A novel highly efficient grating coupler with large filling factor used for optoelectronic integration*

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A novel highly efficient grating coupler with large filling factor and deep etching is proposed in silicon-on-insulator for near vertical coupling between the rib waveguide and optical fibre. The deep slots acting as high efficient scattering centres are analysed and optimized. As high as 60% coupling efficiency at telecom wavelength of 1550-nm and 3-dB bandwidth of 61 nm are predicted by simulation. A peak coupling efficiency of 42.1% at wavelength 1546-nm and 3-dB bandwidth of 37.6 nm are obtained experimentally.

Keywords: silicon photonics, silicon-on-insulator, grating coupler

PACC: 4280F, 4280L

1. Introduction

Silicon-on-insulator (SOI) technology, compatible with the complementary metal-oxide semiconductor (CMOS) technology, is considered to be an ideal platform for intensely integration of active and passive electronic and photonic components in one silicon photonics circuits.[1] Because of the high refractive index between the silicon and silicon oxide, compact and sub-micron scale optical waveguide can be fabricate in the SOI wafers basically. However the large mismatch in mode size between the sub-micron waveguide and optical fibre inherently induces low coupling efficiency between them.

Recently, an attractive approach to achieving high efficient coupling is to use grating couplers at the end of optical waveguides.[2] As light is coupled out of the plane, grating couplers enable the photonics circuits wafer scale testing and can be used to integrate with other devices in one silicon photonic circuit. A uniform shallow etched grating coupler (filling factor = 0.5, etch depth $\sim$ 70 nm) in SOI with a coupling efficiency of 31% and 1-dB bandwidth of 40 nm was reported, and coupling efficiency of 37% was predicted by simulation,[3] and by adding a gold bottom reflector, the experimental coupling efficiency was increased to 69%.[4] However, two lithography steps were needed to form the strip waveguide and shallow etched grating coupler. In order to manufacture the uniform grating coupler with the waveguide in one lithography step, deep even fully etching is applied which will greatly increase the fabrication tolerance and cut the cost at the same time. Several novel grating structures were also proposed to improve the performance of deep or even fully etching uniform grating coupler, such as depositing additional overlay before etching,[5] adding an antireflection interface at the front end of the grating[6] and utilizing photonic crystal holes.[7] Enlarging filling factor of the deep etching grating is an efficient approach to overcome the coupling efficiency decreasing and centre wavelength blue-shift. Grating structure with large filling factor (filling factor = 0.85) was also fabricated with CMOS compatible process, coupling loss of -3.6 dB has been achieved for

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TE polarization.[8] However the grating and the strip waveguide in the top silicon layer were fully etched to the oxide buffer layer. This structure cannot be applied to further electronic process such as iron injection or PN junction formation.

In this paper, a novel grating coupler with large filling factor and deep etching is proposed. The characteristic of large filling factor grating coupler and the reason to achieve high efficiently coupling are discussed. By optimizing relative parameters, simulation results show that as high as 60% coupling efficiency and 3-dB bandwidth of 61 nm are predicted. The measured coupling efficiency and 3-dB bandwidth are 42.1% and 37.6 nm, respectively. The grating coupler with the rib waveguide was formed in one e-beam lithography step on the 340-nm top silicon layer SOI platform. The rib waveguide integration with the large filling factor grating coupler, which is deep etched to low level slab layer thickness, can be used for integration with high speed optoelectronic modulators and switches,[9−11] while the total insertion loss is reduced and the device works at telecom wavelength of 1.55 μm.

2. Design and simulation

A simplified two-dimensional (2D) model demonstrated in Fig. 1(a) is analysed numerically. The structure is based on the existing SOI wafer with a top silicon layer of 340 nm (n = 3.47) and a buried oxide (BOX, n = 1.44) layer of 2 μm. A TE polarization and 1.55-μm wavelength light beam is incident from the waveguide, and received by an optical fibre with a core diameter of 10 μm and 10 degrees with respect to the vertical axis. The grating coupler is designed by using CAMFR,[12] a two-dimensional fully vectorial solver based on eigenmode expansion method.

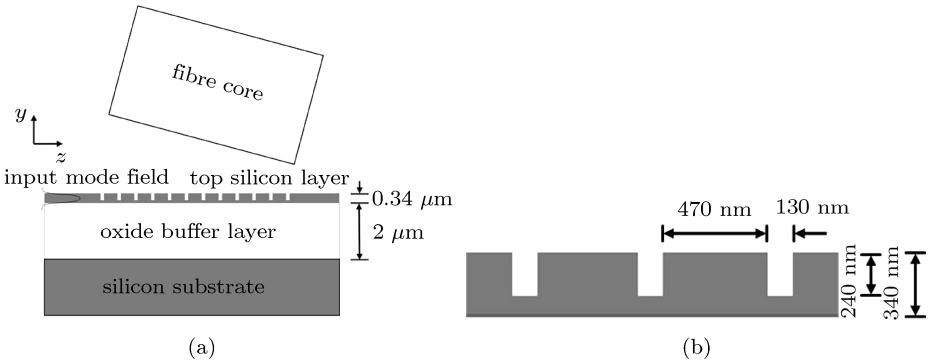


Fig. 1. (a) Simulation model of grating coupler; (b) schematic diagram and the optimized parameters of the grating structure in Fig. 1(a).

The optical field propagation from the waveguide into the grating will be exponentially decaying along the propagation direction as $P = P_0 \exp(-2\alpha z)$, where α describes the strength of grating relevant to the etching depth and filling factor.[2] One part of light will be diffracted upwards as the output light and the other part is diffracted downwards into the substrate as the main leakage. For a uniform grating (filling factor=0.5), deep even fully etching will increase the asymmetry and strength of the grating, therefore enhances the diffraction efficiency of the grating and decreases the light leaking into the substrate, however at the same time the higher back reflection into waveguide, larger mode mismatch with the Gaussian profile output beam and lower effective index in the grating region will essentially deduce the coupling efficiency and cause centre wavelength blue shift. The performance of the deep etched grating can be improved by enlarging the filling factor, which will firstly meliorate the transmission characteristics, and then increase the effective index to adjust the centre wavelength to 1550 nm.

In order to fabricate the rib waveguide with the grating in one lithography step on the 340-nm top silicon wafer, the etching depth of the grating is proposed to be 240 nm, and the thickness of slab layer is 100 nm. According to the Bragg condition, the grating period for coupling out-of-plane should basically fits $\Lambda = \lambda/n_{\text{eff}}$, where λ is the vacuum wavelength and n_{eff} is the effective index of incident waveguide mode. Considering the coupling angle tilted 10 degrees and the modes solving, the grating period 600 nm and fill-

ing factor of around 0.80, a centre wavelength around 1550 nm is given.

Such high filling factor (ff $\sim$ 0.80) implies a very small slot in one grating period, which is almost 130-nm wide and 240-nm deep as schematically shown in Fig. 1(b). The light propagating into the grating is leaked out at each slot interface at the front end of the grating and confined in the slots because of the small scale trench. The distribution of the electric field intensity at the centre of the grating along the propagation direction z is given in Fig. 2, with input optical field intensity normalized. There exist field intensity peaks in the centre part of the slots and relatively low intensity at the interface. It indicates that the optical field is partly confined in the grating slot. The confined light would reflect upwards at the down interface of the slot, because of the high-index-contrast silicon/air. The electric field plot of the optimized grating coupler structure is shown in Fig. 3,

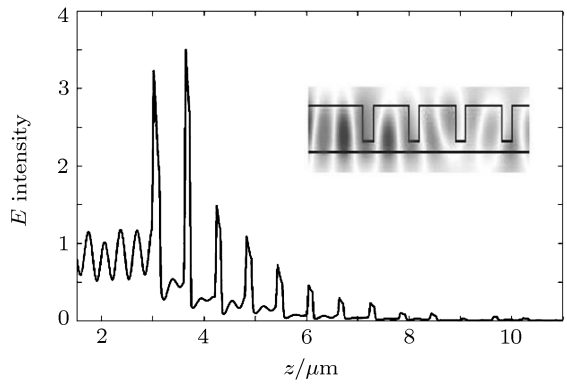


Fig. 2. The distribution of the electric field intensity at the centre of the grating along the propagation direction z with input optical field intensity normalized.

it can be clearly seen that the optical field confined in the grating slots is scattered out efficiently, and the light leaked to the substrate is relatively low. High efficiency grating upwards coupling will be induced because the very small slots act as the high efficient scattering centres.

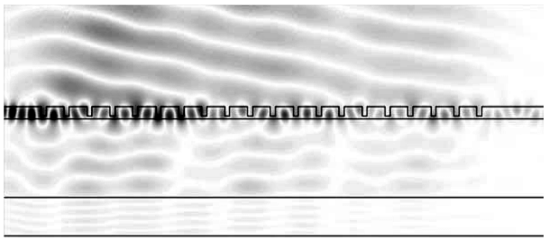


Fig. 3. The electric fields plot of the optimized grating coupler structure.

Since the etching depth is fixed, the filling factor and the period could be properly designed. Figure 4(a) shows the coupling efficiency varying with the filling factor (0.75–0.85) at grating period Λ = 600 nm. It can be found that at period of 600 nm the centre wavelength increases with filling factor enlarging and the coupling efficiency changes dramatically with the filling factor, which is due to the effective index and the optical confinement ability of the slots variety. Additional simulation for other grating periods with different filling factors also reveals such feature. After further optimization, as high as 60% coupling efficiency at around 1550 nm and 3-dB bandwidth of 61 nm are obtained by simulation as shown in Fig. 4(b) with a grating period of 600 nm, etching depth of 240 nm, filling factor of 0.78, though the back reflection ratio is as high as 9% at the whole 3-dB bandwidth.

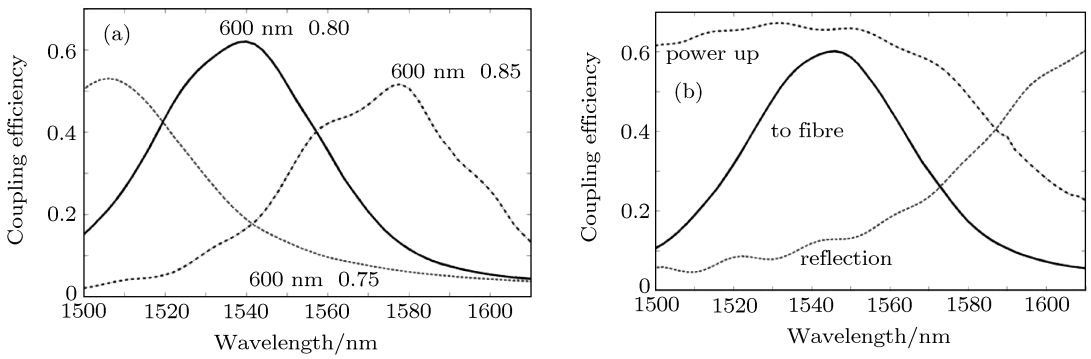


Fig. 4. (a) The simulated coupling efficiency as a function of wavelength varying with filling factors at a grating period of 600 nm. (b) Simulation result of optimized SOI grating coupler at filling factor = 0.78. The total upwards radiated power, coupling efficiency to the fibre and reflection of the grating are plotted.

3. Fabrication and measurement

The grating coupler and the rib waveguide structure were defined using Raith150 electron beam lithography (EBL) and followed inductive coupled plasma (ICP) dry etching, just in one standard silicon processing step. The grating and rib waveguide are both 12-μm wide, and etched 246 nm with a 94-nm slab layer left, measured by the atomic force microscopy (AFM). The top view of scanning electron microscopy (SEM) picture of the grating is shown in Fig. 5, the period and the filling factor of the grating fit the designed pattern very well.

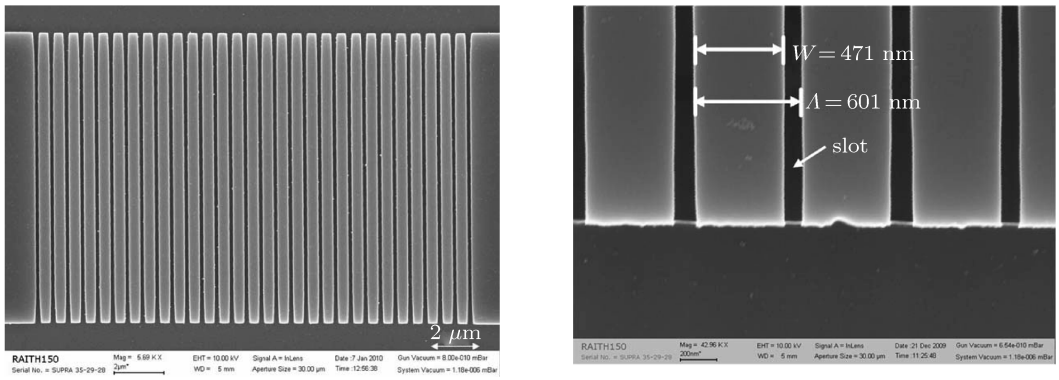


Fig. 5. SEM view of couplers fabricated using EBL. The depth of the grating slot is 245 nm, the period is 601 nm, and the filling factor is about 0.78.

The coupling efficiency is obtained from grating-to-grating transmission measurement by assuming the gratings with the same in- and out-coupling efficiency. Two cleaved single mode fibres, respectively connecting to the lasers and optical spectrum analyser, are symmetrically positioned above the input and output gratings at an angle of 10° with respect to the vertical axis. Here, the input and output gratings are connected by a wide waveguide which shares the same width with the grating area and its propagation loss can be neglected. The coupling efficiency as a function of wavelength is demonstrated in Fig. 6. It can be found that the peak coupling loss is about –3.75 dB (corresponding to coupling efficiency 42.1%) at centre wavelength 1546 nm with 3-dB bandwidth of 37.6 nm. The distinct FP fringe contrast in the spectrum is due to the high back reflection and multimode interference between the two gratings at both ends of the wide waveguide. The wavelength separation between the adjacent transmission peaks are consisting with the waveguide length and the effective index guided modes. The discrepancy between the simulation and experimental results may be due to the ignored waveguide loss, the grating sidewall roughness induced loss and the reflection at the facets between the grating and the fibre.

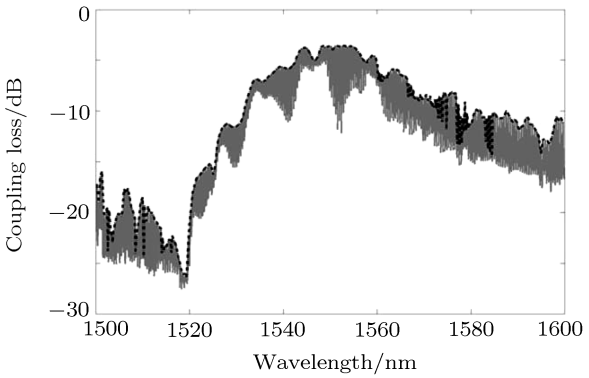


Fig. 6. Experimental results of the coupling loss as a function of wavelength for the grating coupler shown in Fig. 5.

4. Conclusion

A novel high efficiency grating coupler with large filling factor used for optoelectronic integration is proposed. The narrow and deep slots in the grating area result in high optical confinement and act as high efficient diffraction centres, therefore high efficiency coupling is achieved. As high as 60% coupling efficiency at around telecom wavelength of 1.55 μm and 3-dB bandwidth of 61 nm simulation results are predicted. 42.1% peak coupling efficiency at wavelength 1546 nm and 3-dB bandwidth of 37.6 nm has been obtained experimentally.

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