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Slow light in photonic crystals waveguide constructed with symmetrically perturbed structure

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ABSTRACT

Symmetrically perturbed photonic crystal waveguide can be constructed by inserting perturbative dielectric rods into photonic crystal waveguide structure with whose rods' radius distributed according to a certain proportion. Slow light properties in this new structure are studied by using the plane wave expansion method (PWM). In this paper, schemes of adjusting radius of perturbative dielectric rods and adjusting the dielectric constant of perturbative dielectric rods are proposed to optimize slow light properties. The result shows that the scheme for adjusting radius of perturbative rods can realize larger average slow light bandwidth and efficiently control the NDBP value of the waveguide, but it contributes little to obtain smaller group velocity. The scheme for adjusting dielectric constant of perturbative rods can realize smaller group velocity, but can only obtain smaller slow light bandwidth and cannot efficiently enlarge NDBP value of waveguide. Both optimization schemes proposed in this paper realize group velocity that is two magnitudes smaller than the vacuum speed of light meanwhile maintaining large NDBP and low GVD region. Our results provide important theoretical basis for the potential application offered by symmetrically perturbed photonic crystal in future optical networks.

1. Introduction

One of the greatest properties offered by photonic crystal is slow light effect [1], which can be applied into various optical devices. Compared to other methods to realizing slow light such as electromagnetically induced transparency effect (EIT), semiconductor optical amplifier (SOA) [2], light travelling in photonic crystal is restricted by band gap, which owns higher transmission efficiency and thus slow light in photonic crystal has great potential in optical buffers, light switches and nonlinear optical devices [3]. Recently optimization for slow light properties such as group velocity, group velocity dispersion and NDBP mainly focus on varying the symmetry of photonic crystal, including changing dielectric constant of rods, changing radius of rods or making radius distributed according to a certain proportion [4,5]. The group velocity in paper mentioned above is only one magnitude smaller than the light in vacuum, and the decreasing of light narrows the bandwidth of slow light and usually accompany with large GVD [6]. Due to the fact that the symmetry variation realized by inserting radius perturbative dielectric rods into photonic crystal structure can efficiently enlarge band gap and obtain better slow light properties [7,8]. In this paper a new method to vary structure's symmetry is proposed by inserting radius perturbative dielectric rods into photonic crystal waveguide with whose radius of dielectric rods distributed according to a certain proportion, and the slow light parameters such as group velocity, group velocity dispersion and NDBP in our new designed waveguide are researched and compared in the following section.

2. Model of symmetrically perturbed photonic crystal waveguide

2.1. Physical model

The process of constructing symmetrically perturbed photonic crystal waveguide structure used in this paper can be divided into of three parts: Firstly, as shown in Fig. 1(a), photonic crystal with its radius distributed according to a certain proportion ($R_1 : R_2 : R_3 = 0.1a : 0.3a : 0.2a$) is constructed with air as the background and dielectric constant of rods is $\varepsilon = 11.9$ (S_i). Secondly, as shown in Fig. 1(b), based on the photonic crystal structure mentioned above, by inserting perturbative dielectric rods (the radius of rods r is $0.05a$, where a is the lattice constant) into the primitive cell of photonic crystal structure mentioned above, we can get the intact symmetrically perturbed photonic crystal structure shown in Fig. 1(b). Fig. 1(c) shows the calculated band diagram of Fig. 1(b). It can be found that our proposed intact symmetrically perturbed photonic crystal waveguide structure exhibits a band-gap for TM-like modes between $0.230(\omega a/2\pi c)$ and $0.289(\omega a/2\pi c)$.

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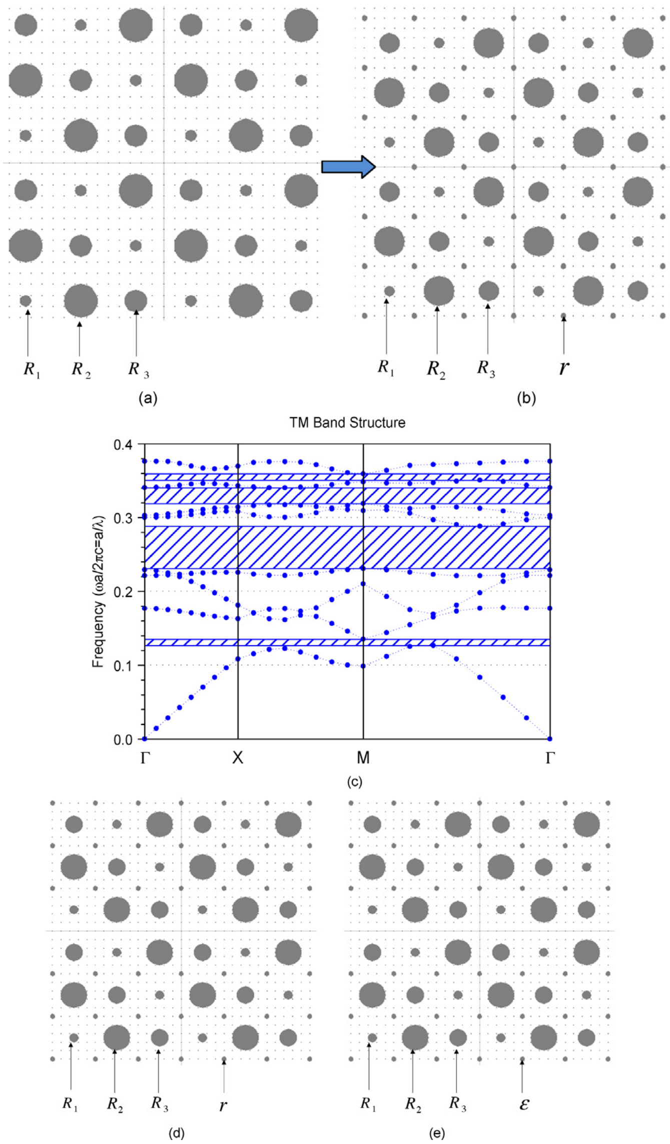

Fig. 1. Physical model of symmetrically perturbed photonic crystal. (a) Structure of photonic crystal with the radius of its rods distributed according to proportion as $R_1 : R_2 : R_3 = 0.1a : 0.3a : 0.2a$; (b) structure of intact symmetrically perturbed photonic crystal; (c) Band diagrams; (d) first optimization: adjusting the radius of perturbative dielectric rods; (e) second optimization: adjusting the dielectric constant of perturbative dielectric rods.

Finally, by removing a line of perturbative dielectric rods in Fig. 1(b), the intact symmetrically perturbed photonic crystal waveguide structure is constructed. In this paper, methods of adjusting the radius and the dielectric constant of perturbative rods are proposed by two methods to optimize slow light properties; the two schemes are shown in Fig. 1(d) and (e), respectively. In Fig. 1(d), we identify the radius of perturbative rods as r and the dielectric constant of perturbative rods as ε. In Fig. 1(d), keep the dielectric constant of all rods as $\varepsilon = 11.9$, studying the regularity of slow light properties in symmetrically perturbed photonic crystal waveguide structure when r changes between $0.01a$ and $0.06a$ with an increment of $\Delta r = 0.01a$. In Fig. 1(e), keep the radius of perturbative rods as $r = 0.05$, studying the regularity of slow light properties in symmetrically perturbed photonic crystal waveguide structure when ε varies among 8.9(Al_2O_3), 10.8,11.9,13,16 and 20(which are common photonic materials as Al_2O_3 InP S_i GaAs,Ge and Fe_3O_4), respectively.

2.2. Mathematical method

The dispersion relation for TE polarized in symmetrically perturbed photonic crystal waveguide is calculated by the plane wave expansion (PWE) method with supercell [11]. The group velocity of the guided mode can be obtained by the inverse of the first-order dispersion as:

$$v_g = \frac{c}{n_g} = \left(\frac{\partial k}{\partial \omega}\right)^{-1} \tag{1}$$

where ω and k is normalized frequency and wave vector, respectively. By inserting the equation of wave vector $k = \omega \times (n/c)^{-1}$ into Eq. (1), the definition of group index can be obtained as:

$$n_g = c\frac{d\omega}{dk} = \frac{d(n\omega)}{d\omega} = n + \omega\frac{dn}{d\omega} \tag{2}$$

Group index is an important parameter of slow light, which describes the degree of decelerating of light. Group index can be called as slow down factor as well. If we try to get slow light, n_g or $\omega\left(dn/dw\right)$ in Eq. (2) must be increased, while $\omega\left(dn/dw\right)$ in Eq. (2) can be easily achieved by increase the first order dispersion of the material, thus slow down factor can be increased accordingly. The group velocity dispersion (GVD) is another important parameter of slow light, it can be described by β_2 or D_λ

$$\beta_2 = \frac{\partial^2 k}{\partial \omega^2} \tag{3}$$

$$D_\lambda = -\frac{2\pi c}{\lambda^2}\beta_2 = -\frac{2\pi c}{\lambda^2}\frac{\partial^2 k}{\partial \omega^2} \tag{4}$$

Usually light travelling in photonic crystal carries various kinds of frequency, which is called wave packet. Thus the shape of wave packet is varying when light travels in photonic crystal. On the condition of large GVD wave packet will dissolve quickly and brings distortion in signal. Therefore GVD should be efficiently decreased.

The concept of normalized delay-bandwidth product (NDBP) a good indicator to describe the ability of storage/delay of slow light device [12]:

$$\mathrm{NDBP} = \bar{n}_g \times \frac{\Delta\omega}{\omega_0} \tag{5}$$

where the $\bar{n}_g$ in Eq. (5) is the average group index [13]:

$$n_g = \int_{\omega_0}^{\omega_0+\Delta\omega} n_g(\omega)\frac{d\omega}{\Delta\omega} \tag{6}$$

where $\Delta\omega$ is the bandwidth with the central frequency of ω_0.

By combing Eqs. (2) and (5), if n_g is much larger than n, so $n_g \cong \Delta n/\left(\Delta\omega/\omega\right)$. Considering that Δn is a constant, thus larger n_g can be obtained only when the bandwidth of slow light $\Delta\omega/\omega_0$ is very small. Therefore, slow down factor and the bandwidth of slow light are mutually exclusive, that is to say the decreasing of group velocity of light constricts the enlargement of bandwidth, and enlarging bandwidth will increase group velocity of light. Thus a compromise between bandwidth and group velocity of light in needed. Due to the fact that photonic crystal is a periodic arrangement of media with differing dielectric constants, the symmetry of photonic crystal is affected by structure parameter, and then we can get the optimization of slow light bandwidth and group velocity by varying the symmetry of photonic crystal. In the following section, we will analyze optimization schemes in detail and show their improvement effects on the slow light properties.