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Slight disorder effects in two dimensional photonic crystal structures

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ABSTRACT

In the actual manufacturing process of photonic crystal structure, unavoidable error can generate slight disorder which may influence the performance of photonic crystal based device. In this work, randomly distributional disorders are applied to the air holes in the photonic crystal structure. Based on this, we investigate the influence of the slight disorder on the photonic crystal band structure and the performance of photonic crystal based devices (waveguide and slab cavity). The studies indicate that the slight disorder provides small influence on the band structure of the photonic crystal. But, the random disorder in photonic crystal waveguide may increase transmission loss obviously when the wavelength of the light and the distribution of disorder break the balance of multiple interferences. Also, the slight disorder can reduce the Q factor of the photonic crystal cavity at a certain degree. The studies may provide some useful guides for further photonic crystal device research.

1. Introduction

Photonic Crystals (PCs) are structures with periodic dielectric materials distribution, which could inhibit the propagation of electromagnetic waves at a certain frequency owing to photonic band gap [1]. The photonic band gap occurs due to multiple constructive and destructive interference between multiple electromagnetic waves scattered from the surfaces within the PC structure [2]. In particular, local defects are introduced to break the lattice periodicity of the PC, which can be effectively used in light guide [3], delay [4] and store [5,6]. So PC structure has many promising applications, such as laser, optical circuit and solar cell. There are several methods to fabricate PC structures, including photolithographic etching, interference lithography, e-beam lithography and inductively-coupled plasma reactive-ion etching [7–9]. In fact, slightly eroded and dilated situations are unavoidable in practical manufacturing, which will generate disorder in PC structures. Moreover, the roughness of the dielectric interfaces is another source of disorder that can also influence the performances of the PC based devices. Therefore, investigations of slight disorder in PC structures are useful for guiding the practical applications of PC structures.

In recent years, much work has already been done to investigate the influence of disorder on the performance of PC based applications. For instance, the influence of positional disorder on the photonic band gap, defect characteristics, and wave guiding properties has studied by experiment [10]. Random high Q cavity has been obtained in geometrical disorder PC waveguide [11]. In theory, disorders in the radius, filling fraction, refractive index, and position have been introduced into PC waveguide property investigation [12]. And the positional disorder has been added into the calculation of the photonic band gap and the transmission property in PC waveguides [2,13,14]. Surface disorder and randomized positions have been employed to investigate the confinement of light in PC cavities [15]. All in all, disorder is an important issue for the practical application of PC structure.

Although the disorders in radius, position and geometry of the air holes have been extensively investigated, less work has been focused on the roughness induced disorder. The PC structure can be fabricated by using the ultrahigh resolution 1.25 nm of Vistec e-beam lithography [16], but the slight roughness in the air hole is still unavoidable. Recently, fabrication disorder (roughness) induced scattering loss in a PC waveguide has been investigated by theory and experiment [17–19]. Also a study about out of plane scattering in a fabrication disordered PC slab waveguide has been given [20]. In this paper, slight roughness induced disorders are randomly applied to the air holes in PC structure to approach the actual situation as much as possible. The effects of the slight disorder on the band structure of PC structure, the transmission property of PC waveguide and the Q factor of PC cavity are investigate by Finite Element Method (FEM). Band structure calculation and PC waveguide study are based on 2D model, and the PC cavity investigation

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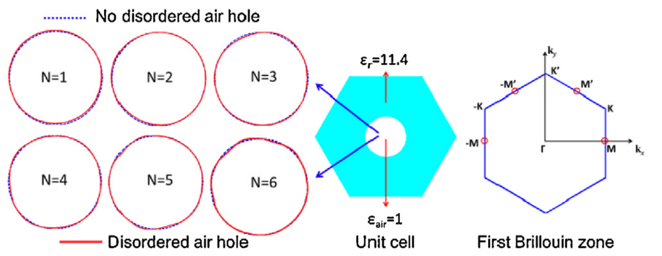

Fig. 1. The diagram of disordered air holes (left), the unit cell of the triangular lattice 2D PC structure (middle) and the high symmetry points on half of the first BZ (right).

is based on a 2D slab model. And all models are applied by fine mesh for obtaining the accurate results.

2. Slight disorder in 2D PC structures

In practical, the roughness of air hole is unavoidable in PC structures fabrication, which can influence the performance of PC based devices. In this section, the slight roughness is introduced in 2D PC structure for investigating the influence of roughness induced disorder on band structure, waveguide transmission and cavity Q factor. For TE mode propagation in a 2D PC structure, the common design is circular patterned air holes periodically etched in dielectric material. As shown in Fig. 1, the circular air hole in unit cell of the triangular lattice 2D PC structure can be described as $r(\theta)$, $\theta \in (0, 2\pi)$. Then the slightly disordered air hole can be described by

$$r_{\text{dis}}(\theta + 2\pi\eta) = r(\theta + 2\pi\eta) + \sum_{n}^{N} \delta\xi_n \sin(n\varphi_n),$$
$$\varphi_n \in (n-1, n)2\pi/N \tag{1}$$

where η and ξ_n are the random variables distributed between the interval 0 and 1, δ is the maximum deviation in radial direction, and $n = 1,2,3\ldots N$. The disorder is introduced by sine modulated deviation which will not change the air holes' filling rate. And N represent the number of the fluctuant deviation, in fact, $N = 6$ is enough to describe most disorder situations in 2D PC structure.

Firstly, we investigate the effect of disorder on the band structure of the PC structure. Here we assume that the disordered air holes are periodically distributed on the dielectric material. So one disordered air hole embedded within a hexagonal cell (as shown in Fig. 1) can be used for band calculation. The disordered air holes with $\delta = 0.01$ ($r = 0.3$) and $N = 1,2,3\ldots6$ are shown in Fig. 1. Obviously, disorder introduced air hole lead the dielectric pattern in unit cell losing high symmetry. For achieving full band structure of the PC structure, it is necessary to calculate the eigen value a least half of the first Brillouin Zone (BZ). In this paper, the 2D PC structure is formed by the periodic distribution of air ($\varepsilon_{\text{air}} = 1$) and no losses dielectric material ($\varepsilon_{\text{r}} = 11.4$ corresponding to GaAs). The unit cell (lattice constant $a = 1$) with six kinds of disordered air hole ($\delta = 0.01$, $N = 1,2,3\ldots6$) is used for calculating the band structure along the lines among the high symmetry points on half of the first BZ (as shown in Fig. 1). The full band structures for disordered and regular PC structures are shown in Fig. 2, which indicate that the slight disorder has small effect on the band structure of the PC. Moreover, the enlarged eighth band curves for regular and disordered PC ($N = 2$ for clearly exhibit only) indicate that the band structure of the disordered PC lose its symmetry on half of the first BZ and has slight deviation from that for regular PC.

In practice, disordered air holes are randomly distributed on PC structure, so the unit cell with one disordered air hole only can achieve qualitative analysis for band structure. For giving a more precise investigation, we employ the super cell (lattice constant $a = 9$) with six disordered air holes ($\delta = 0.01$, $r = 0.3$)

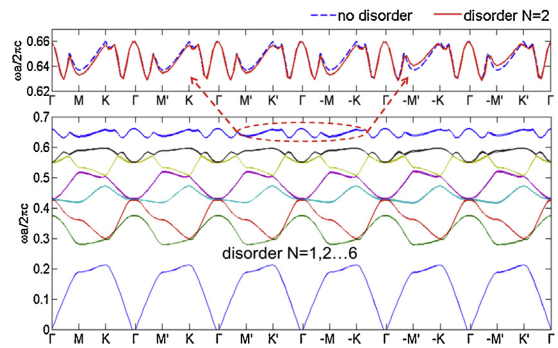

Fig. 2. The full band structures of disordered ($\delta = 0.01$, $N = 1,2,3\ldots6$) and regular PC structures (bottom), the enlarged eighth band curves for regular and disordered ($N = 2$) PC structures (top).

random distribution for band structure calculation. Because the band curves of super cell are complex and hard to exhibit, here we only calculate the band gap widths of the disordered and regular PC structures. The normalized band gap width of regular PC structure is 0.1593(2πc/a), and that for disordered PC structure is 0.1583(2πc/a). Here we randomly calculate 10 different kinds of disordered PC and obtain the same band gap widths. Larger disorder ($\delta = 0.02$) also investigated in periodically and randomly distributed PC structure, which provides more influence on the band structure, but still small.

3. Slight disorder in 2D PC waveguide

A commonly PC based device is PC waveguide which can be achieved by introducing line defect in a prefect PC structure. In order to investigate the influence of disorder on PC waveguide performance, the transmission character of disordered and regular PC waveguides are calculated in this section. The disordered air holes ($\delta = 0.01$) are random distribution, and several random disordered PC waveguides with one row air holes removed are investigated. Here, the transmission properties of only two representative disordered PC waveguide ($\delta' = 0.01$ and $\delta = 0.01$) are exhibited in Fig. 3. The transmission property of one kind of randomly disordered PC waveguide ($\delta = 0.01$) has small deviation from that for the regular PC waveguide. But for another disordered PC waveguide ($\delta' = 0.01$), the transmission has large deviation from the regular PC waveguide around normalized frequency 0.25(2πc/a). The H_z distribution at the abnormal frequency for disordered and regular PC waveguide indicate that the random disordered air holes around the line defect can influence the light propagation in the PC waveguide slightly (disorder $\delta = 0.01$) or seriously (disorder $\delta' = 0.01$). The randomly distributed disorders can change the distance between two air holes surface, which impede the wave scattering through periodic structure. When the multiple constructive and destructive interferences between those disordered scatters are balance, the disorder

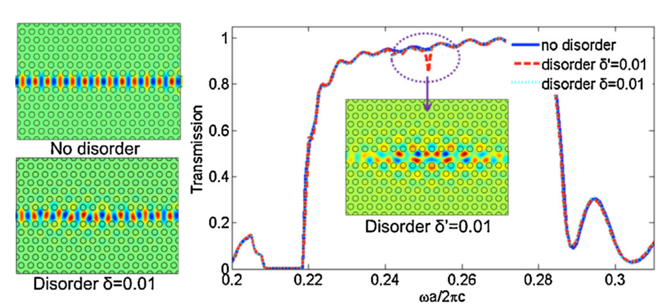

Fig. 3. The transmission properties of two representative disordered PC waveguide ($\delta' = 0.01$ and $\delta = 0.01$) and H_z distribution at the abnormal frequency for disordered and regular PC waveguide.