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Slow light in nonlinear photonic crystal coupled-cavity waveguides

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ABSTRACT

Nonlinear photonic crystals can be formed by inserting Kerr-type nonlinear dielectric rods into perfect photonic crystals. Based on nonlinear photonic crystal, nonlinear photonic crystal coupled-cavity waveguide is constructed and its slow light properties are studied by using the Plane Wave expansion Method (PWM). Both single-defect coupled cavity and two-defect coupled cavity are proposed to optimize slow light properties. The result shows that using single-defect coupled cavity in waveguide is beneficial to obtain larger Normalized Delay-Bandwidth Product (NDBP) but it contributes little to decrease the group velocity of light and enlarging Q factor and delay time; While using two-defect cavity in waveguide can efficiently reduce the group velocity of light and enlarge Q factor and delay time. Compared to normal structures, our new designed nonlinear photonic crystal coupled cavity waveguide owns group velocity that is three magnitudes smaller than the vacuum speed of light. Delay time is of magnitude order of 10 ns and Q factor is of magnitude order of 1000, it means less loss and higher ability of storing energy.

1. Introduction

A photonic crystal [1] is a periodic arrangement of media with differing dielectric constants, one of its most important properties is slow light effect. In recent years, due to the great potential in realizing optical delay lines [2], optical buffers and digital processing [3], light with lower velocity in photonic crystal waveguides gradually attracted widespread interest. Many approaches have been proposed to realize slow light, including Electromagnetically Induced Transparency Effect (EIT), Semiconductor Optical Amplifier (SOA), the nonlinear gain in optical fibers, photonic crystal waveguide, etc. [4–6]. Among these approaches, photonic crystal waveguide is particularly interesting because it can generate slow light at room temperature and precisely manipulate the dispersion relation of the guided modes by subtle structural modification. In this paper we mainly research on slow light properties in Photonic Crystal Coupled-Cavity Waveguides (PC-CCW).

Compared to Photonic Crystal Line Defect Waveguide (PCW), slower group velocity can be obtained in PC-CCW [7]. Recent research on PC-CCW mainly focus on the effect of structural modification on slow light properties, such as filling factor, cavity spacing, etc. [8–10]. Papers mentioned above got lower group velocities (two orders of magnitude smaller than vacuum speed of light) at the expense of bandwidth of slow light, and Q factor offered in these papers are the order of magnitude of 100. Due to the high mode energy and better slow light properties owned by nonlinear photonic crystals [11,12], based on nonlinear photonic crystal, a new nonlinear PC-CCW with either single-defect cavity or two-defect cavity is constructed to realize slow light waveguide with low group velocity, high Q factor and large NDBP. The regulation of slow light parameters mentioned above in our new nonlinear PC-CCW is of great significance for further research on nonlinear photonic crystals.

2. Model of nonlinear photonic crystal coupled-cavity and mathematical methods

2.1. Physical model

The intact nonlinear photonic crystal coupled cavity structure used in this paper can be obtained by the following method: firstly, by inserting rods made from a Kerr-type nonlinear dielectric material into perfect photonic crystal (shown in Fig. 1(a)), we can get Fig. 1(b), whose topology is constructed by the overlay of the square lattice B with Kerr-type nonlinear rods of radius R_B on top of the square lattice A with linear rods of radius R_A. The added lattice B has the same lattice constant a, but is displaced with respect to the lattice A by $a/\sqrt{2}$ along ΓM direction. The dielectric constant of rods used in this work is air ($\varepsilon=1$), and $R_A=0.35a$, $R_B=0.12a$, where the dielectric constant of background is $Bi(GeO_4)_3$ ($\varepsilon=16$). Fig. 1(c) shows the calculated band diagram for the nonlinear photonic crystal that has been designed. It can be found that our proposed nonlinear photonic crystal geometry

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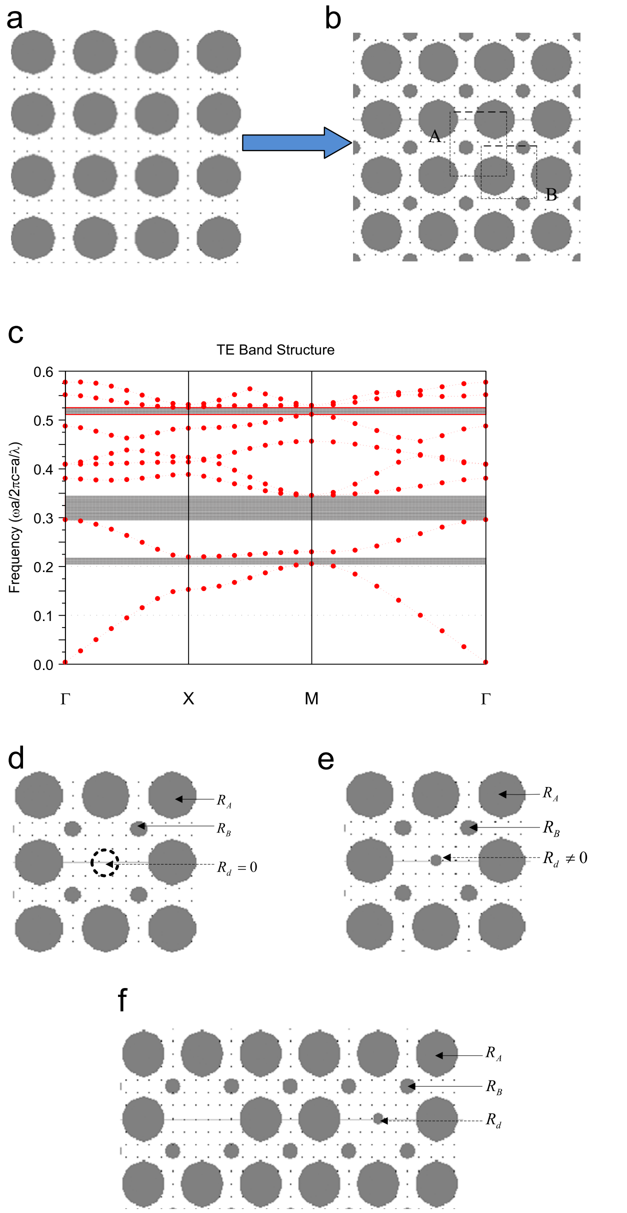

Fig. 1. Physical model of nonlinear photonic crystal coupled cavity structure. (a) Perfect photonic crystal structure, (b) Intact nonlinear photonic crystal structure, (c) Band diagrams, (d, e) Single-defect cavity and (f) Two-defect cavity.

exhibits a band-gap for TE-like modes between 0.2955 ($\omega a/2\pi c$) and 0.3454($\omega a/2\pi c$).

Secondly, by removing the center rod or changing the radius of center rod of the structure mentioned above we can obtain the intact nonlinear photonic crystal coupled cavity structure with single-defect cavity (shown in Fig. 1(d) and (e)) and two-defect cavity (shown in Fig. 1(f)). We identify the radius of center rod in cavity as R_d and the increment of R_d as $\Delta d = 0.02a$, studying the regularity of slow light properties in both single-defect cavity and two-defect cavity when R_d increases from $0.08a$ to $0.14a$.

2.2. Mathematical method

The dispersion relation for TM polarized in the PC-CCW is calculated by the Plane Wave Expansion (PWE) method with supercell [13]. Firstly we introduce the nonlinearity into the dielectric permittivity as an addition to the linear dielectric constant:

$$\varepsilon(r) = \varepsilon_L(r) + \varepsilon_{NL}(r) \tag{1}$$

where $\varepsilon_L(r)$ is the linear part of dielectric constant and $\varepsilon_L(r)$ is the Kerr nonlinear part of dielectric constant. Let us reconsider the Helmholtz problem defined in the strip, where the eigenvalue ω_{k_x} lies in the band gap. The mode profile $E(r|\omega_{k_x}, k_x)$satisfies:

$$\left[\nabla^2 + \left(\frac{\omega_{k_x}}{c}\right)^2 \varepsilon_L(r)\right] E(r|\omega_{k_x}, k_x) = -\left(\frac{\omega_{k_x}}{c}\right)^2 \varepsilon_{NL}(r) E(r|\omega_{k_x}, k_x) \tag{2}$$

Using the theory of supercell algorithm, it is possible to transform this partial differential equation into an integral equation:

$$E(r|\omega_{k_x}, k_x) = \left(\frac{\omega_{k_x}}{c}\right)^2 \int g(r, u|\omega_{k_x}, k_x) \varepsilon_{NL}(u) E(r|\omega_{k_x}, k_x) d^2u \tag{3}$$

With $g(r, u|\omega_{k_x}, k_x)$ is the green function of the supercell algorithm. From paper [11], we model the nonlinearity as:

$$\varepsilon_{NL}(r) = -\delta_{rod}(r) |E(r|\omega_{k_x}, k_x)|^2 \tag{4}$$

where δ_{rod} is 1 inside the rods containing nonlinear material and zero outside. The size of the nonlinear rods in the photonic crystal is assumed to be sufficiently small so that the electric field can be considered constant inside the rods. We number a center rod as 0, thus an approximate discrete nonlinear equation for the electric field in rod n can be written by inserting Eq. (4) in Eq. (3) and by averaging over the rods:

$$E_n(\omega_{k_x}, k_x) = -\sum_m J_{n,m}(\omega_{k_x}|k_x)|E_m(\omega_{k_x}, k_x)^2 E_m(\omega_{k_x}, k_x)| \tag{5}$$

In Eq. (5), $J_{n,m}$ the coupling coefficient, describes the interaction between rod n and m. Due to the symmetry and periodicity of the Green's function and considering the symmetry of the photonic crystal strip, the coupling constant only depends on the distance between two rods, reducing $J_{n,m} = J_{|n-m|}$:

$$J_l(\omega_{k_x}, k_x) = \left(\frac{\omega_{k_x}}{c}\right)^2 \int g(r_0, r_1 + u|\omega_{k_x}, k_x) d^2u \tag{6}$$

where r_1 is denoting the center of rod 0.

In order to get the dispersion relationship of photonic crystal, we can only obtain one eigenvalue equation of Eq. (5). Then change the value of k and n along the Brillouin boundary and repeat the calculation steps. Finally we can obtain the band diagram. In next step we will discuss slow light properties including group velocity, dispersion, and Normalized Delay-Bandwidth Product (NDBP) in PWE:

Form the theory of supercell algorithm, the group velocity of the guided mode can be obtained by the inverse of the first-order dispersion as

$$v_g = (\partial k / \partial \omega_{k_x})^{-1} \tag{7}$$

where ω_{k_x} and k is normalized frequency and wave vector, respectively.

In photonic waveguide, due to the fact that different components in a single pulse carries different group index, thus the degree of decelerating differs from components to components. Therefore pulses will be distorted after the decelerating time. Consequently the coefficient of Group Velocity Dispersion (GVD) must be considered:

$$\beta_2 = d^2k/d\omega_{k_x}^2 = -(1/v_g)^3 \times d\omega_{k_x}^2 / d^2k \tag{8}$$

Though bigger bandwidth is welcomed, large bandwidth usually companies with high group velocity, indicating that enlarging bandwidth and decreasing group velocity are mutually exclusive. Thus the concept of Normalized Delay-Bandwidth Product (NDBP) is proposed. First the average group index can