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Design of high-Q polystyrene nonlinear cavity for ultrafast all-optical switching in mid-infrared photonic crystal slabs with cavity-waveguide structure

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ABSTRACT

In this study, we design a nonlinear cavity with ultrafast response speed material in photonic crystal slabs for all-optical switching. We consider triangular lattice photonic crystal slab made from air holes in anisotropic Tellurium background which is on top of Teflon substrate. The cavity itself is then created by enlarging one of the air holes and infiltrating it with polystyrene. Optimization of structural parameters yields a single mode cavity with quality factor of $Q = 2.5 \times 10^4$, by using the three-dimensional finite-difference time-domain (FDTD) simulation and filter diagonalization approach. This shows great enhancement compared with previous studies in which organic polymer materials have been used. In order to study the coupling characteristic of cavity mode and waveguides, the nonlinear cavity is placed between two waveguides, symmetrically. At the end, we used the FDTD method to investigate shift magnitude of cavity mode resonance frequency under pump light. The designed structure can be helpful to achieve extremely fast response speed in all-optical switching devices with high efficiency in the mid-infrared wavelength range.

1. Introduction

Over the past two decades, photonic crystals (PCs) have been attracting significant interest due to special and applicable properties [1]. PCs are artificially prepared materials with spatially periodic distribution of dielectric permittivity. Analogous to semiconductors energy band gap for electron, PCs are characterized by a region of the frequency spectrum where propagating modes are forbidden which is called photonic band gap (PBG) [2]. Since photons in contrast to electrons are not easily controllable, the analogy between semiconductors and linear PCs cannot be pushed too far. Hence, the challenge is to perfectly control the propagation of light. To cope with this difficulty a novel type of PCs which called nonlinear photonic crystals (NPCs) have been proposed [3]. NPCs have many applications in photonic devices as low-threshold optical limiting [4], short pulse compressors [5], nonlinear optical diodes, [6] and all-optical switching [7–9]. Among the several nonlinear materials that have been extensively used in NPCs, particular attention has been paid to semiconductors, and organic compounds [10–13]. Semiconductor materials, such as Si, GaAs and AlGaAs, are broadly believed to be best suited for PCs, due to the capability of semiconductors manufacturing technology, the ease in combining semiconductor in integrated optical circuit and relatively high refractive index. However, the response time (on the order of a few picoseconds to nanoseconds) and third order nonlinearity (on the order of 10^{-14} cm^2/W) of semiconductors are less than that of the polymer materials, such as polystyrene (ultrafast response time on the order of femtoseconds and large third-order nonlinear susceptibility on the order of 10^{-12} cm^2/W) [14,15]. Thus many scientists and engineers tend to use organic polymer materials as nonlinear component in NPCs [16,17].

Recently, Qin et al. [17] proposed a novel type of PC cavity. The cavity is embedded in a nonlinear hybrid PC slab which is made from infiltrating air hole arrays of a Si PC slab with polymer. Their result for the optimized cavity design yield a maximum Q factor of 1600and relatively large shift magnitude of resonance frequency under pump light.

In this work, we consider PC slab with triangular lattice of circular air holes in anisotropic Tellurium (Te) background on the top of the Teflon substrate. We assume that the air holes are deeply etched in the substrate. At first, by modifying the size of an air hole and infiltrating it by nonlinear polystyrene material, we introduce a nonlinear PC cavity in the mentioned structure. Then,

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we discuss the maximization of Q-factor as a function of geometrical parameters by a three-dimensional finite-difference time-domain (FDTD) method using the harmonic inversion code based on the filter diagonalization method to obtain a high-Q nonlinear PC cavity. In the next step, the high-Q cavity is situated between two waveguides; thus a coupled cavity-waveguide structure is created. Finally, the strength of the coupling between cavity mode and waveguides, plus shift magnitude of cavity mode resonance frequency under pump light is comprehensively investigated by the 3D FDTD method.

2. Structure and computational methods

In this study, we use triangular lattice of circular air holes in anisotropic Te background where the region below the slab is occupied by Teflon ($n^{\text{Teflon}}=1.30$). The air holes are extended through the substrate as well as the slab. The structure under consideration and the first Brillouin zone (BZ) of 2D triangular lattice is shown schematically in Fig. 1. The anisotropic Te has two different principle refractive indices as ordinary-refractive index $n_o^{Te}=4.8$ and extraordinary-refractive index $n_o^{Te}=6.2$ over the wavelength range of 4.50–6.25 μm with an absorption coefficient of $\alpha \approx 1\ \text{cm}^{-1}$ [18–20]. We assume that the periodicity of the PC slab is in the X–Y plane and the extraordinary axis of Te is considered parallel to the Z-axis.

Using anisotropic materials lead to creation of large band gap in PC slabs [20]. Designing PC slabs with large PBG is essential for better in-plane confinement of modes in the PC slabs. Thus, Te was used as the base material in our designed structure.

In this paper, the projected band structures of PC slabs are calculated by plane wave expansion (PWE) method using the MIT Photonic Band Gap (MPB) package [21,22]. We use the supercell approach based on PWE for such calculations, with the assumption that the periodicity of the PC slabs are in the X–Y plane. Since there is no periodicity in the Z-direction, we add sufficient amount of cladding material in the$Z$-direction to original finite height cell to reduce the effect of boundaries on the results (supercell is $1\times1\times4$, 4 lattice periods in the vertical direction).

At the mentioned structure a nonlinear PC cavity can be formed by increasing the radius of an air hole and infiltrating it by nonlinear polystyrene material. Besides, we can enlarge the size of the infiltrated air hole by further elimination of the six nearest-neighbor air holes around it. We have considered polystyrene with refractive index of $n^{\text{polystyrene}}=1.59$ as nonlinear component due to its large Kerr nonlinearity (the third-order susceptibility $\chi^{(3)}$ of polystyrene is $1.15\times10^{-12}\ \text{cm}^2/\text{W}$) and very fast optical response time (up to a few femtoseconds) [23,24]. Schematic configuration of the nonlinear PC cavity is illustrated in Fig. 2

In the following, the proposed cavity is placed symmetrically between two waveguides as an input and output ports. To our knowledge, almost all waveguides in triangular lattice are created by removing a single row of air holes along Γ–K direction. In our proposed structure the input and output waveguides are constructed by removing the air holes in the Γ–M direction [25,26] and modification of some circular air holes to elliptical holes, as shown in Fig. 3.

In order to investigate the transfer frequency spectrum of PC slabs, the Q-factor and the strength of coupling between cavity mode and waveguides we carried out simulation of electromagnetic waves by the 3D FDTD method. This method is implemented in MIT Electromagnetic Equation Propagation (MEEP) package [27]. In our simulations, each unit cell is divided into $24\times24\times24$ grid points. The whole computational domain is surrounded by

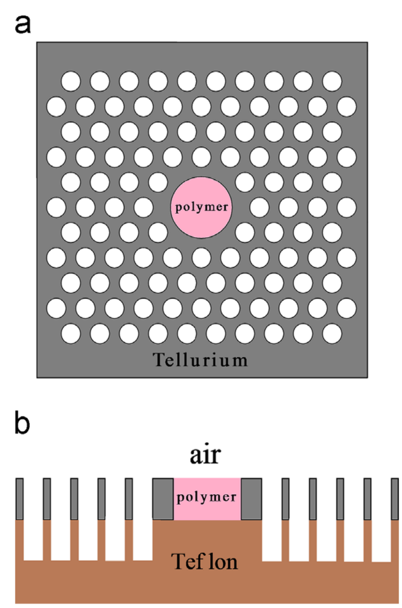

Fig. 2. Schematic representation of nonlinear polystyrene cavity (a) top-view and (b) side-view.

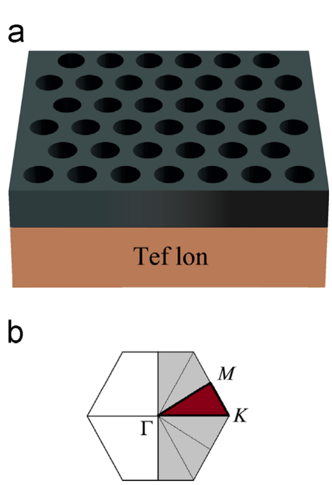

Fig. 1. (a) Schematic representation of PC slab structure with triangular lattice of air holes in anisotropic Te background on top of Teflon substrate and (b) first Brillouin zone of 2-D triangular lattice.

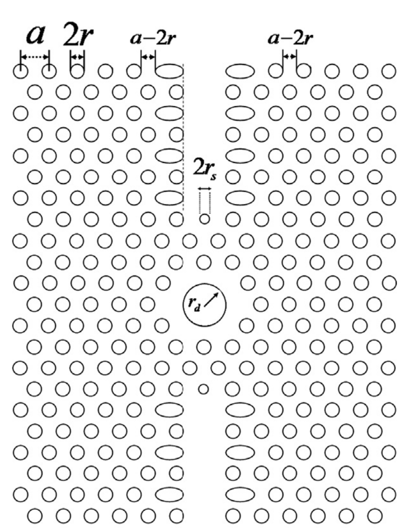

Fig. 3. Schematic representation of the coupled cavity-waveguide structure.