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Effects of structural factors on filtering operation of photonic band gap air bridges with circular and square shape holes

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ABSTRACT

Applying the finite element analysis on the photonic band-gap materials with a cavity at the center for two types of structures, circular and square shape holes with the same cross section, filtering operation of these structures is simulated and compared. Any variations in the structure parameters, such as cavity length, period and hole dimensions, change the transmission peak and frequency bandwidth of these structures. The effects of rotation of square holes and ellipticity of circular holes on filtering operation are studied. Other new structures such as tapered, shortened and non-uniform rotated structures are proposed and filtering characteristics of them are discussed. It is found that, by rotating the square holes around their axis, it is possible to have a blue-shift in the transmission peak wavelength without notable variations in the filter peak and bandwidth. It is concluded that the increase of elliptical holes diameters length causes the decrease of transmission peak and increase of bandwidth with blueshift of the peak wavelength. This shift is larger for one of the elliptical diameter values considered that is along the waveguide length.

1. Introduction

Photonic crystals are proper optical devices with a periodic structure of the refractive indices made by different materials and with dispersion behaviors. The important effect reported in these structures is the existence of a stop band in the transmission spectrum. Such a region is called the photonic band-gap. There is an allowed frequency range between two successive photonic band-gaps so that in some proper conditions a propagating wave can be generated [1,2].

These crystals have some advantages, for example, they can be made in integrated form, able to control the optical wave propagations and their usages for designing the very low-threshold lasers [3]. Photonic crystal fibers [4] have large nonlinear characteristics. Usually, they can be used in the WDM optical communication systems for some proper operations such as super-continuum generation and four-wave-mixing (FWM). Recently, photonic crystals are used in RFs, tera-Hertz integrated circuits [5], couplers, demultiplexers, splitters and bending applications [6–11]. Indeed, optical switching is reported in the literature [12,13]. Photonic crystals with meta-materials are designed and fabricated by using the concept of Kerr effect [14]. In a polarization conversion device [5], one can use a photonic crystal structure with circular or square shape holes in the tera-Hertz frequency range.

Inserting a defect between the periodic structures of the photonic crystals makes them proper waveguides to support the waves with frequencies in the stop-band range. Using this idea, it is possible to design the optical filters with very sharp frequency responses [15,16].

In one of these structures, some circular air holes are inserted in the background of the dielectric waveguide, making an air-bridge photonic crystal structure. They are studied and simulated by using finite-difference-time-domain (FDTD) method [17]. In this paper, such structures are studied and simulated by finite element method (FEM) when two different air-bridge with circular (ABC) [18] and air-bridge with square (ABS) shape holes are used. Some other structures, such as ABS with twisted holes, tapered and chirped configurations are discussed too. Tunability of PC filters is a major challenge of designing optical devices of integrated circuits [19–21]. The purpose of the relevant researches is to design filters with high transmission and small bandwidth.

2. Theory

2.1. Structure description

Based on the proposed structure in [18], the waveguide dimensions, the hole periods P and the cavity or defect length D are the same for ABC and ABS structures as shown in Fig. 1.

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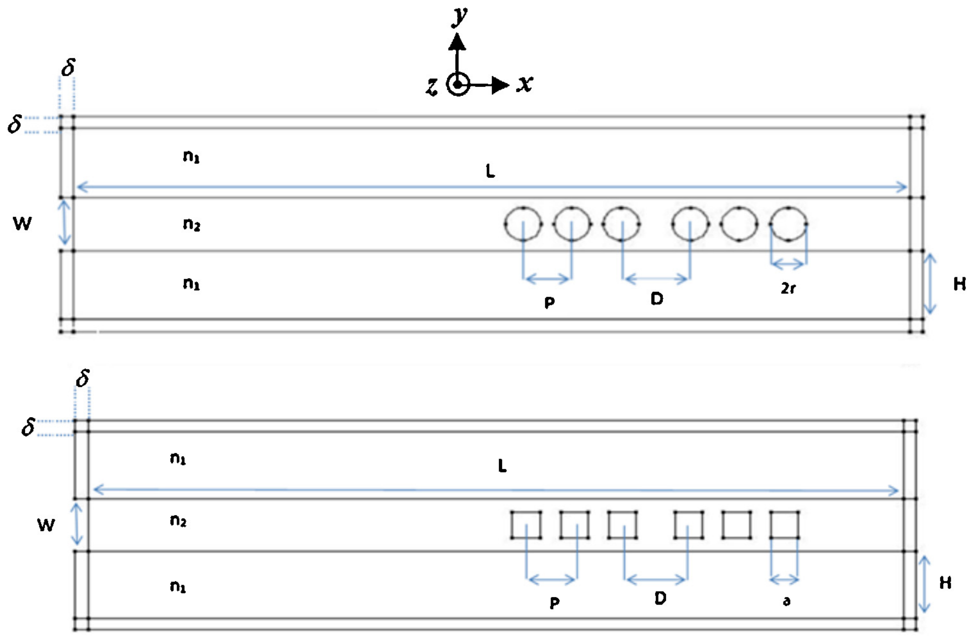

Fig. 1. Schematic diagram of ABC and ABS.

The dielectric silicon waveguide with a predefined index of n_2, a constant length L and width of W along x and y, respectively, is surrounded by air with a width of H. The air layers decrease the radiation losses [17]. Assume that the structure is infinite along the z-direction so that the variations for each field components are considered to be zero along this direction.

It is desirable to have not any reflected waves from the structure edges in an infinite PC which would be interfered with the incident field. Therefore, absorbing boundary conditions [22] are considered for this simulation around the main structure. The outer layer is covered by perfect magnetic conductor (PMC). To decrease the interferences between two incident and reflected waves of holes, we put the holes far from the exciting source.

In this simulation and with an infinite dimension, in such a way that there is not any reflected electromagnetic waves from the structure edges, but perfectly matched layers (PMLs) [23], with a thickness of δ, are used.

The key property of a PML that distinguishes it from an ordinary absorbing material is that it is designed so that waves incident upon the PML from a non-PML medium do not reflect at the interface – this property allows the PML to strongly absorb outgoing waves from the interior of a computational region without reflecting them back into the interior.

The refractive indices of these layers are matched with the neighboring layers, at the end of the dielectric waveguide with $n = n_2$ and air with $n = 1$.

Define ρ as the distance from the PML edge. To diminish the electromagnetic waves inside these layers, the electrical conductivity must be chosen as:

$$\sigma(\rho) = \sigma_m \left(\frac{\rho}{\delta}\right)^2 \tag{1}$$

where σ_m is the maximum value of σ at $\rho = \delta$ with the optimum of [23]

$$\sigma_{opt} \cong \frac{K}{\eta} \tag{2}$$

where η is the characteristic impedance and K is a constant related to the PML order.

2.2. Source description

To prevent the wave scattering in the simulation region and considering the practical conditions, a wave generator is used at the input port of the waveguide. Define the input magnetic field pulse as:

$$H(\lambda, y) = H(\lambda) \times H(y) \tag{3}$$

Its wavelength-dependency has Gaussian shape with the following definition:

$$H(\lambda) = \exp\left(-\frac{(\lambda - \lambda_0)^2}{\gamma}\right) \tag{4}$$

where λ_0 is the central frequency and γ is a constant to cover a wide frequency range. In a case of single-mode guide this source must be considered in the form of [24]:

$$H(y) = \cos(\kappa y) \tag{5}$$

where κ is chosen based on the source width (equal to the waveguide width). Wave propagation is in the x-direction and TM mode is considered in this simulation. Therefore, the desired output is the z-component of the magnetic intensity, H_z, with the following equation:

$$\nabla \times \left(\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)^{-1} \nabla \times H_z\right) - \mu_r k_0^2 H_z = 0 \tag{6}$$

where $\mu_r = 1$, ω is the angular frequency and $n = \sqrt{\varepsilon_r}$ is the refractive index of region.

3. Numerical simulation

To simulate the structure and based on the mesh generation around the corners, field analysis is done by using FEM used in many researches [25–27]. Applying the z-component of magnetic field at the waveguide input, H_{zin}, and computing the output field at the end hole gives the transmission pulse in the form of

$$Transmission = \left|\frac{H_z}{H_{zin}}\right|^2 \tag{7}$$