High efficiency and broad bandwidth grating coupler between nanophotonic waveguide and fibre*

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A high efficiency and broad bandwidth grating coupler between a silicon-on-insulator (SOI) nanophotonic waveguide and fibre is designed and fabricated. Coupling efficiencies of 46% and 25% at a wavelength of 1.55 μm are achieved by simulation and experiment, respectively. An optical 3 dB bandwidth of 45 nm from 1530 nm to 1575 nm is also obtained in experiment. Numerical calculation shows that a tolerance to fabrication error of 10 nm in etch depth is achievable. The measurement results indicate that the alignment error of ± 2 μm results in less than 1 dB additional coupling loss.

Keywords: grating coupler, silicon-on-insulator, coupling efficiency, bandwidth

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1. Introduction

Optical waveguide structures with high refractive index contrast are promising for large scale integration of optical functions on a single substrate. This is due to the fact that the high refractive index contrast allows realization of wavelength or sub-wavelength scale optical components[1−4] which can be interconnected by nanophotonic integrated waveguides. Silicon-on-insulator (SOI) technology is emerging as a promising platform for nano-scale optical waveguides due to the high refractive index contrast between the silicon core and the oxide cladding. This enables high-density integrated optical circuits, which can be fabricated by standard complementary metal oxide semiconductor (CMOS) technology.[5,6] However, the large difference in dimension between the micro-scale fibre and the nano-scale waveguide on a chip causes high insertion loss and high packaging cost. Several approaches have been followed to tackle the problem. A very elegant solution is the inverted taper approach, in which low loss and broadband operation were demonstrated in Refs. [7]–[9]. These structures however still require a lens or high numerical aperture fibre for a reduced optical mode size.

As proposed in the literature, one-dimensional[10] or two-dimensional grating structures[11] can also be used to couple light from a fibre into an SOI waveguide. These grating couplers have the advantage of requiring no polished facets for coupling, which enables wafer scale online testing of photonic integrated circuits. A one-dimensional grating structure with a theoretical coupling efficiency of 37% and experimental coupling efficiency of 31% was reported.[12] Here, we present a grating coupler with a higher theoretical coupling efficiency up to 46%. This result is partly due to the fact that the parameters of the SOI wafer we used are different from those of the previously reported studies.

2. Design of the device

The principle of the grating coupler is shown in Fig. 1. It is used to couple the light from a standard single-mode fibre into a waveguide. An adiabatic taper is still designed to connect the 10 μm wide grating waveguide to the single-mode nanophotonic waveguide with a width of 0.45 μm. This taper with a length of

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100 μm can achieve a theoretical lossless conversion by calculation.

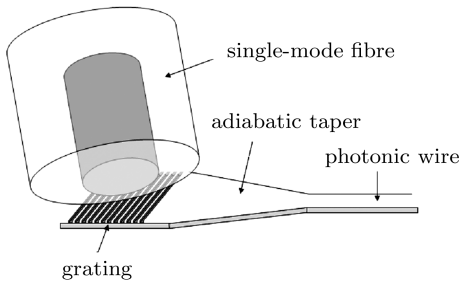


Fig. 1. Schematic of the coupling from fibre to waveguide.

The structure that we propose is depicted in Fig. 2. It consists of an SOI waveguide with a top silicon layer of 340 nm in thickness and a buried oxide layer of 1 μm in thickness in order to prevent leakage of light to the silicon substrate. The structure has a thicker top silicon layer than the reported grating normally has, with a 220 nm thick top silicon layer. The thicker top silicon makes deeper etching possible.

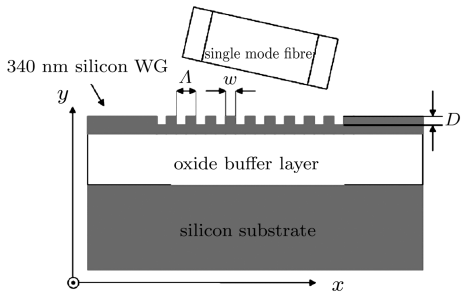


Fig. 2. Proposed device layout for high efficiency coupling to an optical fibre.

It works based on the fact that the etch depth is increased slightly to produce a higher coupling strength which is limited by the refractive-index modulation and the groove depth,[13] at the same time the reflection of the grating is not increased by the thicker top silicon layer. Therefore, a higher theoretical coupling efficiency is obtained in our design. The grating is etched in the top silicon layer ($n = 3.47$) which is on top of a 1 μm thick SiO_2 layer ($n = 1.46$), and air ($n = 1$) is the cladding of the structure. The grating has an etch depth D. The grating period is Λ and the filling factor is FF $= w/\Lambda$, where w means the segment length of un-etched top silicon in one period. To optimize the structure, the influence of D of the grating and Λ on the directionality of the grating (being the amount of power diffraction upwards for a grating) is assessed. We use a short grating with 20 periods, then the whole grating length is 12 μm, which is close to the near-field mode diameter of a single mode fibre. The simulation is performed by using CAMFR,[14] a two-dimensional (2-D) full vectorial solver based on eigenmode expansion. The complete problem is a three-dimensional (3-D) problem, but it can be reduced into a 2-D problem because the width of the grating for coupling, 10 μm, is much larger than the height of 340 nm.[14] But it is expected that in a real 3-D configuration, the coupling efficiency will be lower than that obtained from 2-D model-based simulations. The light is assumed to be of TE polarization and has a wavelength of 1.55 μm in calculation. The design for TM polarization is under different considerations. Some care should be taken when the efficiency values are discussed. In the literature about grating, coupling efficiency is often defined as the fraction of the power that is coupled out by the grating. Here, coupling efficiency is considered as the power coupled into the fibre. We use near vertical coupling (at 10° with respect to the vertical axis) to avoid second-order reflection and consider coupling from the waveguide into the fibre.[14]

The simulation results are plotted in Fig. 3 (for a grating duty cycle of 50%). The coupling curves of vertical coupling and the near vertical coupling at 10° are shown. A higher efficiency is obtained when the second-order reflection is avoided. This figure shows that an optimal coupling efficiency of 46% at a wavelength of 1.55 μm is achieved for $D = 150$ nm and $\Lambda = 580$ nm. We also obtain a large bandwidth with 3 dB bandwidth of 80 nm from 1515 nm to 1595 nm and 1 dB bandwidth of 40 nm from 1530 nm to 1570 nm by using a grating with a large coupling

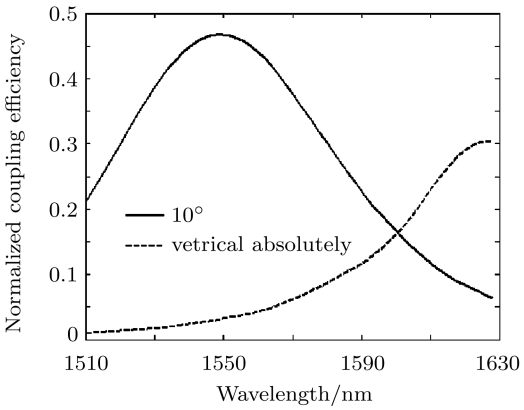


Fig. 3. Simulation results for vertical coupling and near vertical coupling with uniform periods.

strength. The large bandwidth can be used to increase the efficiency of broad band coupling, so it is very helpful in large power pump, nonlinear optics, etc. The main limitations to the efficiency are the coupling to the substrate and the mismatch between an exponential profile and a Gaussian profile. The directionality can be improved by optimizing the thickness of the buried oxide layer.[15]

3. Sensitivity to fabrication error

The effects of variations in etch depth and groove width are analysed to determine whether the proposed device has a reasonable tolerance to fabrication error. Shown in Fig. 4(a) are the resulting coupling efficiencies for different etch depths. For an error of 10 nm the maximum coupling efficiency remains approximately the same but the wavelength with the maximum efficiency is shifted. This wavelength shift can be compensated by adjusting the angle of the fibres, but for most applications the etch depth must be controlled accurately. If the grating is etched too deeply, there occurs not only a shift to longer wavelengths, but an increase in second order reflection. Figure 4(b) shows the effect of a different filling factor. A filling factor change from 50% to 40% or 60% has only a small effect on the coupling efficiency curves. However, in the case of 60% filling factor, the second order reflection is also increased. This is unobservable in the efficiency curve but may be relevant to some applications. In real fabricated structures these errors on the different parameters are present all at the same time. In the worst case where all the effects are present and jointly come to play a role, it is also possible that one error cancels the other. We can conclude that the tolerance to fabrication error is very tight, but achievable. The high accuracy needed is typical for all nanophotonic structures.

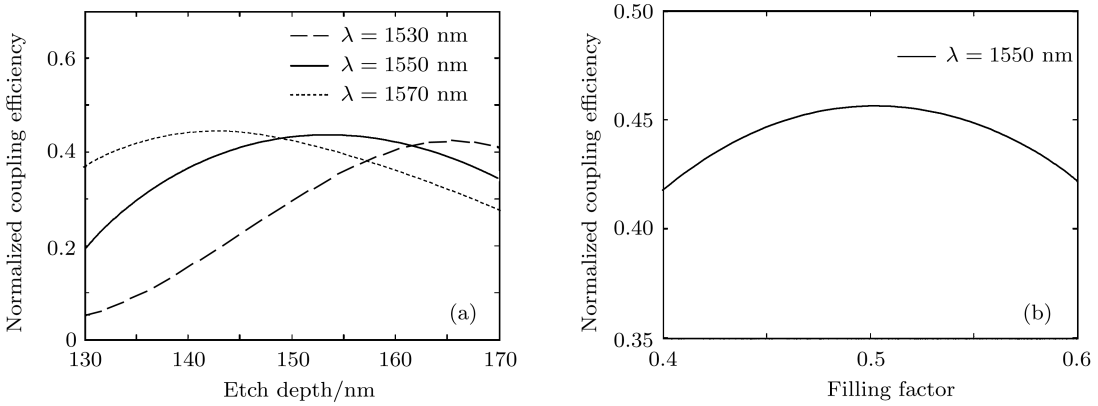


Fig. 4. (a) Coupling efficiency for different etch depths and (b) coupling efficiency for different filling factors.

4. Fabrication

The processing of the diffractive grating structure was performed on a 10 mm × 10 mm SOI wafer, consisting of a 340 nm thick silicon waveguide layer and a 1 μm thick buried oxide layer on silicon substrate. The optical waveguides and the diffraction grating are determined by two steps. The waveguide and the taper are determined by using electronic beam lithography (EBL) firstly, and over etched to buried oxide by inductive coupled plasma (ICP) dry etching. Then the grating is determined on the waveguide by EBL and etched 150 nm deep by ICP.

A scanning electron microscopic (SEM) image of the fabricated uniform grating is shown in Figs. 5(a) and 5(b). The etch depth and the groove width are measured to be about 155 nm and 290 nm, respectively, which are very close to the parameters we design.

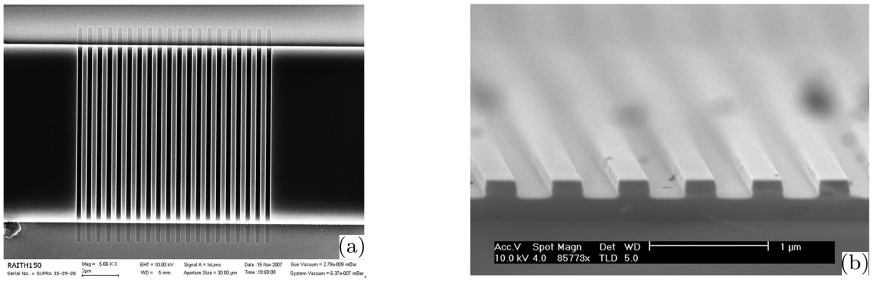


Fig. 5. (a) SEM image of fabricated grating structure on a 10 μm wide SOI waveguide and (b) SEM picture of the cross section.

5. Measurements

In the measurement, light is coupled in by using a near vertical fibre and the output power is measured at a cleaved facet. The input fibre is mounted on a high-precision 6-axis translation stage and set to a 10° angle respect to the vertical direction. The sample is mounted on a 2-axis stage and a microscope objective is used to collect the light from the output facet at the output side. During the initial alignment, the infrared camera is used to monitor the light coming from the facet. When the objective lens is properly aligned, the output light is focused onto the power detector and power transmission is measured, which is shown in Fig. 6.

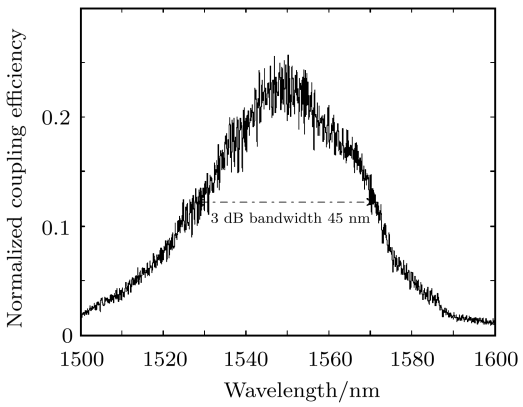
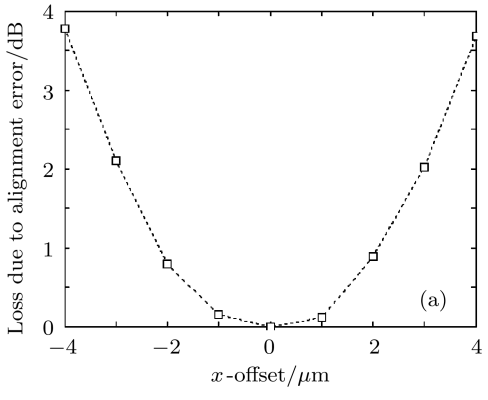


Fig. 6. Experimentally obtained fibre-to-waveguide coupling spectrum showing 25% maximum efficiency and a 3 dB bandwidth of 45 nm.

The maximum fibre-to-waveguide coupling efficiency is 25% at the wavelength of 1.55 μm and 3 dB bandwidth is 45 nm which is from 1530 nm to 1575 nm. We believe that the discrepancy between the measurements and the simulations may be sourced as follows: 1) as mentioned above, the 2-D model is used to simulate the performance for convenience, but the coupling efficiency in a real 3-D configuration will be lower than that obtained from 2-D model-based simulations; 2) the propagation loss that is caused by the roughness of waveguide sidewall. The roughness comes to play a role when over etching cannot be neglected; 3) what we detected by the power detector is the forward diffraction light in the waveguide, there is still some backward diffraction light which cannot be detected leaking in the silicon slab. These extra losses in fabrication and measurement depress the final results in the test.

An important property of the coupler is the sensitivity to alignment error. The coupling loss as a function of horizontal (in plane) position has been measured. In Figs. 7(a) and 7(b), the additional loss caused by alignment error is shown. We define the direction of the light propagating in the grating as the z direction, and the direction perpendicular to the z direction in the plane as the x direction which is also determined in Fig. 1. An alignment error of ± 2 μm only induces less than 1 dB additional coupling loss. To measure the curve in Fig. 7, the position of the fibre is first optimized for the maximum coupling efficiency, afterwards the position of the fibre is scanned in the xz-plane.



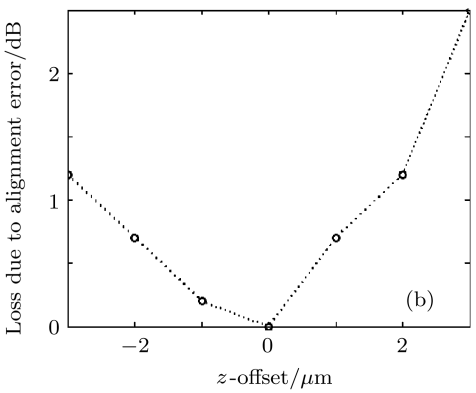


Fig. 7. (a) Alignment tolerances in the x direction and (b) alignment tolerances in the z direction.

6. Conclusions

In this paper, an efficient broadband grating coupler between an SOI waveguide and a single mode optical fibre is studied theoretically and experimentally. Simulation results show that an optimal coupling efficiency of 46% at a wavelength of 1.55 μm and 3 dB bandwidth of 80 nm can be achieved for an etch depth of 150 nm and a grating period of 580 nm, while experimentally 25% coupling efficiency and 3 dB bandwidth of 45 nm are obtained. A tolerance to fabrication error of 10 nm in etch depth is achievable by the analysis of numerical calculations, and measurements show that an alignment error of ± 2 μm results in less than 1 dB additional coupling loss.

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