Waveguiding in planar photonic crystals

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Photonic crystal planar circuits designed and fabricated in silicon on silicon dioxide are demonstrated. Our structures are based on two-dimensional confinement by photonic crystals in the plane of propagation, and total internal reflection to achieve confinement in the third dimension. These circuits are shown to guide light at 1550 nm around sharp corners where the radius of curvature is similar to the wavelength of light. © *2000 American Institute of Physics.* [S0003-6951(00)04038-9]

The planar photonic crystal (PC) concept is a recent innovation[1] that can permit the miniaturization of integrated optical circuits to a scale comparable to the wavelength of light. In principle, this technology makes it possible to fabricate planar optical circuits with a packing density four to five orders of magnitude higher than the present state of the art, thus realizing the original objective of integrated optics.

Waveguiding in a planar circuit requires confinement of the light in three dimensions. This can be achieved by making a three-dimensional (3D) PC.[2–4] However, fabrication of good quality 3D PC structures is a difficult process, and, in terms of fabrication, a more appealing approach is based on the use of the lower-dimensional PCs to achieve confinement of light in all three dimensions. That idea is employed in the case of the thin dielectric slab perforated with two-dimensional (2D) PC.[5–13] In the vertical direction, light is confined to the slab due to total internal reflection (TIR), and in the lateral direction, light is controlled by the means of distributed Bragg reflection due to the presence of the 2D PC. The PC structure that we consider here consists of a periodic arrangement of holes etched into a planar Si slab suspended so that it is surrounded by air on both sides. We have studied the propagation of light in this structure using methods based on plane-wave expansion and the 3D finite-difference time-domain algorithm[9] to analyze Maxwell's equations. Kuchinsky *et al.*[12] have shown that a Si guide imbedded in a PC slab having a thickness equal to 0.5 $\cdot$ pitch of the PC lattice supports two modes: one diffractive, from the periodic PC lattice, and one refractive from the contrast in the index of refraction between the core and the cladding. Johnson *et al.*[13] have shown in the case of a Si slab perforated with a triangular lattice of holes that there is a thickness limit for the PC waveguide above which the band-gap width significantly decreases. In agreement with that work we find that conditions for waveguiding are more restrictive in a waveguide with a finite third dimension than in a 2D PC of infinite extent in the third dimension.[14,15]

The demonstration of waveguiding by photonic band gap (PBG) confinement is a difficult challenge, but a necessary achievement in order to realize the goal of planar optical circuits with higher levels of integration. A recent letter by Tokushima *et al.*[16] reports experiments on light propagation in a structure that lies well outside the parameter space where PC guiding can occur. Baba, Fukaya, and Yonekura[17] reported experiments in structures of the appropriate design but with significant scattering losses. In this letter, we demonstrate waveguiding of a well-defined mode at 1550 nm over hundreds of wavelengths of distance with waveguide losses below the detection threshold of our apparatus.

The dispersion relationship, that is, the photonic band structure, is the key element to understand the nature of equilibrium modes that can support low-loss waveguiding. In Ref. 9 we have presented the band-structure calculations for a Si slab perforated with lattices of both square and triangular symmetry. We have found that in both structures the band gap is opened for TE-like modes, around the normalized frequency $a/\lambda_0=\omega a/2\pi c\approx 0.35$, (a, the periodicity of the lattice; λ_0, the wavelength in air). When we introduce a line defect into the PC by removing an entire line of holes from the 2D crystal lattice, we form the simplest PC waveguide. Photons having an energy within the gap can now propagate only along this line defect. Propagation in the lateral direction is suppressed by the fact that the defect mode is within the frequency band gap of the PC, and free-space propagation in the vertical direction is prevented by means of TIR. 3D analysis shows that the straight line defect, in the lattice of both triangular and square symmetry, can support guided modes around normalized frequency $a/\lambda_0\approx 0.35$.[9,12]

Waveguides were fabricated in a silicon-on-insulator (SOI) wafer. Patterns are defined in polymethylmethacrylate (PMMA), the only lithography mask used, using electron-beam lithography, and then transferred into Si using chemi-

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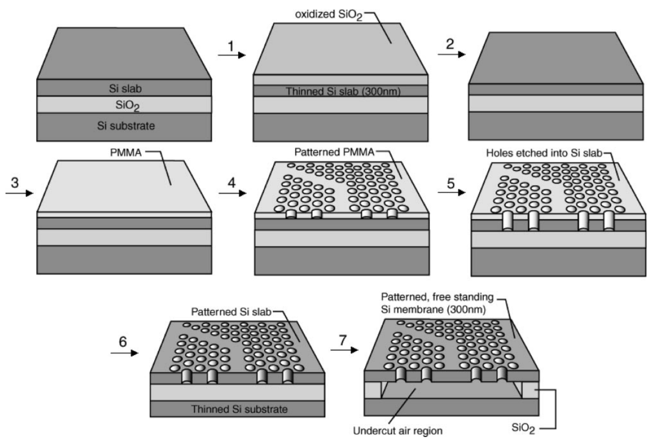

FIG. 1. Fabrication procedure: (1) oxidation and (2) HF dip in order to define the thickness of the Si slab; (3) deposition of PMMA and (4) electron-beam lithography to define patterns in PMMA; (5) CAIBE to transfer patterns into Si; (6) removal of PMMA and thinning of the substrate; and (7) HF dip to remove the SiO_2 layer underneath the waveguide.

cally assisted ion-beam etching (CAIBE). The structure of the wafer and the whole fabrication procedure is shown in Fig. 1. We were able to define 500–1000-μm-long waveguides with different numbers of 60° and 90° bends. The high selectivity and anisotropy of our fabrication process permits us to define high-quality PC structures within SOI wafers (Fig. 2). Further details on the fabrication process can be found elsewhere.[9]

In order to be able to couple the light in and out of the waveguide it is necessary to have access to both the input and the output facet of the guide. To do so, the sample was cleaved from both sides. Prior to cleaving, the sample was mechanically polished from the backside using Al_2O_3 polishing powder, and thinned from 500 to below 100 μm. This thinning enabled us to obtain smooth cleaved edges at both sides of the waveguide (Fig. 2), which helps to reduce the insertion losses during optical coupling from a glass fiber to the PC waveguide. In order to improve the vertical confinement of the light within the slab the sacrificial SiO_2 layer underneath the waveguides was removed by dissolution through the ion-etched holes using HF acid. This process leaves the Si waveguide and PC mirror membrane suspended in air (Fig. 2). The design parameters of the fabricated PC waveguide are: interhole spacing (lattice constant) $a \approx 530$ nm, hole radius $r \approx 208$ nm, and Si slab thickness $d \approx 300$ nm, in the case of the triangular lattice, and $a \approx 500$ nm, $r \approx 200$ nm, and $d \approx 280$ nm, in the case of the square lattice.

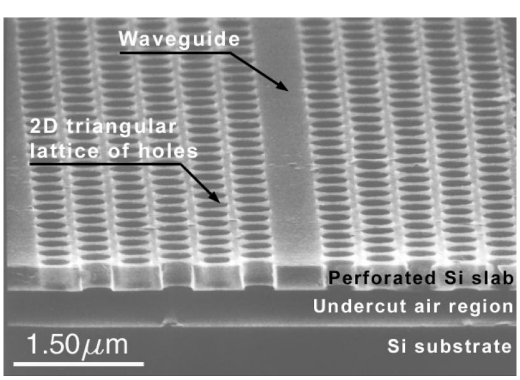

FIG. 2. (SEM) scanning electron microscopy micrograph of the fabricated waveguide of triangular symmetry.

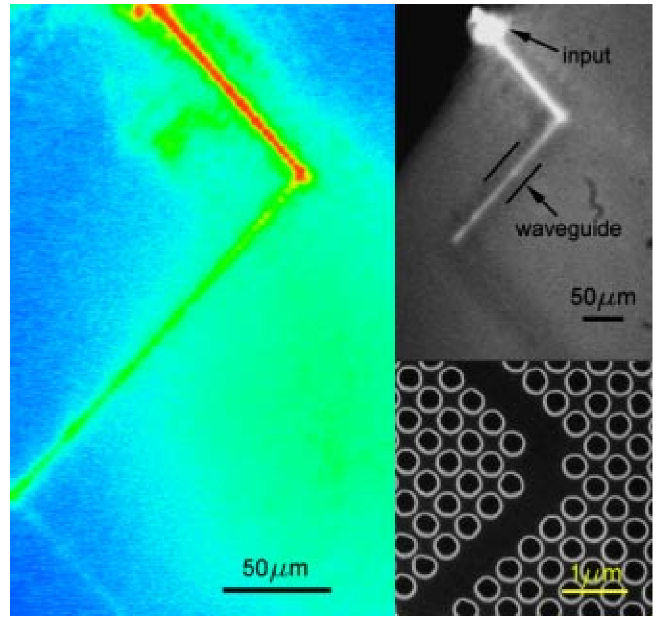

FIG. 3. (Color) Light guided in the waveguide around two 90° bends (top view). It can be seen that the light is confined to the waveguide (upper-right inset). Inset in the lower-right corner shows the SEM micrograph of the corner design in the square lattice. Visualization of light propagation is made possible by coupling intentionally to leaky modes which radiate from the top surface of the guide. Enhanced losses for these modes can be seen at the sharp bends.

An objective of this work was the characterization of guided modes transmitted through planar PC waveguides, and launched into the waveguides from an exterior source. A tunable semiconductor diode laser of rather modest power (4 mW, 1440–1590 nm) was used to characterize optical transmission. Butt-coupling of a single-mode fiber was used to introduce the laser output into the PC. Since the fiber core diameter is around 10 μm, and slab thickness around 0.3 μm, coupling from the fiber to the waveguide was not efficient due to a large mode mismatch, and this problem remains to be solved. However, sufficient optical power ($\sim 10\ \mu$W) is coupled into the guide to carry out the required characterization of waveguiding within these structures. Waveguiding performance was observed by visualization of the guiding structure with two infrared television cameras. The first camera (No. 1), positioned in the plane perpendicular to the sample, was used to observe the light scattered in the vertical direction. The second camera (No. 2), positioned in the plane of the sample, was used to look at the cleaved output facet of the waveguide in order to observe the output (transmitted) signal. By careful manipulation of the input fiber, we were able to observe apparent guiding over two 90° bends with waveguide segments of $\sim 200\ \mu$m lengths (as shown in Fig. 3) as well as guiding around a 60° bend. Baba, Fukaya, and Yonekura have shown similar visualizations of light propagation in PC over shorter distances.[17] However, by reference to the output camera (No. 2), we were able to confirm that true guiding by the PC is obtained by a different set of coupling conditions. Under these conditions, a clear guided mode is observed at the output facet of the waveguide, and very little light is scattered out of the wave-

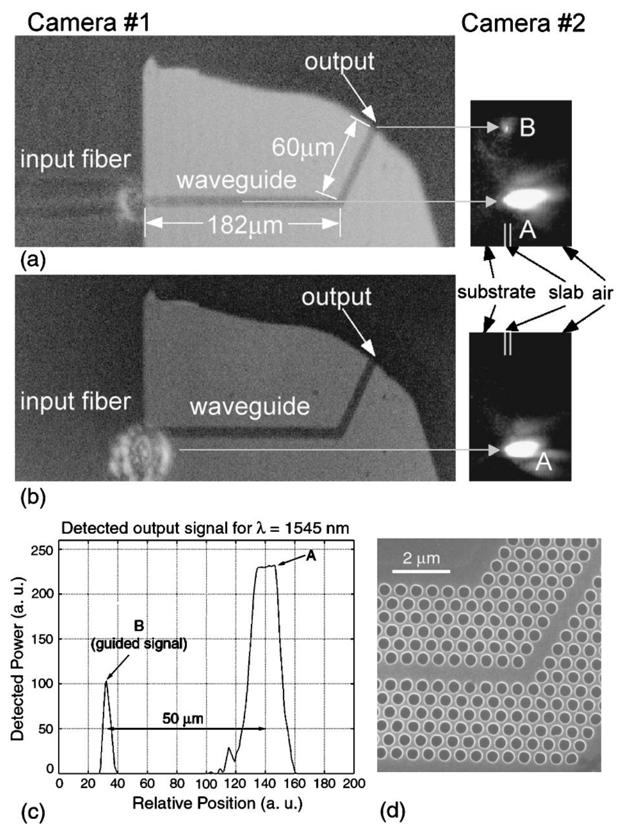

FIG. 4. Waveguiding at $\lambda = 1550$ nm around a 60° bend. Two cameras are used simultaneously, a top (camera No. 1) and in-plane view (camera No. 2) of the tested structure. (a) When the input fiber is aligned to the input of the waveguide, the output signal, transmitted around the 60° bend, is detected (signal B) and (b) when it is misaligned the transmitted signal is not present. The position of the slab is indicated with two parallel lines. (c) Detected output power (arbitrary units) at different positions along the cleaved output facet of the waveguide. Two peaks correspond to the signals A and B. The figure is obtained as a line scan of (a) along the middle of the slab. (d) SEM micrograph of the structure (topview).

guide perpendicular to the wafer. Whereas the image shown in Fig. 3 is instrumental in qualitative visualization of light propagation within the PC structures, the optimization of true waveguiding requires the observation of the guided mode exiting from the PC sample.

For the case where the fiber was correctly aligned to the waveguide, Fig. 4(a), camera No. 2 detected two signals, marked A and B. The light in spot A has a significant component that is not coupled from the input fiber into the waveguide and is, therefore, of little interest for characterization. On the other hand, spot B represents the light that is guided around the sharp 60° bend in the PC waveguide. The distance between the 60° bend and the output of the waveguide was about 50 μm. This distance is sufficiently large to distinguish easily between signals A and B. Figure 4(c) shows the detected output power as a function of position along the cleaved output facet of the waveguide. On the left-hand side is an intensity scan of spot B corresponding to the guided mode. Between B and A any measured intensity would correspond to light scattered out of the guide through the PC (loss in the lateral direction). It can be seen that this intensity is below the threshold of the camera used, at least two orders of magnitude less than the peak intensity of the guided mode. This result suggests that losses in PC waveguides are low enough to support practical device applications.

When the fiber was not aligned to the waveguide, Fig. 4(b), camera No. 2 registered only one signal (A)—the one coming directly from the fiber. The other signal was not present since there was no light coupled into the waveguide. Similarly, when we moved the fiber in the vertical direction, the guided signal (B) was present and not present depending on the relative position of the waveguide and the fiber. Therefore, we can conclude that signal B corresponds to the guided mode in this PC waveguide. Our theoretical analysis of this structure[9] shows, in the frequency range tested in this experiment, that there exist two guided modes: one TE-like, guided due to the PC effect, and another TM-like, guided due to the effective refractive-index contrast. We are currently engaged in experiments to characterize the polarization properties of the guided mode presented here.

We have demonstrated the fabrication and operation of planar PC waveguides. 3D analysis based on Maxwell's equations was used to find suitable dimensions of the PC devices. While on one hand our research results represent encouraging progress toward the use of PC structures in planar photonic circuits, on the other they show that guiding conditions for real guides in three dimensions are more restrictive than previously thought using 2D modeling. We have measured unambiguous guiding in these structures over the entire length of the sample. Under appropriate coupling conditions, this transmission appears to have acceptable low loss, a feature that is currently under study in our laboratory.

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