Efficient coupling between submicron SOI-waveguides and single-mode fibers

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We have demonstrated a waveguide grating coupler for efficient coupling between single-mode fiber and submicron Silicon-on-Insulator (SOI) waveguides. The coupler has good alignment tolerances and can be fabricated using standard silicon processing techniques. We have demonstrated 25% coupling efficiency and a 3dB bandwidth of 65nm. The couplers can be used in two-dimensional arrays to achieve a much higher number of input-output fiber connections than is possible with conventional edge coupling.

Introduction

Silicon-on-insulator (SOI) is a promising material to make high-density photonic integrated circuits, thanks to the high index contrast between the silicon core and the silicon oxide cladding. Low-loss waveguides and components, such as photonic wires (2.4dB/cm for a 500nm wide waveguide) and compact ring resonators (10µm diameter) have recently been demonstrated [1]. Moreover these SOI photonic circuits can be mass produced using industry standard lithography and etching processes. However the interface between SOI photonic circuits and the outside world is still a problem : It is difficult to achieve a high coupling efficiency to fiber because of the huge mismatch in spotsize between the SOI waveguides and a fiber.

Grating couplers can be used to couple top illuminating light into submicrometer thin SOI waveguides [2]. However these grating couplers are typically large (> 100µm x 100µm) and have a very narrow bandwidth and are therefore not suitable for use in integrated optics. We have demonstrated that smaller grating couplers (> 10µm x 10µm) can be used to couple light from and to single-mode fiber with a bandwidth of several tens of nanometers [3]. In this paper we demonstrate the couplers in SOI with a 220nm thin silicon top layer and 1 µm thick buried oxide.

Because light is coupled in out and out from the top, there is no need to cleave or polish devices and it is possible to test the circuits 'wafer-scale', before dicing and packaging. Compared to traditional edge-coupling, the number of input-output fibers can be higher when using surface coupling, because a 2-D array of fibers can be used instead of a 1-D array. Also the alignment tolerances are very good, the alignment sensitivity is comparable to fiber-fiber alignment instead of fiber-submicron waveguide alignment.

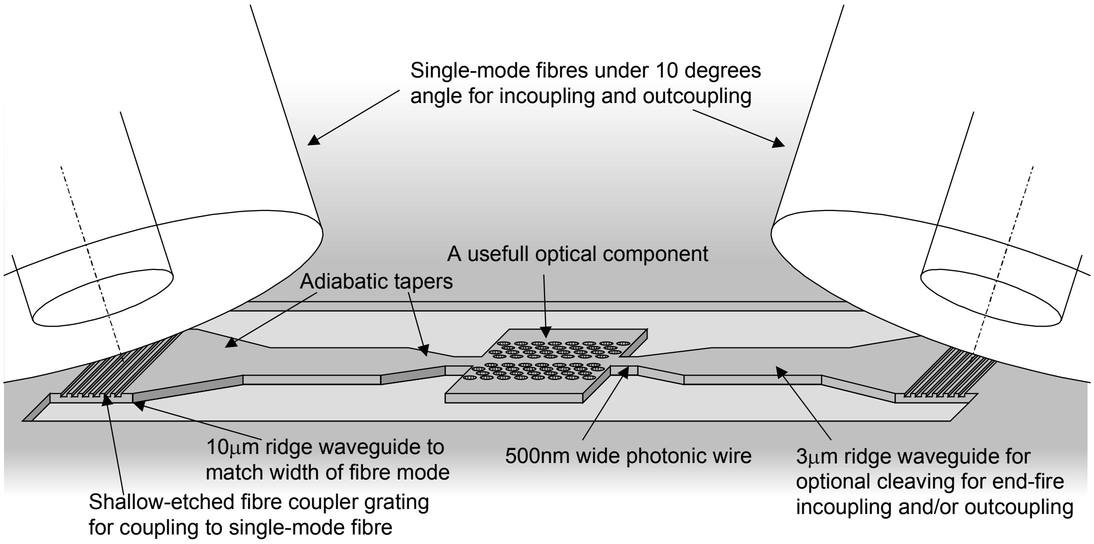
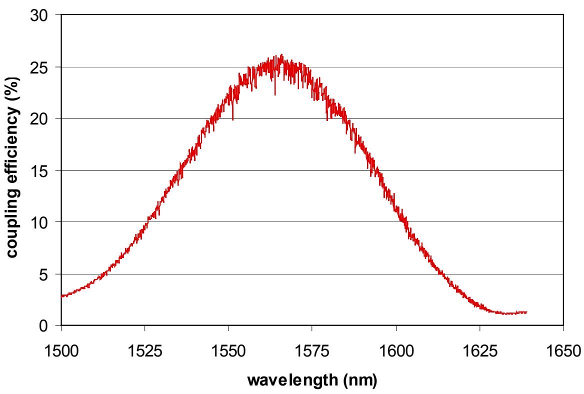


Figure 1. Coupling light in and out with grating couplers. The dimensions of the waveguides and fibers are not drawn to scale for clarity. The intermediate 3μm wide waveguide can be used for cleaving and edge-coupling if we need characterisation of the circuits without the couplers.

Experimental results

The grating has a period of 620nm, 50% fillfactor and is etched 90nm into the top silicon layer. We have measured the transmission from input fiber to output fiber on a waveguide with a coupler at both ends. So the transmission figure includes two grating couplers and the (very small) waveguide loss. The coupling efficiency of one coupler can easily and accurately be determined from this measurement, assuming that the input and output coupler are identical. The fibers are tilted 10 degrees to avoid unwanted backreflection from the grating. The measured coupling efficiency is shown in fig. 2. We have demonstrated a coupling efficiency of 25% and a 1dB bandwidth of 35nm (3dB bandwidth is 65nm). Compared to edge-coupling with tapered lensed fibers, our coupling efficiency is only slightly higher, but the alignment tolerances are much better : An alignment error of ±1μm in any direction results in less than 0.5dB additional loss, as can be seen in fig. 3.



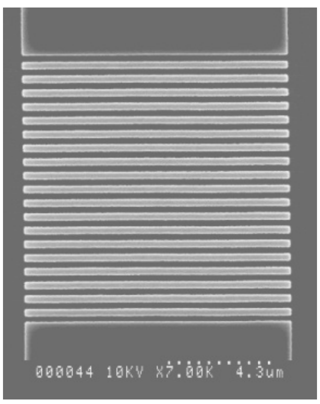


Figure 2. a) measurement of coupling efficiency versus wavelength
b) SEM-picture of the grating coupler (top view)

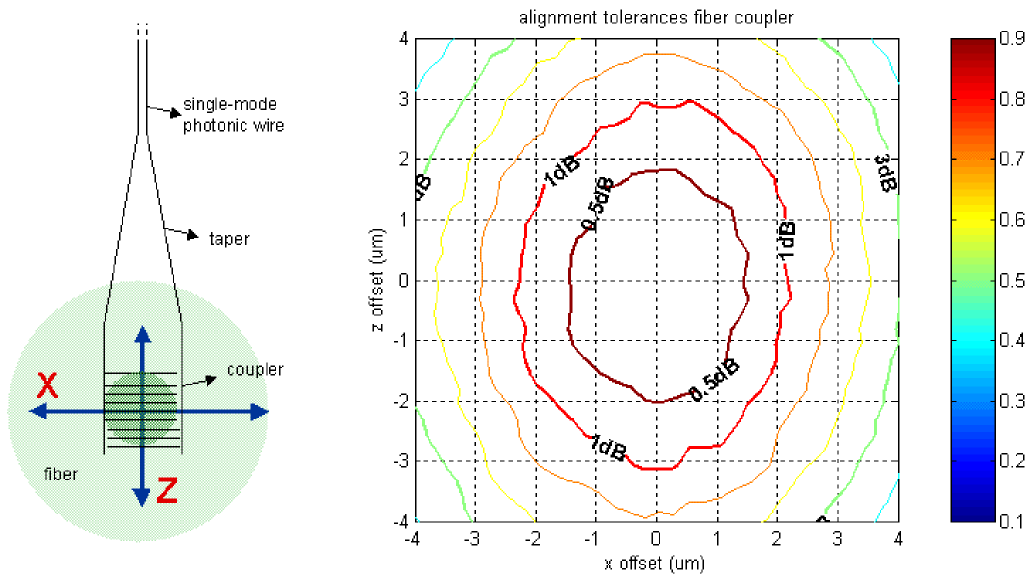


Figure 3. Measurement of the alignment sensitivity of the fiber coupler. The diameter of the -0.5dB contour is larger than 2µm.

The experimental efficiency of 25% is in good agreement with numerical simulations that predict 30%. The efficiency is limited by two factors. Firstly a major part of the light coming from the waveguide is radiated downward into the substrate instead of upward towards the fiber. Secondly there is a mismatch between the field radiated from the grating and the fiber mode. Solutions for these problems are adressed in the next paragraph.

Possible enhancements

The theoretically best solution is the use of a bottom reflector. A dielectric mirror (DBR) can avoid radiation to the substrate if the layer thicknesses are chosen correctly. It is possible to fabricate SOI with a 2-pair DBR mirror below the waveguide [4], and thanks to the high index contrast, a 2-pair mirror is sufficient. Unfortunately this material is not commercially available.

Another option that can be used on standard SOI wafers is depositing a top mirror stack. When properly designed, the cavity that is formed can increase the directionality of the coupler. This has been demonstrated [5] for long, narrowband gratings, but our simulation results show that for the short fiber coupler, the matter becomes more complicated and falls outside the scope of this paper. Also for the field mismatch problem there exist some solutions that work for narrowband gratings.

All the results in this paper were obtained for TE-polarised light, the efficiency of the grating coupler for TM-polarisation is very low. When using high refractive index contrast structures , polarisation sensitivity is unavoidable. This polarisation sensitivity severely limits the potential use in optical communication networks. To solve this problem, we have also proposed a polarisation diversity approach using a 2-D grating as a polarisation splitter/combiner. We have demonstrated an extinction ratio > 18dB and a coupling efficiency of 20%. When using this coupler/splitter as input and output coupler, a polarisation insensitive photonic integrated circuit can be made, using waveguides that are polarisation sensitive. This coupler/splitter is shown in fig.4 but more details can be found in paper [6].

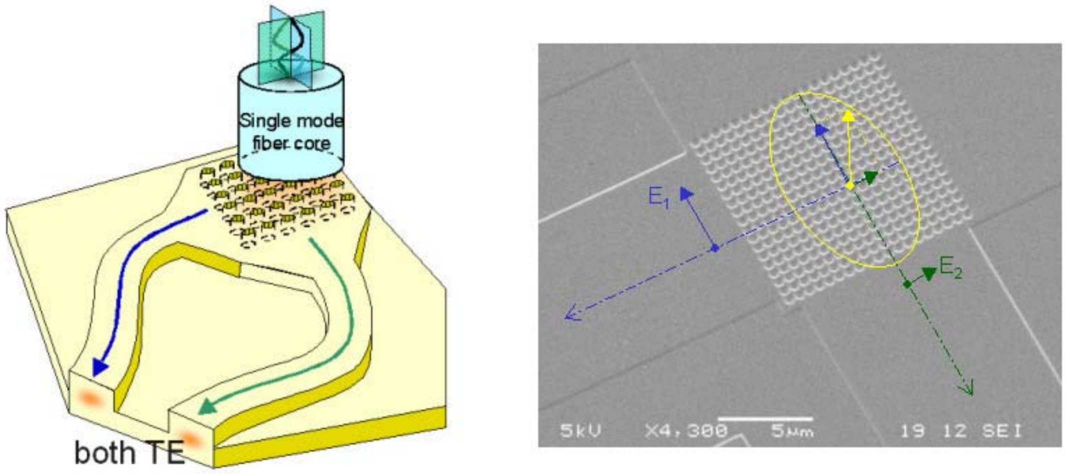


Figure 4. Two-dimensional waveguide grating coupler used as polarisation splitter.

Conclusions

We have demonstrated a waveguide grating coupler for efficient coupling between single-mode optical fibers and submicron SOI waveguides. We have also proposed enhancements to increase the coupling efficiency.

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References

[1] P. Dumon, W. Bogaerts, J. Van Campenhout, V. Wiaux, J. Wouters, S. Beckx, R. Baets, " Low-loss, single-mode photonic wires and ring resonators in Silicon-on-Insulator", accepted for publication is Proceedings of the Leos Annual Meeting 2003, Tucson, USA, Oct 2003

[2] R.M. Emmons, D.G. Hall, "Buried-oxide silicon-on-insulator structures : waveguide grating couplers", IEEE J. Quantum Electron., vol. 28., pp164-175, Jan 1992

[3] D. Taillaert, W. Bogaerts, P. Bienstman, T.F. Krauss, P. Van Daele, I. Moerman, S. Verstuyft, K. De Mesel, R. Baets, "An out-of-plane grating coupler for efficient butt-coupling between compact planar waveguides and single-mode fibers" , IEEE J. Quantum Electron., vol. 38, pp. 949-955, July 2002

[4] M.K. Emsley, O. Dosunmu, M.S. Unlu, "Silicon substrates with buried distributed bragg reflectors for resonant cavity enhanced opto-electronics" , IEEE J. Sel. Top. Quantum Electron., vol. 8, pp. 948-955, July/August 2002

[5] A. Narashima, E. Yablonovitch, "Efficient optical coupling into single mode Silicon-on-Insulator thin films using a planar grating coupler embedded in a high index contrast dielectric stack.", CLEO 2003 conference, Baltimore, USA, paper cwa46, June 2003

[6] D. Taillaert, H. Chong, P. Borel, L. Frandsen, R. De La Rue, R. Baets, "A compact two-dimensional grating coupler used as a polarization splitter", IEEE Photonics Technology Letters, vol. 15(9), pp. 1249-1251, Sep. 2003