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Photonic bandgap properties of 8-fold symmetric photonic quasicrystals

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Abstract

The bandgap properties of 2D 8-fold symmetric photonic quasicrystals (PQCs) composed of a set of rods are numerically investigated for various fill factors, dielectric constants and propagation angles using the finite difference time domain (FDTD) method. Some interesting properties are found besides the known results: (i) the central frequency of the bandgap shifts to low frequency as r/a increases; (ii) an optimum fill factor to obtain the largest gap width exists, which decreases with increasing dielectric constant; (iii) compared with the behavior for a given fill factor, the variation of bandgap width for the optimum fill factor increases much more significantly with the dielectric constant. Selection guidelines for 8-fold symmetric PQC designs are provided for optimum fill factors and variation of the relative bandgap width at different dielectric constants.

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Keywords: Photonic quasicrystals; 8-Fold symmetry; Photonic bandgap property; FDTD method

1. Introduction

It is firmly established that photonic crystals (PCs) can support photonic bandgaps (PBGs). However, to achieve a complete PBG, materials with refractive index of $n > 2.0$ are required. In contrast, artificial photonic quasicrystals (PQCs) do not require such a high refractive index for a complete PBG. Recently, wide complete bandgaps with small refractive index have been demonstrated in PQCs with 8-fold [1–7], 10-fold [4,8] and 12-fold [9,10] symmetry. In the case of an octagonal quasicrystal composed of a set of rods, a complete PBG in TM polarization can be realized for a very small dielectric constant of $\varepsilon = 2.4$ ($n = 1.55$) [4]. Furthermore, the threshold value for the dielectric constant in such a system can be as small as $\varepsilon = 1.6$ ($n = 1.26$) to open a complete PBG [6]. This implies that novel PBG devices can be achieved for telecommunication optical materials and can be directly compatible with current optical fiber devices. In recent years, some of the optical properties of PQCs have been presented. Gauthier et al. [11] examined the propagation properties of 12-fold PQCs. Romero-Vivas et al. [6] studied the optical properties of 8-fold PQCs with various dielectric constants from 1 to 8. Hase et al. [4] demonstrated that the bandgaps of 8-fold PQCs are almost independent of the incident angle. Roper et al. [7] reported variations of the spectral position and width of photonic bandgaps with the size of the unit cell and fill fraction within the unit cell. However, less attention has been paid to the effect of the fill factor and dielectric constant on the position and size of the bandgap of 8-fold PQCs.

In this study, the bandgap properties of a 2D 8-fold symmetric PQC composed of a set of rods are numerically investigated for various fill factors, dielectric constants and propagation angles using the finite difference time domain (FDTD) method. In particular, the optimum fill factors are identified for different dielectric constants and variation

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of the bandgap width with dielectric constant for a given fill factor and for the optimum fill factors is addressed.

2. Results and discussion

The primary techniques used to simulate and obtain the band properties of photonic crystals are frequency and time domain analyses. For periodic crystals, plane wave expansion analysis in the frequency domain can yield the band structure within a reasonable computational time. However, the 8-fold PQCs examined here are non-periodic in the propagation direction. Thus, plane wave expansion analysis is not practical. Instead, the FDTD method with uniaxial perfectly matched layer (PML) boundary conditions can be used in all simulations [12]. To obtain the photonic band of PQCs, pulse excitation was chosen. The pulse is wide enough in the frequency domain to cover the range of normalized frequencies of interest.

The PQC investigated was an octagonal quasicrystal composed of a set of dielectric rods. As shown in Fig. 1, the rods represented by white circles stand normal to the x–y plane in air at each vertex of an octagonal quasiperiodic tiling pattern. This octagonal quasicrystal pattern is tiled by squares and rhombuses at an acute angle of 45°, with the sides of both the squares and rhombuses being the same and representing the lattice parameter a. The incident light is parallel to the x–y plane and its orientation relative to the x-axis is defined by the incident angle θ, which is sketched in Fig. 1. The incident angle is $\theta = 0°$ when the light is parallel to the x-axis.

Such an octagonal PQC possesses a full bandgap in TM polarization, while a very small bandgap in TE polarization [2]. Since the primary interest in photonic crystals is

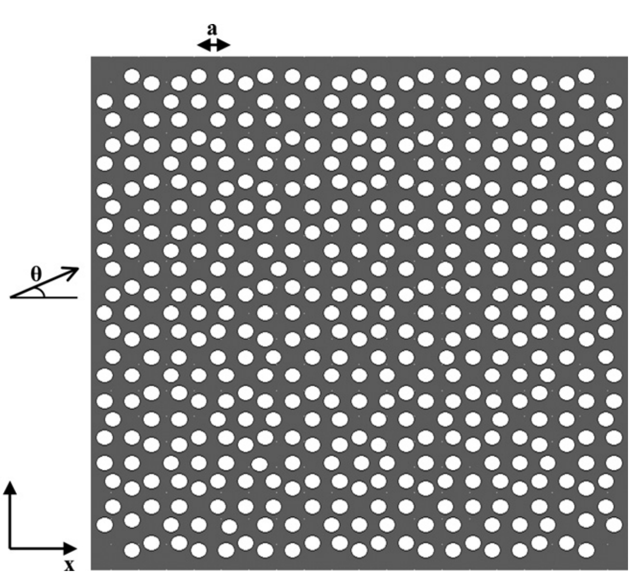

Fig. 1. The 8-fold symmetric quasi-periodic structure. Dielectric rods are depicted in white, while air is in black. An arrow indicates the direction of the incident light.

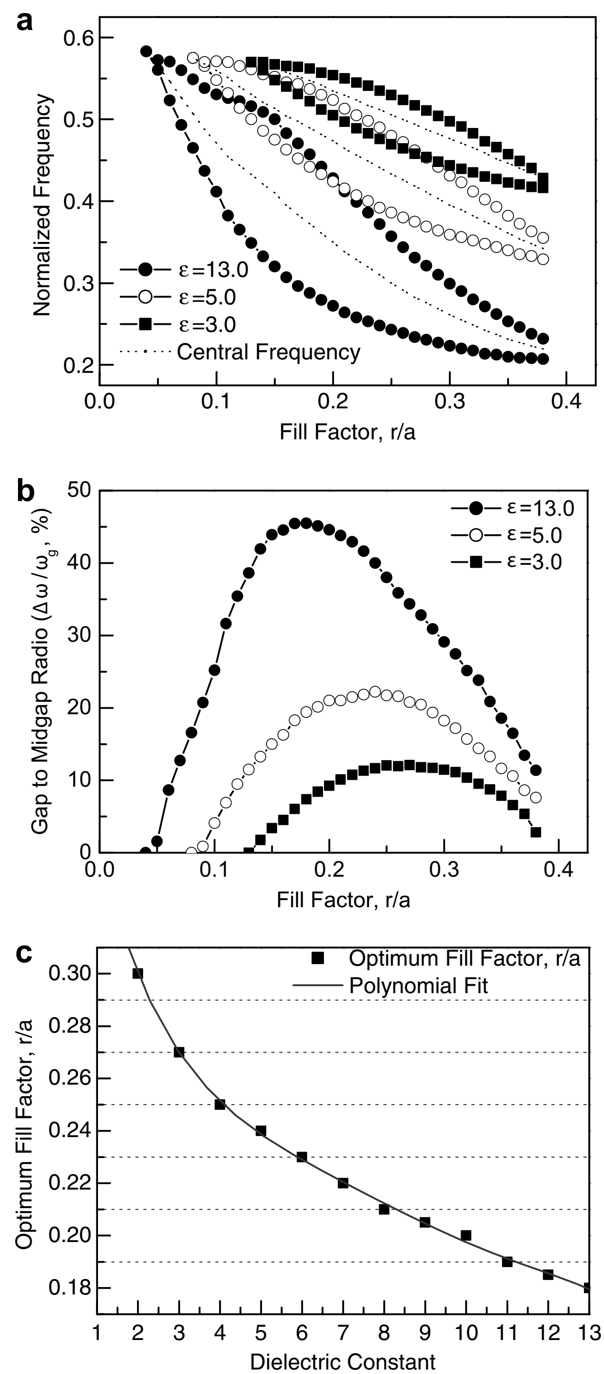

Fig. 2. (a) Band edges of the first bandgap as a function of the fill factor for selected value of ε in TM polarization. (b) Relative bandgap width as a function of the fill factor for selected value of ε. (c) Optimum fill factor as a function of the dielectric constant (points) together with an polynomial fit (line).

the study and exploitation of the bandgaps we focus on examining the large bandgaps for TM polarization.

The band edges of the first bandgap as a function of the fill factor r/a are plotted in Fig. 2a with three different dielectric constant of $\varepsilon = 3.0$, $\varepsilon = 5.0$ and $\varepsilon = 13.0$ for an incident angle of 0°. Fig. 2b shows the relative bandgap width $\Delta\omega/\omega_g$ as a function of the fill factor r/a. Here, $\Delta\omega$