful in wavelength selective applications such as coarse wavelength division multiplexing (CWDM), or coupling the pump wavelength to recently demonstrated Raman lasers or amplifiers in silicon, or in single wavelength applications such as optical interconnect. It also uses materials that are CMOS compatible and removes the need for anti reflection coatings at the input and output facets. Furthermore, work is underway to broaden the spectrum of the devices by grating chirping and by varying the duty cycle of the gratings.