

# Demonstration of highly efficient waveguiding in a photonic crystal slab at the 1.5- $\mu\text{m}$ wavelength

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Highly efficient transmission of 1.5- $\mu\text{m}$  light in a two-dimensional (2D) photonic crystal slab waveguide is experimentally demonstrated. Light waves are shown to be guided along a triple-line defect formed within a 2D crystal and vertically by a strong index-guiding mechanism. At certain wavelength ranges, complete transmission is observed, suggesting lossless guiding along this photonic one-dimensional conduction channel. © 2000 Optical Society of America

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Compact, lossless, and broadband guiding of light is essential for building future large-scale optical integrated circuits. Photonic crystal waveguides offer a new guiding mechanism that is fundamentally different from that of a traditional waveguide based on total internal reflection. A photonic crystal is a periodic dielectric structure that exhibits a photonic bandgap, a frequency range over which propagation of light is strictly forbidden.<sup>1</sup> The introduction of line defects into a photonic crystal structure creates an optical channel for propagation of light.<sup>1</sup> If the line defect is properly designed, the resulting guiding mode falls within a photonic bandgap and is highly confined. Because of its confining ability, a photonic bandgap material can be viewed as a compact mirror for light guiding and bending. The guiding mode can also be designed to be broadband and thus gives rise to a compact, broadband photonic crystal waveguide.

Early theoretical simulation suggested that lossless guiding and bending of electromagnetic waves is possible with a two-dimensional (2D) or a three-dimensional (3D) photonic crystal.<sup>2-5</sup> Subsequently, a successful experimental demonstration of a 2D guide and bend was performed at millimeter wavelengths.<sup>6</sup> Guiding of optical light by a fiber configuration is also possible.<sup>7</sup> More recently, fabrication of a 1.5- $\mu\text{m}$  2D crystal waveguide was also reported.<sup>8</sup> However, to our knowledge there has been no successful experimental demonstration of perfect waveguiding at optical wavelengths by use of either 2D or 3D photonic crystals. The main difficulty is that a pure 2D photonic crystal does not guide light well in the third direction, which leads to unavoidable leakage.

This Letter reports the experimental demonstration of efficient guiding of light at the 1.5- $\mu\text{m}$  wavelength by use of a 2D photonic crystal slab. Light is shown to be guided along a one-dimensional (1D) optical channel, defined by a triple-line defect formed within a 2D crystal slab. At certain wavelength ranges, complete transmission is observed. This is to our knowledge the first experimental demonstration of lossless guiding in a photonic crystal at optical wavelengths.

The photonic crystal sample consists of a triangular array of 2D holes, lithographically etched through a thin slab of GaAs. The hole array has a lattice constant  $a_0$ , and the hole diameter is  $d = 0.6a_0$ . This design gives a large photonic bandgap.<sup>9</sup> The GaAs slab has an underlying 2- $\mu\text{m}$ -thick  $\text{Al}_x\text{O}_y$  layer and a thin  $\text{SiO}_2$  layer on top; see Fig. 1(a). The straight waveguide is created by introduction of a triple-line defect along the  $\Gamma K$  symmetry direction. The diameters ( $d' = 0.8a_0$ ) of the defect holes are wider than those of the regular holes. Figures 1(a) and 1(b), show scanning electron microscope images of the side and top views, respectively, of the fabricated sample. Conventional ridge waveguides located on either side of the lattice are used for efficient coupling of laser light into and out of the photonic crystal section of the sample. The waveguides have a lateral width of 1.4  $\mu\text{m}$ , which is well matched to the modal extent of the triple-line defect. Nanofabrication of the sample is achieved by

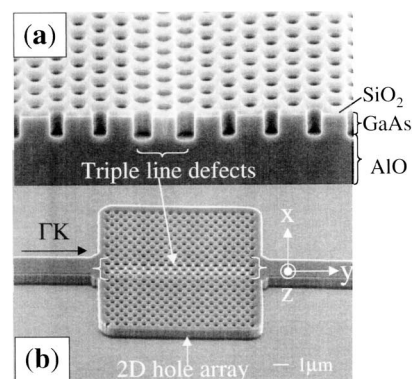


Fig. 1. (a) Cross-section scanning electron microscope view of the fabricated triple-line defect embedded within a triangular array of holes. The defect holes have a larger diameter,  $d' = 0.8a_0$ , than the regular holes,  $d = 0.6a_0$ . (b) Scanning electron microscope top view of the triple-line defect waveguide structure. The ridge waveguides are used to facilitate coupling of laser light into and out of the 2D slab hole array.

means of electron-beam lithography and reactive-ion beam etching.<sup>10,11</sup>

Our photonic crystal slab guide has three unique features: One is that, contrary to the guiding principle of a conventional waveguide, it steers light in the lower-index region. Second, the use of a slab design provides strong index guiding of light vertically, even within the photonic bandgap spectral region.<sup>11</sup> Third, it is made with a triple- instead of a single-line defect. Although a single-line defect also supports a guiding mode, its center frequency is too close to the lower photonic band edge.<sup>12</sup> Any slight process variation may shift the guiding modes into the adjacent allowed band and cause the guide to become lossy. On the other hand, a triple-line defect structure has an effective index lower than that of a single-line defect, thus pushing the guided-mode frequency away from the lower band edge and more into the bandgap.

One potential drawback of the triple-line defect is that it is no longer single mode but instead has three guided modes. In Fig. 2, a theoretical calculation of the TE guided-mode dispersion is shown. The frequency  $\omega(a_0/\lambda)$  and the wave vector  $k(2\pi/a_0)$  are plotted in reduced units. The filled circles represent the fundamental (first) even mode. The open and the filled triangles represent the first odd and the second even modes, respectively. The conduction band, valence band, and light-cone regions are also indicated. The three guided bands extend from  $\omega(a_0/\lambda) = 0.273$  to  $\omega(a_0/\lambda) = 0.30$ , covering  $\sim 36\%$  of the bandgap. Experimentally, since the incoming laser light has an even symmetry, it cannot be coupled into an odd mode. Hence, at any given frequency in the guided band, there is only one even guided mode. A triple-line defect may then be treated as a single-mode waveguide.

To test the guiding efficiency and the bandwidth of our photonic crystal guide we carry out in-plane transmission measurement. The laser light is coupled laterally into the input ridge waveguide [see Fig. 1(b)], transmitted through the triple-line defect, and then coupled into the output ridge waveguide. The output light is then split and fed into a calibrated In-GaAs photodetector and an infrared camera. In the inset of Fig. 3 a modal profile image of the output light, obtained from a 16-period photonic crystal waveguide ( $a = 410$  nm) at  $\lambda = 1.550$   $\mu\text{m}$ , is shown. The observed image has a clean, round modal profile and is Gaussian-like. This profile indicates that the measured output signal is not derived from the undesired air mode or the substrate leaky mode.<sup>11</sup> Rather, it is a true measure of a well-confined photonic crystal guiding mode in the slab layer.

As the first step of the experiment, three spectra are taken from three different guiding samples: (i) a 2D hole array with a triple-line defect [see Fig. 1(b)], (ii) a 2D hole array with no defect, and (iii) no 2D hole array and no defect (the reference spectrum). By ratioing spectrum (i) to (iii), we obtain the absolute guiding efficiency ( $\eta$ ) of a triple-line defect. Similarly, by ratioing spectrum (ii) to (iii), we obtain the bulk transmittance ( $T$ ) of the 2D slab hole array. In Fig. 3,  $\eta$  is shown by filled circles as a function of both  $\lambda$  and  $\omega$

for a 16-period sample with  $a_0 = 410$  nm. The guide has a high guiding efficiency and is broadband. Furthermore, at the fiber communication wavelength  $\lambda \sim 1540$ – $1565$  nm, perfect guiding efficiency is observed. This is believed to be the first demonstration of complete guiding of light by a photonic crystal, 2D or 3D, in the optical wavelengths. For  $\lambda = 1535$ – $1575$  nm,  $\eta > 70\%$  is observed. The slightly higher than 100% efficiency at certain frequencies suggests that a photonic crystal guide confines light better than the reference guide.

To map the entire guiding-efficiency spectrum, i.e.,  $\eta$  versus  $\omega (= a_0/\lambda)$ , we vary both  $a_0$  and  $\lambda$  experimentally. To achieve this goal we fabricate six samples with values of  $a_0 = 400, 410, 430, 450, 460, 470$  nm. Also, three laser modules are used to tune  $\lambda$  from 1290 to 1680 nm. This combination allows complete mapping of guiding efficiency throughout the entire photonic bandgap regime.<sup>13</sup> In Fig. 4 the measured  $\eta$  and  $T$  are shown by the red triangles and the black circles, respectively. Also shown in Fig. 4 are the theoretically computed  $T$  (black curve) and  $\eta$  (red curve). The numerical simulation consisted of sending a Gaussian input pulse into the input waveguide, measuring the flux in the output waveguide, and normalizing the flux against the flux of a straight waveguide for determination of absolute

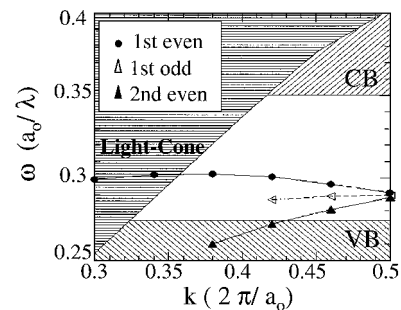


Fig. 2. Computed dispersion of the 2D photonic crystal slab waveguide. The three guided bands cover  $\sim 36\%$  of the bandgap. The conduction band (CB), valence band (VB), and light-cone regions are labeled.

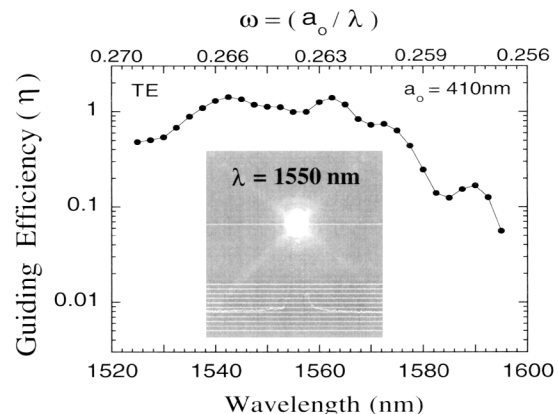


Fig. 3. Absolute guiding efficiency ( $\eta$ ) plotted as a function of  $\lambda$ . At  $\lambda \sim 1540$ – $1565$  nm, a perfect guiding efficiency is observed. Inset, infrared image of transmitted output light at  $\lambda = 1.550$   $\mu\text{m}$ .

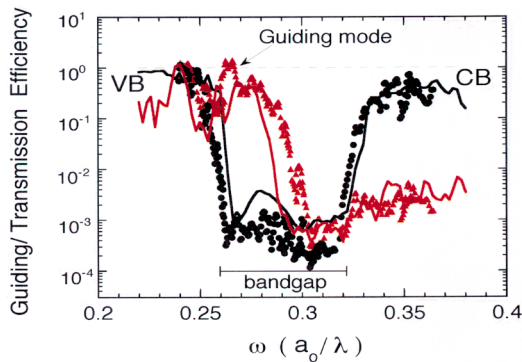


Fig. 4. Absolute guiding efficiency ( $\eta$ ) and transmittance ( $T$ ) as a function of  $\omega$  over the entire photonic bandgap region.

transmittance. For  $T$ , the theory correctly predicts the transmission efficiency at both the conduction band and the valence band to within  $\Delta\omega(a_0/\lambda) = 0.1$ . In the bandgap region,  $\omega(= a_0/\lambda) \sim 0.26-0.32$ , both the predicted line-shape spectrum and the intensity attenuation ( $T \sim 10^{-3}-10^{-4}$ ) agree with experimental data. For  $\eta$ , highly efficient guiding starts from the lower-frequency end [ $\omega(a_0/\lambda) = 0.26$ ] and extends into the midgap at  $\omega \sim 0.29$ , consistent with the prediction of Fig. 2. Moreover, although photonic bandgap attenuation is strong ( $T \sim 4 \times 10^{-4}$ ) at  $\omega(a_0/\lambda) \sim 0.265$ , a near-perfect  $\eta$  value of  $\sim 100\%$  is observed. This correlation clearly demonstrates a strong guiding effect introduced by the formation of a triple-line defect and by the existence of a photonic bandgap. The observed  $\eta$  also agrees with the computed curve, except that it extends slightly into the midgap by  $\Delta\omega(a_0/\lambda) \sim 0.1$ . It is possible that the etched defect holes are slightly larger than the nominally designed  $d' = 0.8a_0$ , and thus the guiding mode is pushed more into the bandgap.

To achieve an even-wider bandwidth we need to push the guided modes farther into the midgap. In principle, this can be done by a further increase in the defect hole size to  $d' > 0.8a_0$ . In practice, however, nanofabrication difficulty prevents us from achieving this increase, as the nearest hole-to-hole spacing will be too small. One possible solution is to introduce a nonuniform triple-line defect, such that the middle line has a hole size  $d' = 0.8a_0 + \Delta d$  and the outer lines have a hole size  $d' = 0.8a_0 - \Delta d$ . As the guided-mode electric field intensity is concentrated mostly in the middle defect line, this arrangement effectively raises the guiding-mode energy while maintaining the hole-to-hole spacing.

In summary, the design, fabrication, and testing of a triple-line defect embedded in a 2D photonic crys-

tal slab has been reported. This new class of photonic crystal waveguide guides light in the lower-index region, with a near perfect guiding efficiency at the optical communication wavelength  $\lambda \sim 1.5 \mu\text{m}$ . Such lossless guiding of light in a lower-index region is a consequence of strong photonic confinement made possible by a photonic bandgap.

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13. The laser has a typical wavelength tuning range of  $\Delta\lambda = 50-80 \text{ nm}$ , which is not sufficient to cover the entire bandgap spectral range of  $\sim 400 \text{ nm}$ . Owing to this experimental limitation, multiple lasers and samples with different  $a_0$  were used to map the dispersion spectrum.