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Modal analysis of waveguides based on a triangular photonic crystal lattice

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Photonic crystals[1] (PC) have recently attracted a lot of attention as promising candidates for three dimensional (3D) localization of light. By forming defects in a host PC we can form localized electromagnetic states and control propagation of light.

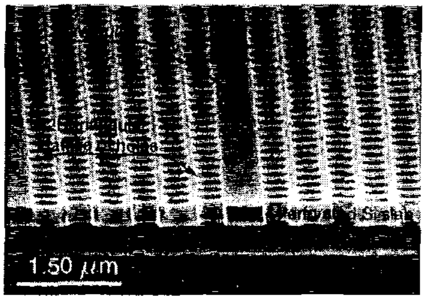
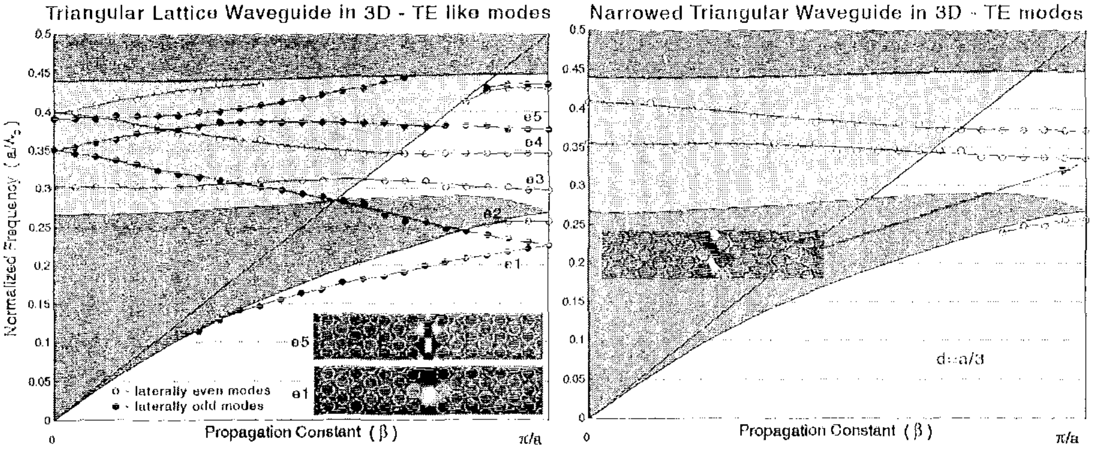


Figure 1. Fabricated single line defect waveguide.

The structure that we are interested in is a thin silicon slab perforated with 2D lattice of holes[2]. By removing single line of holes we can form the simplest photonic crystal waveguide – single line defect waveguide[3]. In such a structure light is confined to the waveguide in the vertical direction by the means of total internal reflection, and in the lateral direction by distributed Bragg Reflection, due to the presence of 2D PC. We have developed a new fabrication procedure to define these waveguides into silicon on insulator material[4]. The waveguides are suspended in air in order to improve vertical confinement of light and symmetry of the structure (Figure 1). We have analyzed the structure shown in the Figure 1 by using three-dimensional finite difference time domain algorithm (3D FDTD). In the Figure 2(a) we show dispersion diagram for both guided (in the white region) and leaky modes (in the light gray region) supported in the structure. It can be seen that there are five guided modes located in the bandgap of the triangular PC lattice. By exciting one of these modes with an external light source we can guide the light within the waveguide and achieve high transmission around sharp bends[3]. However, due to the presence of the leaky modes in the same frequency range, coupling efficiency will not be very good. Light coupled into the leaky modes is scattered in the vertical direction and represents loss mechanism of the waveguide.

By reducing the width the waveguide we can reduce the number of guided modes. One way of doing it is to reduce the distance between two PC walls by translation in x direction. However, this produces waveguide sections of different widths (Figure 3(a)) which can affect bending efficiency of the waveguide.



(a) (b)

Figure 2. Dispersion diagrams of modes supported in (a) single line defect waveguide, and (b) "narrowed" waveguide with d=a/3. Insets represent field distribution of the B_z component in the middle of the slab. Regions where there exist modes of the patterned Si slab are represented with dark-gray color, and light cone with light-gray color.

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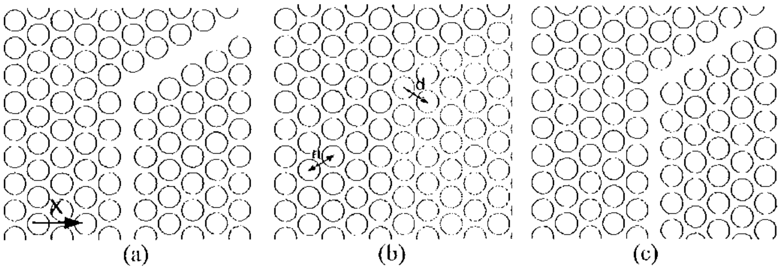

Figure 3. Different types of PC based waveguides. **d** is the vector that connects two nearest neighbor holes.

Here, we propose another way for making narrow waveguides. If in the PC shown in the Figure 3(b) we offset the "red holes" by translation along **d** vector (high symmetry direction in the PC lattice) we form waveguide sections of the uniform widths (Figure 3(c)). By changing the value of |**d**| we can control the width of the waveguide (for |**d**|=*a* we form a single line defect waveguide shown in the Figure 1). Figure 2(b) shows dispersion diagram for the modes supported in the narrow waveguide with |**d**|=*a*/3. It can be seen that the number of guided modes in the bandgap is reduced. Of more importance is the fact that it is now possible to operate the waveguide in the frequency range where there are no leaky modes present (e.g. a/λ=0.34), and therefore improve the coupling efficiency. It is interesting to note that the mode crossings observed in the Figure 2(a) are no longer present. The modes e1 and e3 of the single line defect waveguide cross because they have different symmetry with respect to the reflection symmetry plane in the center of the waveguide. Since narrow waveguide (Figure 3(c)) doesn 't have that reflection symmetry, these two modes mix and anti-crossing occurs (Figure 2(b)).

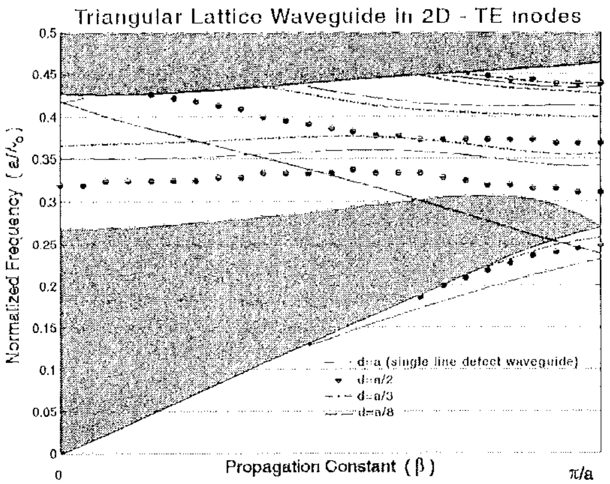

Figure 4. Dispersion diagram for modes guided in the 2D photonic crystal waveguide for four different waveguide widths. Waveguides are of type shown in the Figure 3(c). Effective index of Si is assumed to be $n_{eff}=2.6$

In the Figure 4 we show dispersion diagrams for guided modes supported in a two-dimensional waveguide (infinitely extended in the vertical direction) for four different waveguide widths (different values of d=|**d**|), a result of 2D FDTD analysis. It can be seen that even very narrow waveguide (|**d**|=*a*/8) can support two guided modes.

In conclusion, we have performed modal analysis of both conventional single line defect waveguides and proposed "narrowed" waveguides. We have shown that the proposed structure has fewer guided modes than the conventional one, and based on the dispersion diagram-type analysis, we predict that it will have better coupling properties. At present we are working on the experimental verification of these properties. We are also engaged in the quantitative experimental verification of the predicted high transmission efficiency around sharp bends in the photonic crystal waveguides. Our previous work shows that waveguides formed in the perforated Si slabs are promising candidates for achieving this high transmission efficiency.

References:

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