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High-efficiency, large-bandwidth silicon-on-insulator grating coupler based on a fully-etched photonic crystal structure

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A grating coupler for interfacing between single-mode fibers and photonic circuits on silicon-on-insulator is demonstrated. It consists of columns of fully etched photonic crystal holes, which are made in the same lithography and etching processes used for making the silicon-on-insulator wire waveguide. The holes have a diameter of around 143 nm, and are defined with electron-beam lithography. A peak coupling efficiency of 42% at 1550 nm and 1 dB bandwidth of 37 nm, as well as a low back reflection, are achieved. The performance of the proposed fully etched grating coupler is comparable to that based on the conventional shallowly etched grating, which needs additional fabrication steps.
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In recent years, silicon-on-insulator (SOI) has been considered as a promising platform for photonic circuits, largely driven by its complementary metal-oxide semiconductor (CMOS) compatible fabrication technology.[1,2] Additionally, the SOI structure can offer high-density integration of photonic devices, made possible by the high refractive-index contrast between Si and the surrounding material (SiO_2 or air). On the other hand, this high index contrast also makes it more difficult to couple light between the photonic circuits on SOI and the outside world (e.g., optical fibers). One approach to solve this problem is to combine a Si inverse taper and a medium index contrast waveguide, e.g., made of polymer or silicon nitride.[2–4] A coupling loss of ~0.8 dB has been demonstrated. However, in this approach, additional fabrication processes were involved, and normally a fiber with high numerical aperture or a lensed fiber had to be employed to obtain the best mode matching. Another solution is the fiber grating coupling. By making diffractive grating slots on top of an SOI waveguide, light can be coupled to a standard single-mode fiber mounted nearly vertically above the chip.[5–12] This approach also avoids cleaving of the sample, and enables wafer-scale testing. A coupling efficiency of 31% and a 1 dB bandwidth of 40 nm were reported originally.[5] However, in this design, an additional lithography and etching step is necessary for making the shallowly etched grating. Methods for improving the coupling efficiency of such a vertical grating coupler have also been demonstrated, but at the expense of further complexity of the fabrication process.[7–9]

It would be of great interest if the grating can be made in the same processing step as the SOI photonic circuits, i.e., if the grating has the same etching depth as the SOI wire waveguide.[10–12] However, the fully etched air slots make the index contrast of the grating very strong. As a result, a large amount of back reflection is present.[10] This back reflection is an adverse effect. It may result in obvious Fabry–Pérot (FP) fringes in a transmission spectrum, and may also affect the performance of an on-chip active device, e.g., a laser.[13] The coupling efficiency and the bandwidth are limited as well in this case. Very recently, some trials have been put to optimize such a fully etched grating coupler. A resonant coupling scheme has been proposed to reduce the back reflection, but only in a narrow wavelength band.[11] Thus, the coupling bandwidth of the grating decreases significantly. A grating coupler composed of a square-lattice nanohole array has also been reported with a peak coupling efficiency of 34% and a 3 dB bandwidth of 40 nm.[12] However, the back reflection is still about 9% at the peak coupling wavelength. In this letter, we introduce an SOI grating coupler utilizing fully etched photonic crystal holes. The proposed fully etched photonic crystal holes are engineered in such a way that a weak contrast grating is still maintained. A peak coupling efficiency of 42% and a 1 dB bandwidth of 37 nm (3 dB bandwidth: 68 nm) is obtained experimentally, together with a low back reflection. The performance of the present fully etched grating coupler is comparable to what has been reported with the shallowly etched grating coupler.[5]

First, a simplified two dimensional (2D) model as demonstrated in the inset of Fig. 1(a) is analyzed numerically.[14] The grating here is formed by replacing part of the top Si layer ($n=3.476$) in an SOI structure with an artificial material of a lower refractive index ($n=2.55$). The thickness of the top Si layer is 250 nm, and the buried oxide (BOX) layer ($n=1.445$) is considered to be infinitely thick. The periodicity and the duty cycle of the grating are 681 nm and 50%, respectively, and 25 grating slots are employed. Figure 1(a) shows the calculated coupling curves when transverse electric (TE) light is incident from the SOI waveguide. The peak coupling efficiency to a fiber mounted at 10° to the vertical direction reaches 46% at 1550 nm, and the 1 dB bandwidth is 40 nm. The back reflection is below 2% at the peak wavelength. Practically, the artificial low index material can be made with, e.g., a 2D photonic crystal membrane. Here, we choose a triangular lattice of air holes in Si, as shown in the inset of Fig. 2(b). It is well known that if the lattice constant a is sufficiently small, a photonic crystal can be treated as a homogeneous material, and its effective refractive index can be engineered by varying the filling factor. Figure 2(b) shows the calculated TE band diagram and the equal frequency contour of such a 2D photonic crystal when $d=0.66a$ (d: the

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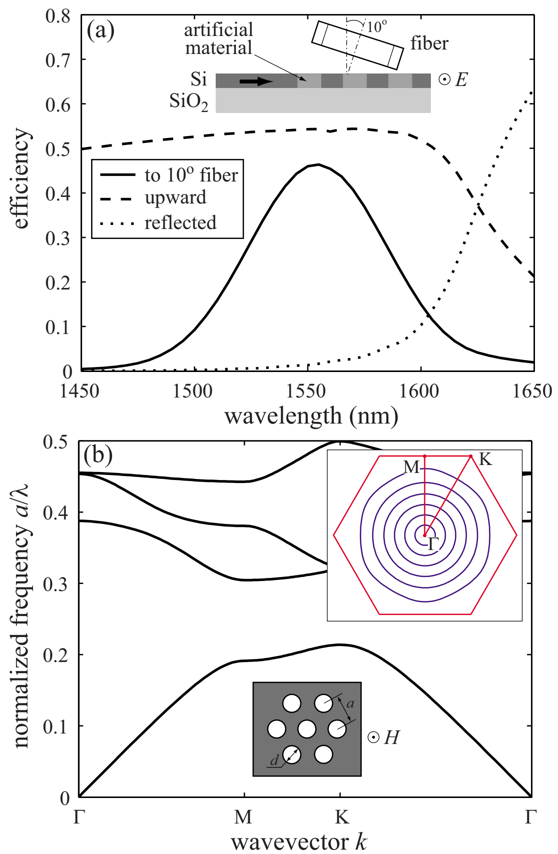

FIG. 1. (Color online) (a) Coupling efficiency from a simplified model shown in the inset. Solid line denotes the power coupled to a fiber mounted at 10° to the vertical direction; dashed line denotes the power diffracted upwards; dotted line denotes the power reflected back in the SOI waveguide. (b) 2D TE-mode band structure of a photonic crystal shown in the bottom inset, which consists of a triangular lattice of air holes in Si. Top-right inset shows the equal frequency contour of the first TE band, where the innermost and outermost contours correspond to the normalized frequencies of 0.03 and 0.18, respectively.

diameter of the air hole). One can find that the photonic crystal exhibits an effective refractive index of ~2.55 for normalized frequencies below 0.18. It is also isotropic in all the in-plane directions.

The designed grating coupler was fabricated with standard Si processing technology, including 100 keV electron-beam lithography (JEOL JBX-9300FS) and fluorine-based inductively coupled plasma reactive-ion-etching. The SOI structure used here has a top Si layer thickness of 250 nm. Some pictures of the fabricated samples are shown in Fig. 2. The photonic crystal has a lattice constant a of 227 nm (i.e., the normalized frequency for 1550 nm light is $a/\lambda=0.146$) and air-hole diameter d of 143 nm (i.e., $d=0.63a$). By checking the cleaved cross-section, we confirmed that the Si material was fully etched in the holes. The grating coupler is formed by omitting every second column of holes in the photonic crystal as shown in Fig. 2(b). This gives an effective periodicity of $3\times 227=681$ nm and an effective duty cycle of 50% for the grating. The grating section has a width of 10 μm and a length of about 15 μm consisting of 25 columns of air holes. This dimension matches well with the mode size of a standard single-mode fiber. Two such grating couplers were connected by adiabatic tapers and a short section of SOI wire waveguide with 450 nm width for transmission measurement.

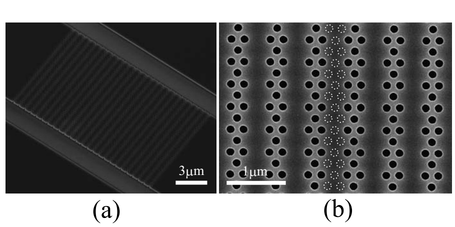

FIG. 2. (a) Bird's-eye view of a fabricated photonic crystal grating coupler. (b) Close look of the photonic crystal holes. One column of the omitted holes is indicated by the dotted circles for reference.

The fabricated grating coupler was further modeled rigorously by a three-dimensional (3D) finite-difference time-domain (FDTD) method. The BOX layer is again assumed to be infinitely thick. The simulated coupling curves are presented in Fig. 3(a), which matches well with those from the simplified structure discussed in Fig. 1(a). Practically, the thickness of the BOX layer can pose a significant influence on the coupling efficiency, due to the interference effect from the downward diffracted light beam.[10,11] As shown in Fig. 3(b), the peak coupling efficiency can vary from 59% to 24% with different BOX layer thicknesses. In this letter, two sets of samples, with 1 or 3 μm thick BOX layers, were prepared. They are close to the structures where the maximal or minimal coupling is obtained. The measured coupling spectra to a fiber mounted at 10° to the vertical direction are shown in Fig. 3(c). The coupling efficiency of a single grating coupler is extracted from the grating-to-grating transmission measurement, and by assuming the same coefficient for the in- and out-coupling. One can find that the peak coupling wavelength is located around 1550 nm, which is in good agreement with the simulation result. The peak coupling coefficients are 42% and 18% for the two structures, respectively. Both are slightly lower than the simulated coefficients shown in Fig. 3(b), probably due to the nonuniformity of hole diameters in the photonic crystal. It can be improved by applying a proximity correction to the electron-beam exposure. The 1 dB coupling bandwidth for the structure of 1 μm thick box layer is 37 nm (3 dB bandwidth: 68 nm), which is about 70% wider than what has been reported for such a fully etched grating coupler.[12] The back reflection in the SOI waveguide can be extracted from the FP fringe contrast of the transmission spectrum, which is only about 0.3 dB at the peak coupling wavelength, corresponding to a back reflection of 1.7%. It is also significantly smaller than the previous demonstrations.[10–12] On the other hand, this level of back reflection is still high as compared to the shallowly etched grating, and it also becomes more obvious in the longer wavelength side. This is due to the relatively wide second-order Bragg reflection peak as shown in Fig. 3(a), and it can be shifted further away from the peak coupling wavelength by slightly increasing the fiber tilt angle. Figure 3(d) presents the measured coupling spectrum to a fiber mounted at 15° to the vertical direction. In order to keep the peak coupling wavelength at 1550 nm, the lattice constant a of the photonic crystal was made to be 234 nm (the hole diameter d is the same, i.e., 143 nm). The coupling efficiency and the bandwidth are very similar to those measured for 10° fiber. The FP fringe contrast decreases to about 0.15 dB, corresponding to a back reflection of 0.9%, in the whole 3 dB bandwidth. It is worth to note that this amount of contrast is close to the power fluctuation of the measurement system. In principle, the back reflection discussed above is over-estimated.

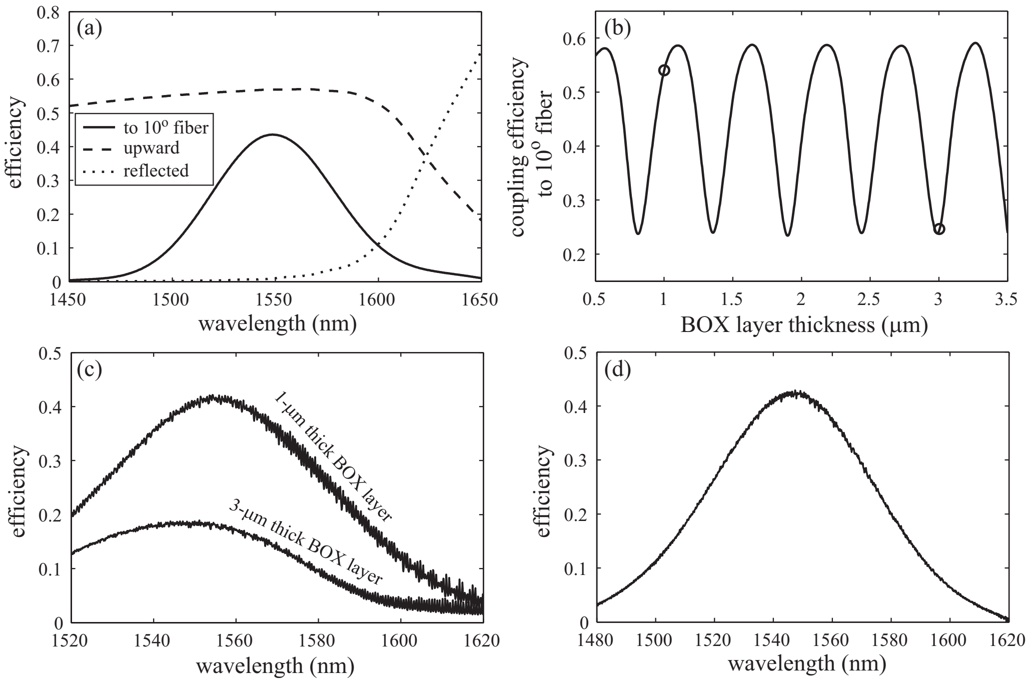

FIG. 3. (a) 3D FDTD simulation of a fabricated structure with $a=227$ nm and $d=149$ nm. (b) Influence of the BOX layer thickness on the coupling efficiency. The open circles indicate the structures used in the experiments. (c) Measured coupling spectra for structures of 1 and 3 μm thick BOX layers. (d) Measured coupling spectrum to a fiber mounted at 15° to the vertical direction (1 μm thick BOX layer, $a=234$ nm, $d=143$ nm).

In conclusion, we have presented a fully etched photonic crystal based grating coupler, which can efficiently couple light between a single-mode fiber and an SOI wire waveguide. The proposed grating can be fabricated in the same processing steps as the SOI circuits. Thus, it does not add any extra fabrication complexity and cost. A peak coupling efficiency of 42% and a 1 dB bandwidth of 37 nm has been achieved. The back reflection is as low as 0.9% in the SOI waveguide. The performance is close to that of a shallowly etched grating coupler which requires an extra lithography and etching step. The proposed photonic crystal grating coupler provides a fast and cost-effective approach for testing/prototyping SOI circuits at wafer level.

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