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Highly Confined Three-Dimensional Photonic Crystal Waveguide with Sharp Bend

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1. Introduction

In recent years, there has been a rapidly growing interest in application of a photonic crystal for realization of ultra small optical circuits or optical integrated circuits (IC). A phonic crystal can act as a base medium for this optical IC, in which we can incorporate devices such as nano-ampere laser arrays, sharp-bend optical waveguides, signal modulators, wavelength mul-demultiplexors, and so on. (See illustration in Fig. 1 [1]). The soundness of this concept mainly relies on an ability of photonic crystal waveguide that can perfectly confine light and efficiently guide light around sharp corner without radiation loss. These features of the photonic crystal waveguide were first predicted for two-dimensional (2D) case [2], and the experiment in 2D case has been conducted to prove the theory [3]. An experiment using 3D photonic crystal has also been conducted recently [4], but the waveguides created were confined in only one dimension as the same as in 2D case, not two dimensions as they should be. Thus, a full confinement of electromagnetic (EM) wave utilizing 3D photonic crystal has not been disclosed yet, nor has the guideline for designing of the waveguide been shown. In this paper, by theoretical calculation, we demonstrate a method to create fully confined straight waveguides and bending waveguides in 3D photonic crystal for the first time.

2. Model and Method of Calculation

Recent reports show that the stacked-bar structure can serve as a promising structure for realization of 3D photonic crystal in optical wavelengths [5-6]. We, therefore, choose to study the waveguide created in this stacked-bar structure. The material of stripe is assumed to be GaAs [5]. The width and thickness of stripe is $0.25a$ and $0.3a$ respectively, where a is a lattice constant. Figure 2 shows a schematic depicting a waveguide. The waveguide is created by removing one stripe from one layer. It is confined by the upper (which is not shown in the figure) and lower layers of photonic crystal. We use a finite-difference time-domain method (FDTD) to simulate the propagation of EM wave. We use a Mur's absorbing boundary condition as a boundary condition [7]. A dipole or light source is placed at the entrance of the waveguide and is excited with a continuous wave (CW).

3. Results and Discussion

Straight Waveguide

When there is no waveguide in a 3D photonic crystal, an omnidirectional bandgap exists from frequency f=0.380 [c/a] to f=0.444 [c/a]. We use FDTD to examine the guided modes of a straight waveguide. The EM field patterns are obtained for different frequencies within the bandgap. It is found that guided modes exist for a polarization that electric field E is parallel to Z-axis but there is no guided mode for E//X-axis polarization. We derive the dispersion relation of ω-k or the band structure for the guided modes and show it in Fig. 3. The lower cutoff frequency is expected to be about f=0.392 [c/a] when k vector is 0.

Waveguide with Sharp Bend

Suppose a straight waveguide like the one shown in Fig. 2 is created. One can then create a 90° bend within the same layer of this waveguide. But the structure of the waveguide after a 90° bend will be different from Fig. 2, i. e., one will have to remove small parts from every single bars to create the waveguide. It is expected that the guided modes before and after the bend will also be dissimilar, and the EM

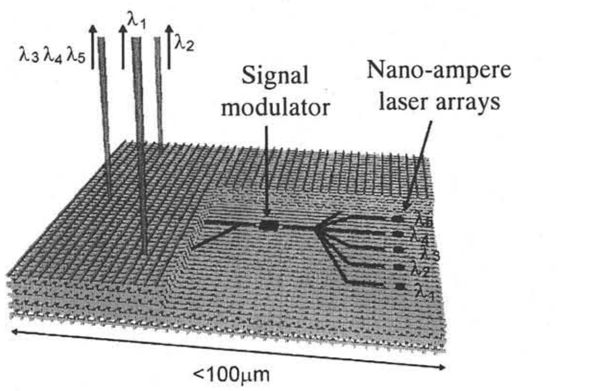

Fig. 1 Schematic diagram of ultra small optical circuits.

wave will not be able to couple smoothly. Therefore, a reflection loss at the bend can be large. In fact, we have calculated the propagation of EM wave in this case by FDTD and verified the above assumption.

Now, to make the guided modes identical for before and after the bend, we let the EM wave go up one layer to the upper layer as shown in Fig 4. The propagation of EM wave within this bending waveguide is calculated. Figure 5(a) and (b) show electric field patterns at the lower and upper layer of the waveguide respectively. It is clearly seen that the EM wave is guided along the lower layer of waveguide and then smoothly elevated up and bent to the upper layer. The amplitude of EM wave after and before the bend is the same, which means the transmittance is approximately a unity.

Finally, we calculate the EM field pattern of the cross section of the waveguide to see how many layers of the photonic crystal is needed to confine the EM wave. The result is shown in Fig. 6. It is seen that EM wave is perfectly confined within about 12 layers of photonic crystal (i. e., 2 layers of bending waveguide sandwiched by 5 layers on each side). In fact, the FDTD simulation of a bending waveguide created in more than 12 layers of photonic crystal did not yield any noticeable difference from that with 12 layers.

4. Conclusions

We have theoretically shown that the 3D photonic crystal waveguide can be created in the stacked-bar structure by removing one stripe. Crossing waveguides of the adjacent layers can create the bending waveguide and by this way, the guided modes after and before the bend remain the same so that the transmission through the bend is optimized. These results provide very important guidelines for designing of the 3D photonic crystal waveguide.

Acknowledgement

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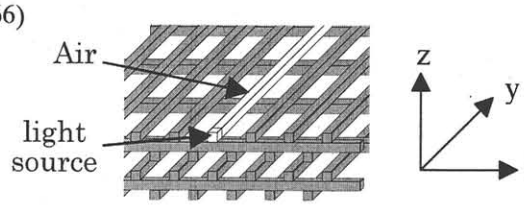


Fig. 2 Schematic of air waveguide created by removing one stripe.

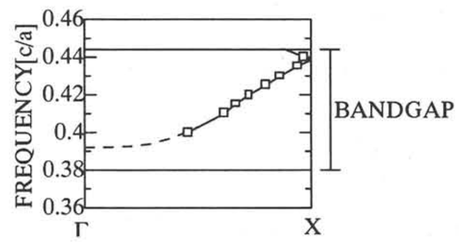


Fig. 3 Band structure of guided modes of waveguide shown in Fig. 2 calculated by FDTD method.

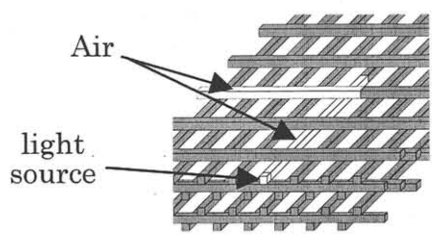
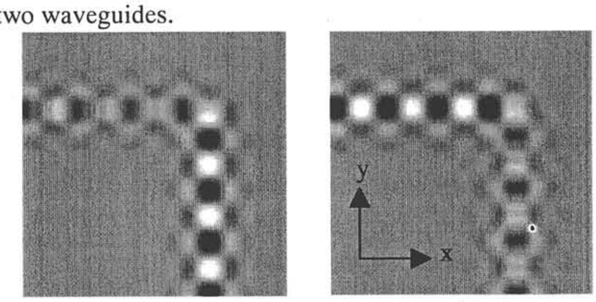


Fig. 4 Schematic of bending waveguide created by crossing two waveguides.



(a) (b)

Fig. 5 Electric field patterns at the (a) lower layer and (b) upper layer of waveguide.

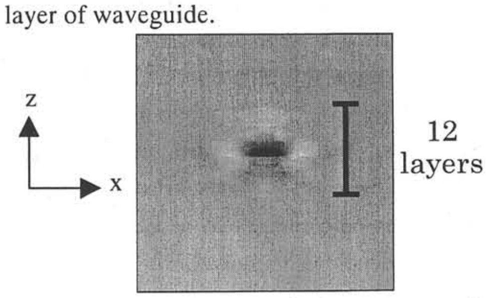


Fig. 6 Electric field pattern of the cross section of the waveguide.