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Slow-light transmission with high group index and large normalized delay bandwidth product through successive defect rods on intrinsic photonic crystal waveguide

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ABSTRACT

We proposed a strategy with successive cavities as energy reservoirs of electromagnetic energy and light-speed reducers introduced in the first and second rows of rods on the walls of an intrinsic photonic crystal waveguide (PCW) for slow-light transmission in the PCW concerning applications for optical communication, optical computation and optical signal processing. Subsequently, plane-wave expansion method (PWE) is used for studying slow-light properties and finite-difference time-domain (FDTD) method to demonstrate the slow-light propagating property of our proposed structure. We obtained group index as exceedingly large as 6123 with normalized delay bandwidth product (NDBP) as high as 0.48. We designed a facile but more generalized structure that may provide a vital theoretical basis for further enhancing the storage capacity properties of slow light with wideband and high NDBP.

1. Introduction

Slow light has great significance in the next generation of optical devices and hence received a considerable attention from the scientific community. Slow light in photonic crystal waveguides (PCWs) has a wider bandwidth as compared with that by other mechanisms for instance electromagnetically induced transparency [1], stimulated Brillouin scattering [2] and stimulated Raman scattering [3]. The PCWs have attracted significant attention due to their numerous and diverse applications in optical buffers for optical computation and optical signal processing [4,5]. Introducing properly arranged rods of shaped defects with different types of extrinsic material inside an intrinsic photonic crystal (PhC) can lead to two mechanisms for confining the light within the waveguide: [6], index guiding of modes [7] and gap guiding of modes. For the index guiding mechanism, the guided modes of PCWs are defined by total internal reflection [8] of light at the interface between a high- and a low-index medium. Gap guiding of modes occurs in a line defect channel with photonic bandgap regions surrounding the line defect [9,10]. The combination of the two guiding effects can be used for shaping the guided modes in a waveguide [9]. However, to obtain satisfied slow-wave property, other measures have to be introduced in the waveguide. In this paper, we introduce a series of defect rods to form a series of cavity loads as energy reservoirs of electromagnetic energy to a conventional PCW, also called intrinsic PCW, to improve the slow-wave property of the waveguide, as shown in Fig. 1(a). Accordingly, the influence of the defect rods can be optimized to obtain wide bandwidth, high group index and large normalized delay bandwidth product (NDBP). The unit cavity is formed by a defect rod, also called as extrinsic rod, and its surrounding regular rods, also called as intrinsic rods. The reason for each defect rod in a PhC can lead to a cavity because there is wave localization in the defect rod, while wave localization is equivalent to the wave behavior in a cavity. These extrinsic dielectric rods are arranged in the form of a wave to maximize the slow wave effect. As is known, a cavity can store energy and a certain amount of time is required to store energy into a cavity, therefore, the successive cavities loaded on an intrinsic PCW can greatly slow down the speed of light traveling in the complex waveguide proposed.

2. Physical model and theoretical method

Slow-light phenomena in photonic devices has an important application for optical signal processing and reduction of device sizes and power consumption. Therefore, dispersion and slow light based on PCWs play a critical role in the field of optical communication and optical signal processing. The dispersion relation of modes carried dielectric

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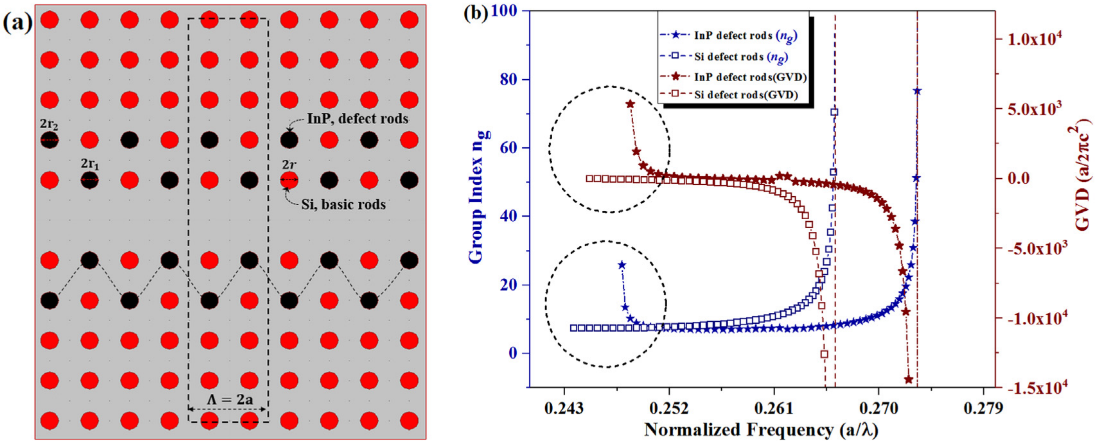

Fig. 1. (a) Schematic structure diagram of PCW with extrinsic defect rods (black color) of the first and second rows into intrinsic rods (red color) where $\Lambda = 2a$ and the dashed rectangle indicates the boundary of the supercell selected for PWE calculations; (b) slow-light properties ($\bar{n}_g$, GVD) versus normalized frequency for PWC without extrinsic defect rods (square shape) and PCW with extrinsic defect rods (star shape). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

properties of extrinsic material, intrinsic PhC and geometry of PhC structures. For optimization of these parameters for slow-light mode at nearly constant slope in dispersion relation, we consider an intrinsic square-lattice PhC ($10a \times 11a$) from dielectric (Si, index 3.46) rods (with radius $r = 0.22a$ where a is the lattice constant) entrenched in an air background. By removing the central row of rods in the PhC, a W1 PCW is obtained. The proposed extrinsic defect rods of InP semiconductor material with refractive index of 3.1, are in the first and second rows as shown in Fig. 1(a). The dashed rectangular shape in Fig. 1(a) is a supercell ($2a \times 10a$), that has been selected for plane-wave expansion (PWE) method calculations, where $\Lambda = 2a$. Mostly, we will focus on adopting the performance of slow-light on point and line defects at the same time. Based on this property, we will achieve matching among the cavities and the intrinsic waveguide for slow light. Generally, we can categorize our strategy in three steps: firstly, doping intrinsic PCW by extrinsic defect rods to see their influence on group index and group velocity dispersion (GVD). The distribution of extrinsic defect rods must be in such a way that can lead to positive and negative GVD at different frequencies so that at some frequencies the GVD can be approximately zero. Secondly, change the radius of the defect rods in the cavities that are lined up along the first row on the walls of the PCW. Finally, to optimize the effect of second row cavities on GVD and bandwidth, we fix the radius of the defect rods in the cavities on the first row on the walls of the PCW at the highest value of bandwidth and change the radius of the cavities that are lined up along the second row.

One important factor for device applications based on slow-light PCWs is the group velocity v_g, defined as the inverse of the derived wavenumber (k) with respect to angular frequency (ω):

$$v_g = \left(\frac{dk}{d\omega}\right)^{-1} = \frac{C}{n_g} \tag{1}$$

where n_g is the group index and v_g is considered as the group speed of light in the medium (PhC). For a medium with group velocity v_g depending on frequency, it is called as a medium with GVD. The GVD is a characteristic of a dispersive medium and defined by the derivative of the inverse of the group velocity with respect to angular frequency:

$$GVD = \frac{a}{2\pi c^2}\frac{dn_g}{dU} = \frac{a}{2\pi c}\frac{d}{dU}\left(\frac{1}{v_g}\right). \tag{2}$$

From the dispersion curves of PCWs, n_g and GVD parameters can be obtained as a function of normalized frequency U defined as $U = \omega a/2\pi c = a/\lambda$. The full description of slow light in PCWs is best categorized by using group index, normalized bandwidth, GVD and NDBP [11]. These parameters directly affect the system performance. For high bit-rate operation, a wide bandwidth is required for numerous nonlinear applications depending on the group index [12]. Nevertheless, the group index and bandwidth are inversely proportional for a given structure; consequently, the NDBP is indispensable for quantify the performance of slow light and it is defined as the product of average group index n_g and normalized bandwidth $\left(\Delta\omega/\omega_0\right)$:

$$NDBP = \bar{n}_g \cdot \frac{\Delta\omega}{\omega_0} \tag{3}$$

where n_g is closely within ±10% [13]. This range is sensible since most of the applications are restricted by the propagation loss issue rather than by a dispersion issue [11].

3. Simulation results and analyses

For further investigation, the influence of introducing the extrinsic material based defect rods on the slow-light performance of PCW was studied in detail. We found that the best mode was for inserting InP rods (Fig. 1a) arranged like the shape of a wave through the first and second rows on the walls of the intrinsic PCW. The GVD and n_g with and without defect rods are illustrated in Fig. 1(b). We can observe clearly from this result that the InP defect rods provided a positive GVD and a negative GVD, which are important for dispersion compensating applications [14]. Nonetheless, the positive GVD is less than 10^4as shown in the inset circle in Fig. 1(b). Next, we move to find the appropriate conditions to generate GVD in the range of $-10^7 \sim 10^7$ with high group index. The target is achieved by changing the radius r_1 of defect rods in the cavities in the first row while keeping the radius of defect rods in the cavities in the second row as $r_2 = r = 0.22a$. The radius r_1 is changed in the range $\left(0.080a \le r_1 \le 0.105a\right)$ with the step $0.005a$. We only studied this range because the purpose of our structure is to generate GVD in the exceeding range of $-10^7 \sim 10^7$. Dispersion curves are obtained by using PWE method with supercell treatment [15,16].

Fig. 2(a) shows the calculated dispersion diagram for varying r_1 according to the values aforementioned. We have clearly indicated that the dispersion curve of the guided mode is moving down to occupy the area of lower-frequency as r_1 increases. The n_g and GVD are the first and second derivatives of the dispersion relation. Consequently, a wider bandwidth can be obtained with a closely constant slope of dispersion curve, i.e., we can obtained flat band with large NDBP. The n_g and GVD for $0.080a \le r_1 \le 0.105a$ are shown in Fig. 2(b, c) and NDBP values with slow-light properties are illustrated in Table 1. We can see clearly from Fig. 2(b) and (c) that the values of group index increase and the bandwidth with flat band decrease with increasing radius r_1 while keeping $r_2 = r = 0.22a$. As can be seen from Table 1, the highest value of $\bar{n}_g$ is 233.54 at $r_1 = 0.105a$ matching with the lowest