Highly efficient nonuniform grating coupler for silicon-on-insulator nanophotonic circuits

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We present design, fabrication, and characterization of a silicon-on-insulator grating coupler of high efficiency for coupling between a silicon nanophotonic waveguide and a single mode fiber. By utilizing the lag effect of the dry etching process, a grating coupler consisting of nonuniform grooves with different widths and depths is designed and fabricated to maximize the overlapping between the upward wave and the fiber mode. The measured waveguide-to-fiber coupling efficiency of 64% (−1.9 dB) for the transverse electric polarization is achieved by the present nonuniform grating coupler directly defined on a regular silicon-on-insulator wafer. © 2010 Optical Society of America

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Silicon-on-insulator (SOI) platform is promising for the mass production of large scale and dense integration of photonic circuits. The large refractive-index contrast between the silicon core and the underlying oxide buffer enables small waveguides, sharp bends, and thus very compact functional components. However, together with the benefits, there are still some issues to be solved. One of them is the coupling problem inherent from the huge mode mismatch between an on-chip silicon nanophotonic waveguide and an external single mode fiber.

Grating couplers, performing as an attractive vertical coupling scheme for the silicon waveguide, have been widely demonstrated. The advantages like the capability of on-wafer testing, potential implementation of low-cost packaging [1], and the versatility as a duplexer [2], a polarization beam splitter [3,4], or a power splitter [5] make the grating coupler an important component for the photonic integrated circuits. However, the measured coupling efficiency, typically, with a maximum of 20%–35% for a standard SOI grating coupler [1,6], is still not competitive for practical applications. Advanced structures using a bottom reflector [6–8] or a silicon overlay [9] were proposed to improve the coupling efficiency by reducing the downward substrate leakage, but at the expense of an increased fabrication complexity. An alternative method is to improve the mode matching between the upward field and the fiber mode by using a nonuniform grating coupler. A duty cycle apodized SOI grating coupler shows a maximum coupling efficiency of 61% in theory, which can be improved to 92% if adopting a special wafer with a bottom Bragg reflector [8]; another nonuniform design based on size-varied fully etched rectangle holes was also proposed [10]. But until now, no experimental result has been reported.

In this work, we theoretically and experimentally demonstrate a highly efficient nonuniform grating coupler based on a regular SOI wafer by utilizing the lag effect [11,12] in the inductively coupled plasma reactive ion etching (ICP-RIE) process. The lag effect describes the dependence of the etch rate on the feature size in a dry etching process. As a result, it induces the etching nonuniformity, i.e., the smaller etch width leads to the shallower etch depth. Although the etching nonuniformity is usually detrimental for most applications, it can offer more freedom to realize a nonuniform grating coupler by using etching grooves with reasonable etch widths.

In order to investigate the lag effect, we use a Raith 150 electron beam lithography (EBL) system to define a series of lines with step-increased widths in the ZEP520 resist. The pattern was transferred into the SOI structure by the ICP-RIE etching. Then the fabricated sample was cleaved and investigated by using a scanning electron microscope (SEM). The width and the depth of each etch groove were measured to get the etching nonuniformity. All the data together with a SEM photograph of the cross section of the testing sample are shown in Fig. 1, where we can see the obvious phenomenon of the lag effect especially when the etch width is smaller than 300 nm. The experimental data are fit by a third order polynomial expression, which determines the relation between the etch width and the etch depth in the following design.

Figure 2 shows the schematic structure of our nonuniform grating coupler defined on a regular SOI wafer (SIMOX Technology) with a 250 nm thick crystalline silicon ($n=3.45$) layer over a 3 μm thick buried oxide ($n=1.45$) layer. For the wavelength of 1520 nm in our design, the oxide thickness is almost optimal for a minimal downward leakage. Like in a standard grating coupler setup, a single mode fiber is positioned with a tilt angle θ to the normal direction above the grating to avoid backreflection [6]. The angle is set to 15° due to the limitation of our characterization platform. In order to eliminate the fiber's facet reflection, an index-matching gel ($n=1.46$) is utilized to fill the space between the fiber and the grating. Due to the viscosity of our gel, we believe

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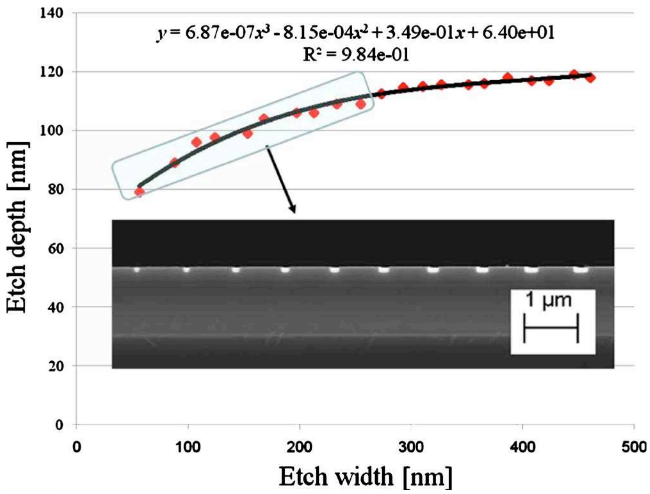

Fig. 1. (Color online) Relation between the etch width and etch depth (lag effect) obtained through SEM measurement. Inset: SEM micrograph of the cross section of a testing sample.

that the etch grooves are still mainly filled by air.

For a grating coupler, in order to achieve a maximum overlapping between the upward wave and the fiber mode (approximately a Gaussian profile with a beam diameter of 10.4 μm), the leakage factor that describes the leakage-caused attenuation in the grating waveguide should present a specific distribution along the propagation direction as demonstrated in [8]. The leakage factor distribution as shown in Fig. 2 requires position-dependent perturbation of the waveguide, which leads to a nonuniform grating design. By utilizing the lag effect, we can fabricate controllable grooves with different etch widths and etch depths. The difference in two dimensions can enhance the variation range of the leakage factor, and thus we can achieve the leakage distribution ranging from 0.01 to 0.33 by using etch grooves with reasonable feature sizes, which are possible to be defined by our EBL system. Furthermore, increasing the groove width and the groove depth from the left edge of the grating (see Fig. 2), designed to meet the leakage distribution, will lead to a smooth transition from the blank waveguide to the grating region and hence very small reflection.

It is not trivial to design a nonuniform grating coupler since every groove should be individually treated and the corresponding grating pitch should be carefully tuned to achieve an expected radiated angle for the upward wave. For simplicity, we treat the nonuniform grating structure as a sequential combination of different grating cells as shown in Fig. 2. Hence, we can analyze the individual grating cell as in a uniform design. Figure 3(a) depicts the grating cell for the band analysis, where periodic boundary conditions are put at the vertical sides, and perfectly matched layers together with perfect electric conductor boundaries are applied to the horizontal sides. The groove width, groove depth, and cell width (i.e., the period of the corresponding uniform grating) are labeled as w, d, and a, respectively. Figure 3(b) shows the band diagram of a grating cell for the transverse electric (TE) polarization (with electric field parallel to the grating lines) along the z direction. Essentially, the grating coupler is an application of the grating waveguide's leaky mode above the light line. The adopted mode in a practical design is usually located on the third band, corresponding to the -1 diffraction order of a diffraction grating. In order to meet the phase matching condition, the mode wave vector along the propagation direction should be the same as the leaky wave in the gel. Hence, for the light radiating with a tilt angle θ in the covering gel, the normalized wave vector of the leaky mode can be written as

$$k = n_{\mathrm{gel}} \sin(\theta) a/\lambda, \tag{1}$$

where λ is the light's wavelength. For a grating cell with known etch width (as well as etch depth according to Fig. 1) and output angle, we can tune the cell

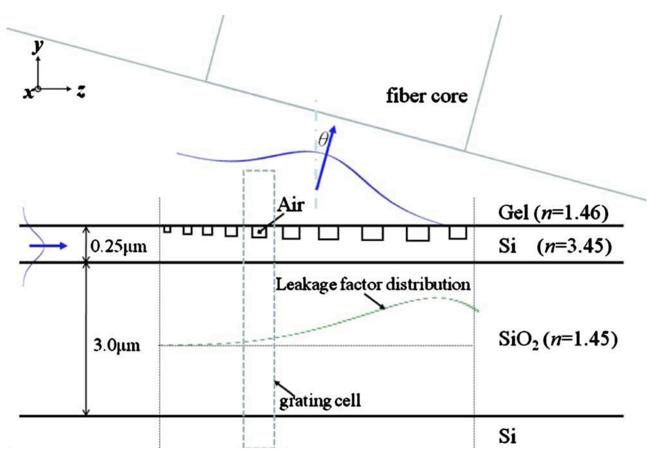

Fig. 2. (Color online) Schematic structure of the present nonuniform SOI grating coupler. Blue curves (solid) represent the input and output power distributions when light is propagating upward from the waveguide to the fiber; green curve (dashed) represents the leakage factor distribution in the grating region in order to achieve a Gaussian profile output. The dashed box shows a grating cell.

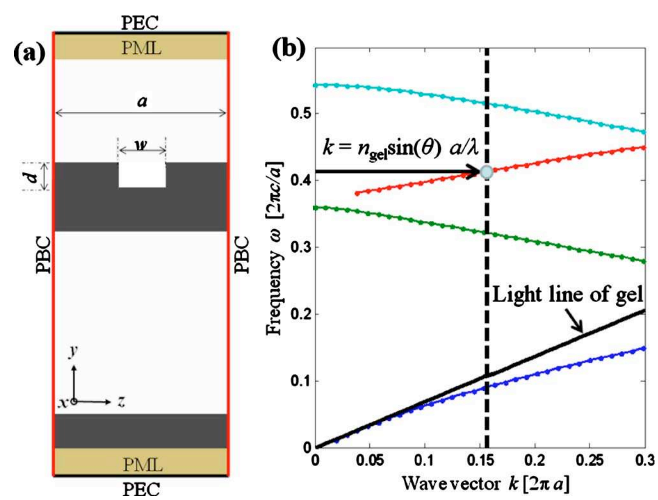

Fig. 3. (Color online) (a) Depiction of a grating cell for band analysis: PBC, periodic boundary condition; PEC, perfect electric conductor; PML, perfectly matched layer. (b) Band diagram of a grating cell ($w = 160$ nm, $d = 102$ nm, $a = 631$ nm).

width to match the leaky mode at the targeted wavelength. Once the cell structure is fixed, the leakage factor of the grating cell can be extracted by numerically monitoring the propagation loss in the corresponding uniform grating coupler. Note that only the leakage loss is included during the propagation simulation.

Figure 4 summarizes the mapping from the etch width to the grating cell width and the leakage factor. Based on the mapping, a nonuniform grating coupler can be sequentially assembled one grating cell by one grating cell according to the leakage factor distribution. The groove width in our design is between 60 and 340 nm. Figure 5 shows the calculated waveguide-to-fiber coupling spectrum for the designed nonuniform grating coupler, as well as the power radiated upward and downward. We can see a maximum coupling efficiency of 74% (due to the good mode matching) near 1520 nm. The reflection at the waveguide to the grating interface is almost eliminated and the coupling loss is mainly due to the downward leakage, which implies that the efficiency can be improved further if the directionality of the grating coupler can be improved as shown in [6–9].

The inset in Fig. 5 shows the SEM top view of a fabricated nonuniform grating coupler. The grating was etched under the same condition as the testing sample for etching nonuniformity. The coupling efficiency of a grating coupler can be obtained by characterizing the transmission spectrum of a pair of grating couplers, provided that the propagation loss due to the bridge waveguide between the two gratings is small enough to be ignored. The measured coupling spectrum for the TE polarization was also shown in Fig. 5 for comparison. One can see that a maximum coupling efficiency of 64% (about −1.9 dB) is achieved at 1524 nm and the 1 dB bandwidth is about 43 nm. The coupling efficiency is almost two times larger than that for a standard uniform grating coupler and the wideband makes it possible for application both at 1490 and 1550 nm. The discrepancy between the simulation and the experiment is mainly due to the accumulated fabrication errors and the possible deviation from the simulation parameters like the refractive index.

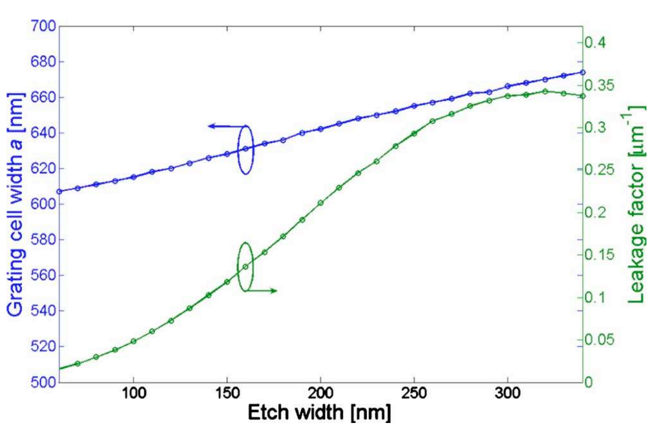

Fig. 4. (Color online) Calculated mapping from the etch width to the cell width and the leakage factor to achieve 15° tilt of output beam at 1520 nm.

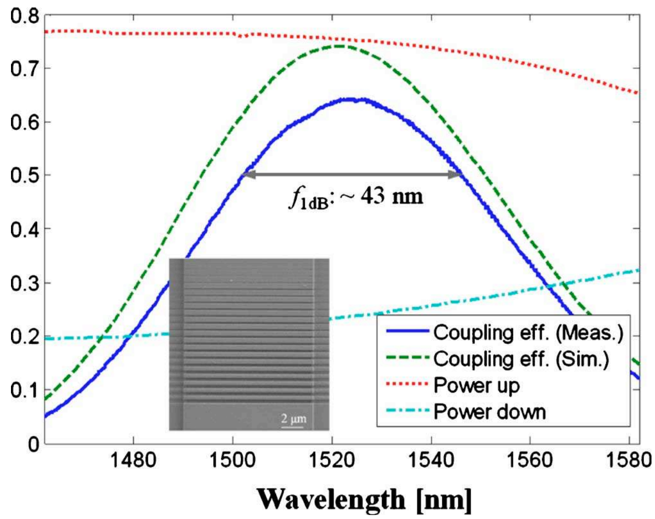

Fig. 5. (Color online) Theoretical and experimental results of the waveguide-to-fiber coupling spectra for TE polarization, as well as the calculated power radiated upward and downward. Maximum coupling efficiency of 64% (−1.9 dB) and 1 dB bandwidth of 43 nm were obtained experimentally. Inset: SEM top view of a fabricated nonuniform grating coupler.

In conclusion, utilizing the lag effect during the ICP-RIE etching, we have successfully fabricated a nonuniform SOI grating coupler with a maximum coupling efficiency of 64% (−1.9 dB), as well as a 1 dB bandwidth of 43 nm. To the best of our knowledge, it is the best waveguide-to-fiber coupling efficiency obtained experimentally for a grating coupler directly defined on a regular SOI wafer.

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