Abnormal propagation and interface refraction of light in a photonic crystal and their applications

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ABSTRACT

We analyze the abnormal refraction and propagation when a light beam of finite and practical width enters a photonic crystal from a uniform medium. The beam propagation in the photonic crystal is very complex, and in many cases, is beyond the realm of refraction (even with a renormalized refractive index given by photonic band calculation). Generally, light propagation is restricted to a triangular region (or a fan), although the light may not fill the whole triangle, nor is the light intensity uniform in the triangle. It is found beam divergence does not have a definite connection with the fan shape of the region of light propagation, in contrast to dynamic X-ray theory. A new origin of the fan shape is suggested. Also simulations indicate that at microscale, a narrow light beam may zigzag in a photonic crystal with sufficiently high index contrast. An application of this phenomenon is to make a wide angle bend for waveguides. The designed bending structure has low loss and matches the mode size of a typical single-mode waveguide for fiber-optic communications. Our simulations are based on two-dimensional photonic crystals.

Keywords: Photonic Crystal, Superprism phenomena, sharp waveguide bend, fiber-optic communications, planar lightwave circuits, beam zigzag, abnormal refraction, beam steering, Borrmann fan, Dynamic X-ray theory.

I. INTRODUCTION

Abnormal refractions at an interface between a photonic crystal and a uniform medium have recently been investigated. [1,2] In certain context, they have been called superprism phenomena, although the nature and diversity of the phenomena actually extend beyond those in a prism with super high refraction power. Double branching, negative refraction, and high wavelength sensitivity make these phenomena stand out from the prism refraction, which is well explained by a simple refractive index. The key to understand these phenomena is considered to be the underlying photonic band structure. The direction of lightwave propagation inside a photonic crystal is believed to be normal to the equi-frequency surface, which is a conceptual extension of the equi-energy surface for the electrons in a traditional crystal. One of the most impressive work was the photonic band structure measurement by monitoring the abnormal beam refraction. [3]

From its birth, photonic crystal has been believed to lead optics into a new era of miniaturization. Highlighting this expectation are the wavelength comparable lattice constant, the high isolation offered by total reflection at the gap frequencies, and high transmission around sharp bends in photonic crystal waveguides. [4] However, very few useful devices have been built based on effects unique to photonic crystal. In the past few years, telecommunication has been the major drive for integrated optics. Due to the dominant usage of fibers in communication, almost all integrated optical communication devices become fiber-optic orientated in recent years. One major problem for photonic crystal devices is their mode size mismatch with the modes of an ordinary single-mode fiber. For example, although the high transmission through sharp bends was theoretically predicted, the experimental observations are mostly discouraging. [5,6] The high loss is mostly attributed to the mode mismatch. Actually, even the loss in a straight photonic crystal waveguide [7] is very high compared to a normal integrated optical waveguide. One simply has difficulty to generate a field of 1 μm size to couple into a photonic crystal waveguide.

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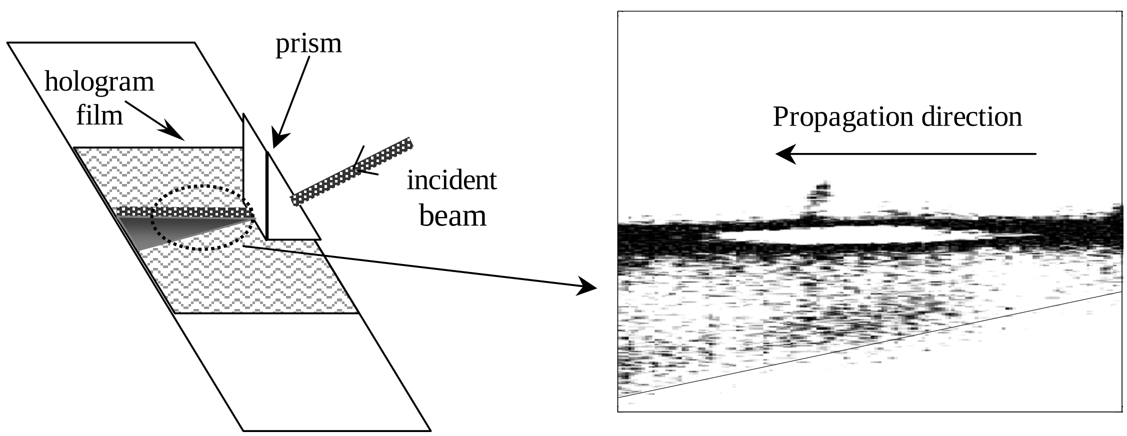
II. BEAM PROPAGATION MECHANISM: fan shape and other complex patterns

As some authors pointed out [1], similar abnormal refraction phenomena were discussed before in X-ray diffraction [8] and weakly modulated gratings.[9,10] However, photonic crystal present a complete new situation for such abnormalities in that the periodic potential or modulation is much stronger compared to the two cases previously studied. Due to the weak periodic modulation in X-ray and grating cases, the two-wave approximation [9] furnishes an adequately accurate theory. The essence of the two-wave approximation is that a secondary wave is generated by the periodic modulation with a wave vector corresponding to the sum of that of incident wave and grating vector. In a more detailed study, the dynamic theory of X-ray diffraction revealed that the two waves actually coupled together while propagating and converting between each other. Actually, a similar theory was developed for holographic grating, [11] although researchers have concentrated on its final results on grating diffraction efficiency and has paid little attention to its description of the wave propagation. In the X-ray theory, the propagation is actually analyzed in more detail. However, due to the restriction of numerical computation facilities in early last century, the theory was mostly developed through analytic derivation and the discussion was limited to the cases of either an infinitely wide beam (pure planar wave) or an isotropically uniform spherical wave(assuming a point source of X-ray just above the crystal surface). The Borrmann fan was explained in the case of a perfect uniform spherical incident wave.



(a) (b)

Figure 1 (a) Experimental configuration. A hologrm film is carried on a microscopic slice. A high index prism is used to couple light into the film. (b) Magnified part of the film (a real photo): A narrow beam light propagates in holographic grating from right to left almost horizontally, spreading over a triangular region. The lower border of the triangle is indicated by a thin drawn line as predicted by theory.

However, from some experiments on holographic gratings, we have found if the width of the incident beam w_0 satisfies

$$\lambda << w_0 << L \tan \theta_d, \qquad (1)$$

where λ is the wavelength, L is the length of the grating region, and θ_d is the angle between the central wave vector of the incident wave and that of the diffracted waves, then a triangular bright region is always present when incident angle approximately satisfies the Bragg condition, as shown in Fig. 1, where the average index is about 1.5, index modulation is about 0.012 and grating period is about 1 μm, and light wavelength is 0.63μm. Through 2-dimensional(2D) finite difference time domain (FDTD) simulations in sinusoidal gratings and photonic crystals, we confirmed that a perfectly uniform spherical wave is not the necessary condition for a triangular shape of light propagation region. Figure 2 shows that when a beam of finite width is incident on a dielectric structure with 2D periodic modulation, the wave component $\boldsymbol{k}_0$ of the incident beam will be converted into the wave with the wave vectors $\boldsymbol{k}_g$ given by the Bragg condition

$$\boldsymbol{k}_g = \boldsymbol{k}_0 + \boldsymbol{K}. \qquad (2)$$

Since inequality (1) is satisfied even in the case of 10-μm-diameter waveguide mode, one can neglect all other wave components in the incidence beam besides that of centeral one $\boldsymbol{k}_0$. The $\boldsymbol{k}_0$ beam is continuously converted into $\boldsymbol{k}_g$ wave along its propagation, as in the case of Fig. 2(a). If the periodic modulation is weak, such a conversion will take a long propagation distance. The incident Gaussian beam width is around 30 μm. Simple geometric drawing as shown in Fig. 2(b) shows that all these secondary waves will propagates within the triangular region limited by the two lines originating from the incident point and pointing to the $\boldsymbol{k}_0$ and $\boldsymbol{k}_g$ directions, respectively. Furthermore, the secondary waves generated by the incident wave will be converted back into $\boldsymbol{k}_0$ along their own propagation paths, simple geometric drawing again reveals that the derivative $\boldsymbol{k}_0$ waves generated by the secondary $\boldsymbol{k}_g$ waves fall in the aforementioned triangular region still.

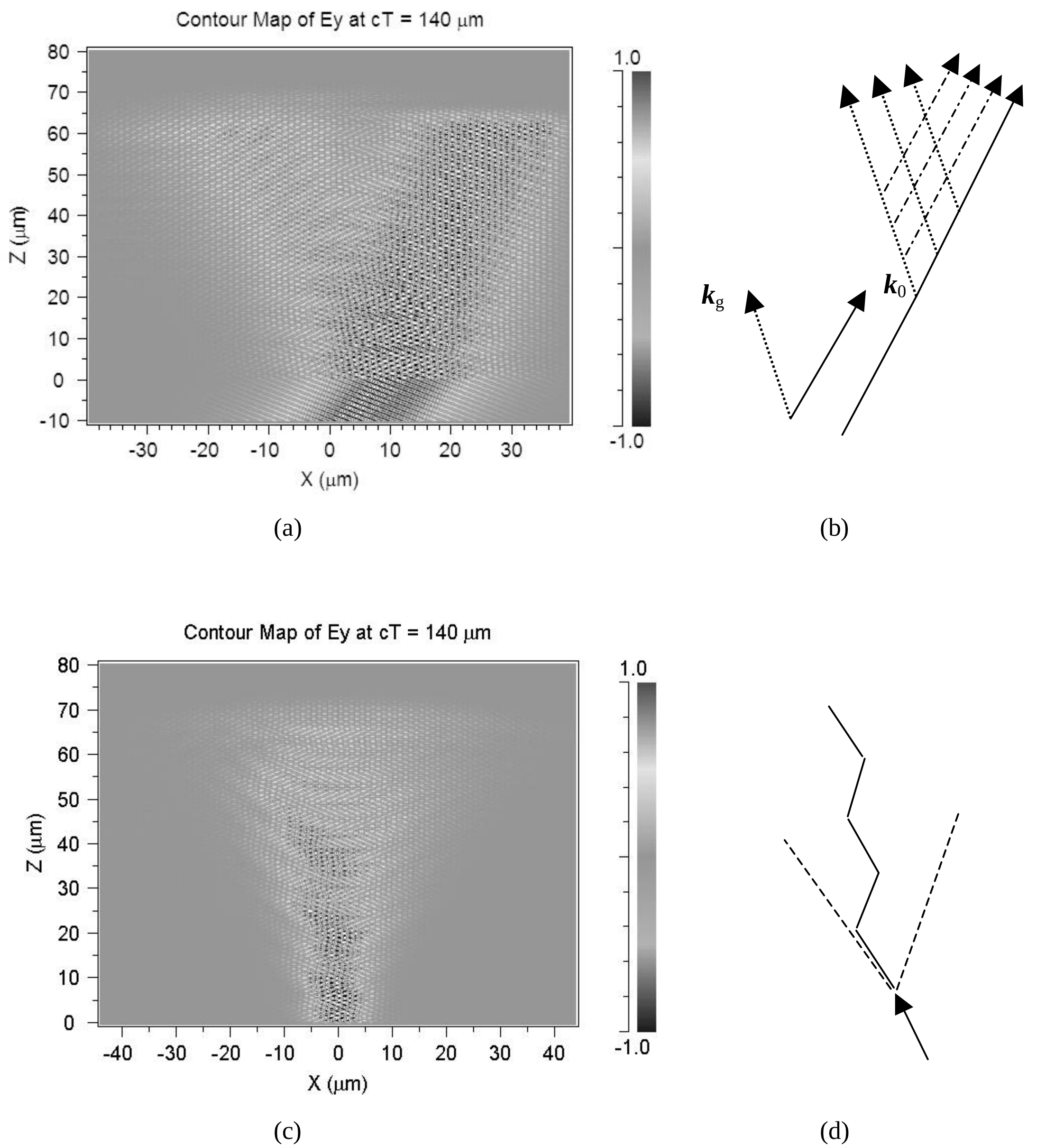


Figure 2 (a) Wide incident beam in sinusoidal grating, obvious triangular region. (square lattice a=1μm, n_0=1.5, sinusoidal index modulation amplitude 0.3, w_0=30 μm, angle of incidence(AOI) 30º) (b) Sketch of our explanation of case (a). (c) Narrow beam in photonic crystal with index contrast 0.5, triangular propagation not obvious on micro-scale. (a=1μm, n_0=1.5, dn=0.5, w_0=10 μm, AOI=-30º). All at 1.55 μm wavelength. (d) Sketch of our explanation of case (c).

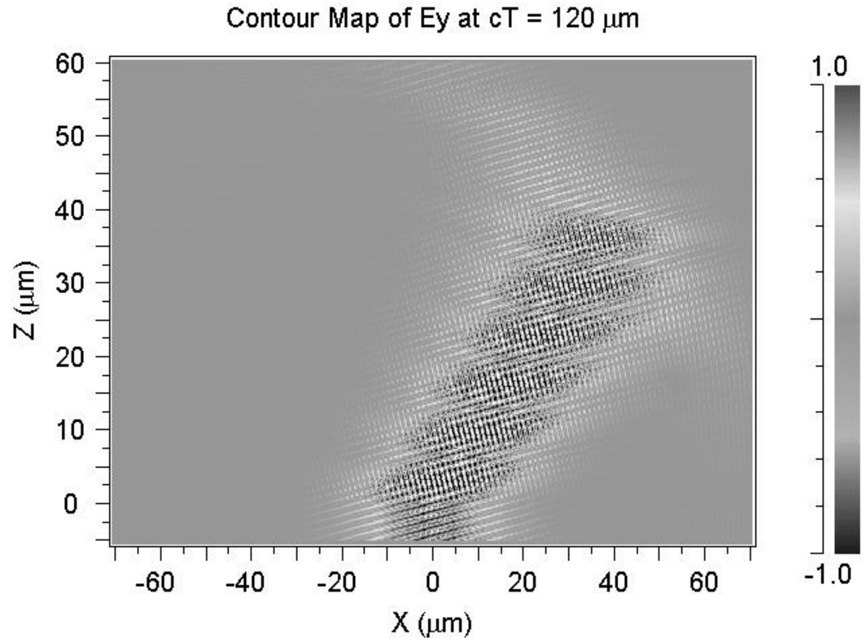


Figure 3 A well defined beam in the case of "negative refraction." (triangular lattice a=1 mm, n0=1.5, sinusoidal index modulation amplitude 0.3, w0=30 mm, AOI=-9.5º, beam deflected by 54.5º)

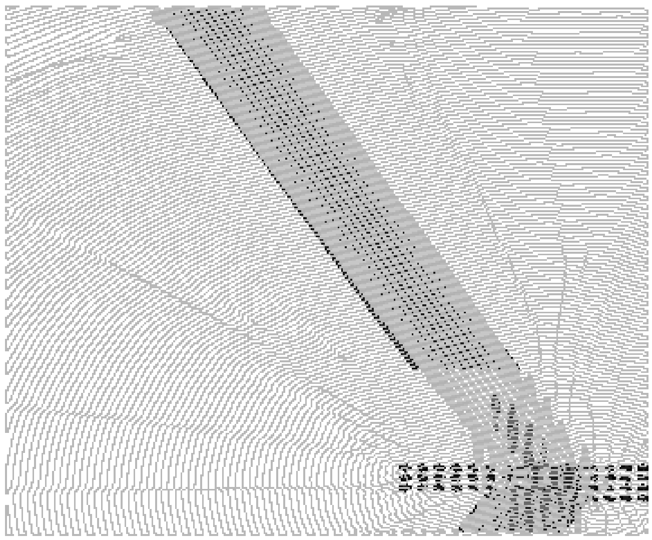
From these arguments, we can see that the divergence of the incidence beam is not a requisite for the fan shape propagation region; rather the coupled two waves with mutual conversion along the way is essential for the triangular shape. In the case of multiple Fourier components in effect(as in step index photonic crystals), the triangle will be delineated by the outmost diffracted wave vector with the incident wave vector $\boldsymbol{k}_0$. In many cases, we found one edge of triangle has strong intensity of light, while the remaining part of the triangle has relative low intensity. From another viewpoint, one can say there is a beam propagating in the grating, but the beam is continuously scattered along the way. The scattered wave is in the triangular region aforementioned.

Any doubt in this explanation should be dismissed by looking at Fig. 2(c), where the strong periodic index modulation results in a very short distance of conversion between two types of waves. In this case, the wave actually zigzags in the photonic crystal. By examining the wave pattern, one recognizes that for different segments of the wave propagation, only one wave component, either $\boldsymbol{k}_0$ or $\boldsymbol{k}_g$ is dominant. However, if two lines are drawn from the incident point, directed along $\boldsymbol{k}_0$ and $\boldsymbol{k}_g$, respectively, the region of non-zero electric field is almost confined by these two lines, as sketched in Fig. 2(d). It may not always fill in the whole area between them, or the intensity may vary significantly inside the triangle depending on the particular conditions. We need to point out that the phenomena we have found are more *sophisticated* than negative refraction, double branching or multiple branching, although we have found under certain conditions, a well-directed beam is possible, as shown in Fig. 3. The beam scans over a wide angle while the incident beam rotates over a small angle. The condition for such a well-defined (or well-directed) beam in a weakly modulated grating or a photonic crystal is subject to more study.

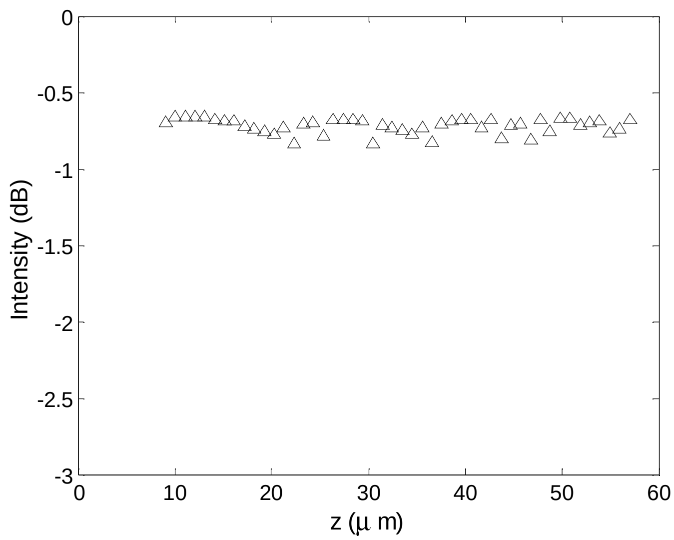
III. APPLICATION: low-loss wide angle bends for normal waveguides

For the application of photonic crystals in planar lightwave circuits, in order to match the mode size of fibers, one may consider keeping the ordinary channel waveguides as the "transmission lines", while utilizing the photonic crystals at "nodes" or special interest points, such as switching nodes, demultiplexing nodes, or as simple as a sharp bend. The theoretical prediction for the sharp bends in photonic crystal waveguides applies to a waveguide of one removed row wide [4], which corresponds to a field size about 1 to 2 microns for typical optical wavelengths. A typical fiber mode of a single-mode fiber has a diameter of about 10 μm. The mode mismatch is obvious. For a

10μm diameter fiber mode and 1μm diameter photonic crystal waveguide mode, assuming both are Guassian and circular, one computes a coupling loss of more than 10 dB per interface.



(a)



(b)

Figure 4 (a) Layout, a short waveguide at the bottom, followed by 3 layers of PC, then a long output waveguide. (b) Waveguide mode intensity calculated along the output waveguide (z axis pointing upward in subfigure a).

On the other hand, one aspect of the abnormal refraction phenomena that has not been paid attention to is the beam diameter required to observe the reported delicate angular sensitivity. One easily computes that for a typical fiber mode of 10 μm diameter traveling in a medium with refraction index around 1.5, the divergent angle is around 4º, assuming a free-space wavelength of 1.55 μm. This poses a serious problem for the utilization of superprism phenomena which have an angular sensitivity of 1 degree. In many experiments, the light have to be collimated to within 1º divergence before incidence onto the photonic crystal.[1] This would not be practical for actual integrated optical devices. An alternative is to consider a waveguide with 4 times the size of a regular waveguide, which gives a divergent cone half angle 1º. This requires to enlarge the waveguide dimension by 4 times, which results in multimode behavior and is unacceptable in most applications. We have discovered an application where both these two problems can be avoided. It is based on the beam zigzag illustrated in Fig. 2(b). By terminating the photonic crystal at the point where beam is completely converted to $\boldsymbol{k}_g$ wave, a wide beam deflection is achieved within a micron scale region. Consider a few-layer 2D photonic crystal composed of air holes in polymer(assume refractive index 1.5). with two waveguides on both sides, as shown in Fig. 4(a). The two waveguides have an angle 47.5º with respect to each other. The waveguide modes are 10 μm wide. One clearly sees that the light path turns a wide angle and exactly directs into the second (upper) waveguide. As shown in Fig. 5(b), the transmission loss is about 0.7 dB. Although it's not perfectly lossless, this structure illustrates that photonic crystals with dimensions higher than one can work with a fiber-compatible mode at very low loss. This device is compact in size. Also the efficiency is not sensitive to the fabrication error because the refraction of the beam depends mainly on first few Fourier components of the periodic index modulation, therefore insensitive to small perturbations. The reduced device size also eliminates the accumulation of loss along the propagation distance.

IV. CONCLUSION

We have supplied a new explanation for the fan shape light propagation pattern in a periodic structure, beam divergence is found not a necessary condition for fan shape. For narrow beams, zigzagging may occur(but such zigzagging will be smeared out in macroscopic scale and only fan shape is visible for human eyes). We also demonstrate that a photonic crystal based structure design that can work with waveguide modes of around 10 μm size. This structure is able to deflect light at a wide angle of 47.5º with less than 1dB insertion loss.

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