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Electro-optic modulation property of slow light in coupled photonic crystal resonator arrays

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A novel-designed compact, ultrafast electro-optic slow light modulator based on two-dimensional coupled photonic crystal resonator arrays (2D CPCRAs) has been studied. The 2D CPCRAs, realized in silicon-on-insulator (SOI) slabs with nonlinear polymer as filling material, exhibit a single guided mode with low group velocity in all crystal directions. We realize fast electro-optic tuning of the slow mode in a wide frequency range with low modulating voltage in this structure. Numerical analysis shows that the frequency shift is nearly linearly increasing with the applied voltage. In addition, for a certain frequency, changing the modulating voltage can tune the group delay of slow mode easily.

Keywords: coupled photonic crystal resonator arrays, slow light, electro-optic polymer.

1. Introduction

Low group velocity is crucial in a variety of applications, ranging from optical delay lines, all-optical buffers, and enhanced matter interaction [1, 2]. Although photonic crystals can be employed to achieve low group velocities at their band edges, this is limited to a very narrow range of wave vectors in one particular direction. Recently, two-dimensional arrays of coupled photonic crystal resonators have been a study focus which exhibit flat bands (which means reduced group velocities) over the entire range of wave vectors in all crystal directions [3, 4]. This can decrease the sensitivity of coupling and minimizes the distortion of an optical pulse propagating through the structure.

However, for real application, the controllable all-optical devices are the most critical components [5–7]. For example, all-optical buffers and optical storages must be able to turn on to store and turn off to release optical data at a very rapid rate by an external command. However, the seemingly simple function is very difficult to implement. Up to now, tunable photonic crystal devices are rarely developed due to the lack of suitable materials with attainable changes in the refractive index being large enough, as well as the lack of fabrication technique for those tunable materials.

Among the available materials for photonic applications, such as InP, GaAs, silicon-on-insulator (SOI) and polymers, the polymers [8, 9] have attracted great interest due to their low temperature fabrication, good mass production possibilities with low processing cost, easy fictionalizations, and the possibility of tuning their optical properties.

It is well known that the electro-optic effect has an ultra-high response speed of the order of nanosecond. Recently, ROUSSEY *et al.* [10] demonstrated theoretically and experimentally that the second-order nonlinear susceptibility can be drastically enhanced in annealed proton exchange waveguide with photonic crystal structure based on lithium niobate. This property opens up the possibilities for ultrafast tunable PC devices with low power.

In this paper, we investigate a novel-designed two-dimensional coupled photonic crystal resonator array (2D CPCRA) realized in two-dimensional photonic crystal slabs of nonlinear polymer as substrate material, which can dynamically tune the slow light properties and realize optical devices that could store and release optical pulses. Firstly, the slow light transmission properties in two-dimensional arrays of coupled photonic crystal resonators based on polymer substrate have been discussed. Secondly, we theoretically analyze local field effect enhancement induced by the slow light transmission and calculate the attainable refractive index changes in the structure proposed. Finally, we research the slow light modulation by external voltage, including frequency shifting, transmission control and storing time tuning.

2. Fabrication and photonic band gap calculation

The aim of this section is to describe the photonic crystal structure under study. We consider polystyrene as a suitable polymer material because its refractive index $n = 1.59$ is much larger than those of other polymers used in optical devices [11].

Figure 1 sketches the structure of slow light CPCRA. 2D CPCRAs studied in this paper consist of a triangular lattice (period a) with hexagonal Si dielectric rods filled polystyrene substrate, the refractive index of the polystyrene substrate is n ($n = 1.59$) [12]. By periodically modifying dielectric rods of a lattice photonic crystal slab, in our design, every third lattice dielectric rod in both the x and z directions can be removed, as shown in Fig. 1**a**. Figures 1**b** and 1**c** depict the unit cell and directions of high-symmetry points, Γ, M, and K of the CPCRAs shown in Fig. 1**a**. This structure can be viewed as a 2D array of single-defect photonic crystal cavities formed by removing a single Si dielectric rod. Two electrodes are placed on each side of the waveguide. The external electrostatic field is parallel to Z axis, allowing the largest electro-optic coefficient (γ_{33}) in polymer to be used.

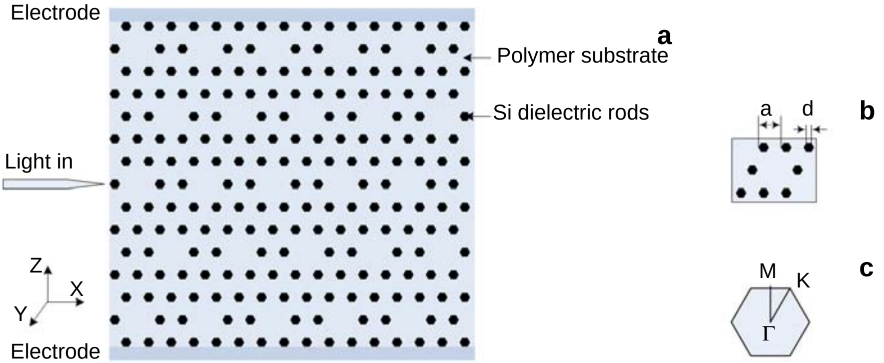

Fig. 1. Schematic configuration of the simulated and fabricated structure in polymer substrate (**a**); unit cell (**b**); the first Brillouin zone (**c**).

In order to model a fully characterized photonic crystal waveguide (PCW) with cutoff frequencies very close to the telecommunication wavelength of 1550 nm, this waveguide was designed using a lattice spacing of a = 443 nm with Si dielectric rods of width d = 177.2 nm.

All theoretical results presented in this paper were obtained by the two-dimensional finite difference time domain method and the plane wave expansion method [13]. Figure 2 shows the photonic band structure and spatial mode profile for TM-like modes of the CPCRA. A complete band gap between 0.2546 and 0.3329 (normalized frequency, in unit $\omega a/2\pi c$) can be observed. In the photonic bandgap, there is a single flat guided mode over the entire range of wave vectors and in all crystal directions.

Figure 3 presents the calculated transmission spectrum. We can observe a transmission peak in the middle of the bandgap. The isolated transmission peak is actually

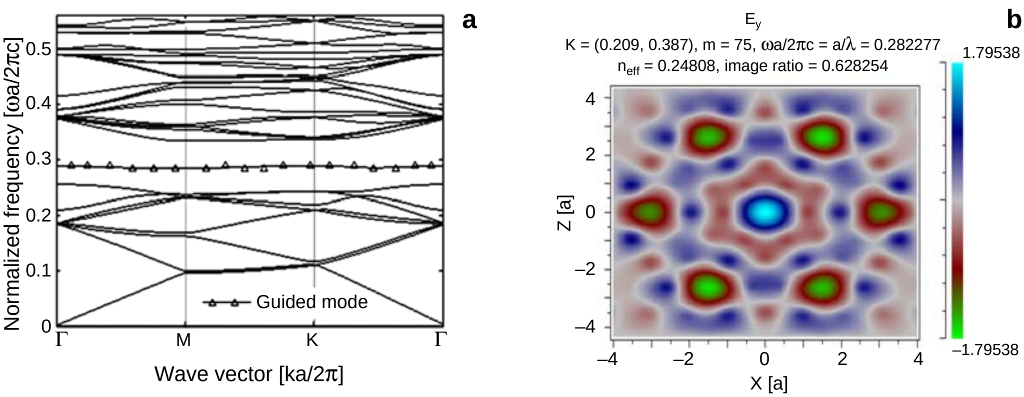

Fig. 2. Calculated band diagram of the polymer coupled photonic crystal resonator arrays (**a**); calculated spatial mode profile of the CPCRA structure for TM polarization (**b**).

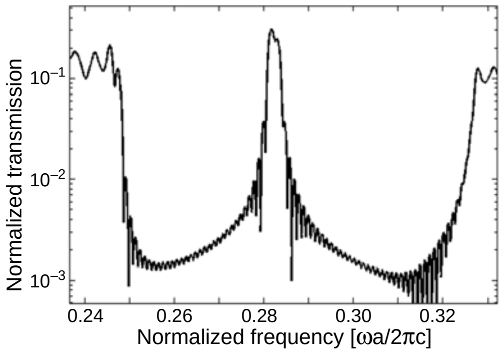

Fig. 3. Simulated transmission spectrum for TM-like modes.

a thin transmission band separating two photonic bandgaps. It can be seen that the normalized frequency of the transmission peak corresponds to the guided mode in the band diagram obtained by plane wave expansion method. Indeed, for the fabrication of tunable photonic crystal, it is easier to obtain a good extinction ratio by tuning a thin peak rather than an edge of the bandgap.

As a standard definition for group velocity is the derivation of the band diagram as follows,

$$v_g = \frac{\partial \omega}{\partial k} = \frac{c}{n + \omega(\mathrm{d}n/\mathrm{d}\omega)} = \frac{c}{n_g} \tag{1}$$

In our case, since the propagation is along the ΓM direction, we calculate only the group velocity for this direction as shown in Fig. 4.

We can note the existence of an almost flat horizontal band in the band gap that corresponds to a very low group velocity. In the vicinity of band edge, the group

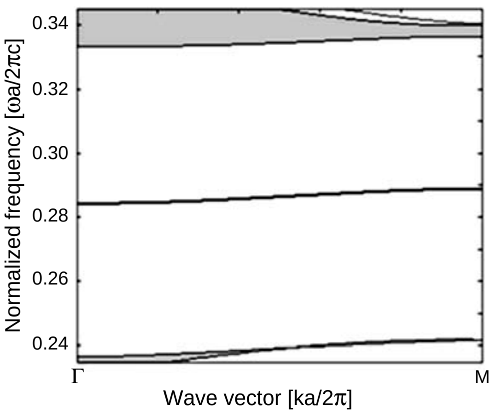

Fig. 4. The guided mode along the propagation direction ΓM.

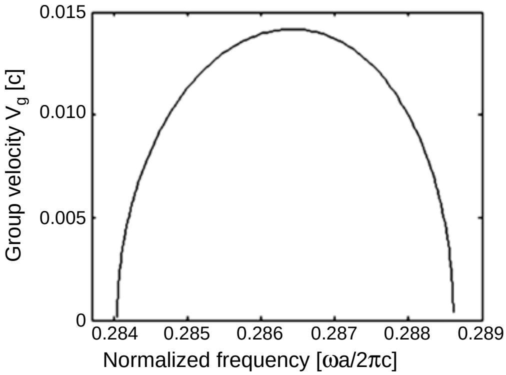

Fig. 5. Group velocity of the guided mode versus frequency along the propagation direction *ΓM*.

velocity approaches zero. We have calculated an average value of the group velocity in the structure $v_g = 0.009c$ (c – group velocity of light in vacuum), as shown in Fig. 5.

3. Modulator

An optical wave propagating through a nonlinear electro-optic material presents a refractive index change Δn in proportion to the electric modulating field inside the nonlinear material based on the Pockels effect, namely, the variation depends on the second-order susceptibility $\chi^{\langle 2 \rangle}$, which is expressed as [8]:

$$\Delta n_{\text{poly}} = -\frac{1}{2} n_{\text{poly}}^3 \gamma_{33} \frac{U}{d} \tag{2}$$

where γ_{33} is the linear electro-optic coefficient, Δn_{poly} represents the extraordinary refractive index of polystyrene, U is the applied modulating voltage, d is the distance between electrodes.

It is well known that nonlinear effects can be greatly enhanced in systems with slow group velocity as a result of the compression of local density of states. Nano-structuring enhances the second-order nonlinear susceptibility $\chi^{\langle 2 \rangle}$ of the material compared with the bulk material. The effective susceptibility in a slow light structured material has previously been proved to depend on the local-field factor f [14]:

$$\chi_{\text{PC}}^{\langle 2 \rangle} = f^3 \chi_{\text{bulk}}^{\langle 2 \rangle} \tag{3}$$

where $\chi_{\text{bulk}}^{\langle 2 \rangle}$ is the second-order susceptibility in the bulk polystyrene and f is the local-field factor. In this case, the electro-optic coefficient becomes $\gamma_{33} f^3$. The modified index variation can be expressed as [10]:

$$\Delta n_{\text{poly}} = -\frac{1}{2} n_{\text{poly}}^3 f^3 \frac{U}{d} \tag{4}$$

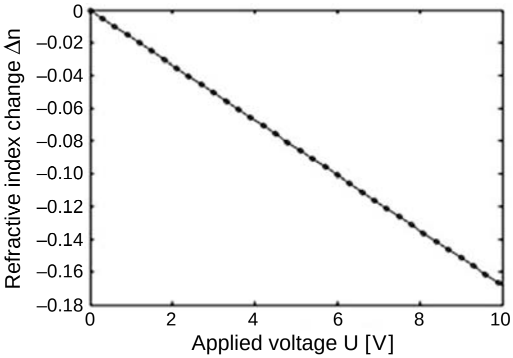

Fig. 6. Variation of the refractive index for an applied voltage obtained from Eq. (4).

The local field inside the photonic crystal structure can be calculated following the same calculation as in Ref. [9]. The local field factor is calculated with the group velocity inside the bulk polystyrene substrate $v_g^{\mathrm{bulk}} = c/n_{\mathrm{poly}}$, and the group velocity in photonic crystal structure v_g^{PC}. The local field factor f in PCW can be calculated as,

$$f = \sqrt{\frac{v_g^{\mathrm{bulk}}}{v_g^{\mathrm{PC}}}} \tag{5}$$

Thus, Eq. (4) becomes

$$\Delta n = -\frac{1}{2} n_{\mathrm{poly}}^3 \gamma_{33} f^3 \frac{U}{d} \tag{6}$$

Considering CPCRA discussed in the above section, with the reduction of group velocity, the local field factor increases sharply. Taking the average of the group velocity of the guided mode, the result is 0.009c, considering $\gamma_{33} = 80$ pm/V [8], $n_{\mathrm{poly}} = 1.59$, the distance between the two electrodes $d = 12.6a = 5.58$ μm. Substituting $v_g^{\mathrm{PC}} = 0.009c$ into Eq. (5), we obtain the local-field factor f to be 6.177. Thus variation of the refractive index versus the applied voltage is as shown in Fig. 6.

Due to the slow light of the guided mode, the value of Δn decreases sharply. When the modulating voltage is 10 V, Δn reaches –0.17. The result shows the significance of the slow light in the enhancing electro-optic effect.

Considering that the position of photonic bandgap (PBG) and guided mode depend directly on the value of the refractive index of substrate material, a significant shift of the guided slow mode has been obtained with external voltage variation. Taking into account $f = 8.36$ and $U = 0$ V (corresponding to the situation without an applied voltage), 5 V and 10 V, the guided mode shifts to higher frequency, as Fig. 7 shows. The normalized frequencies of the guided mode are 0.2878, 0.2968, 0.3063,

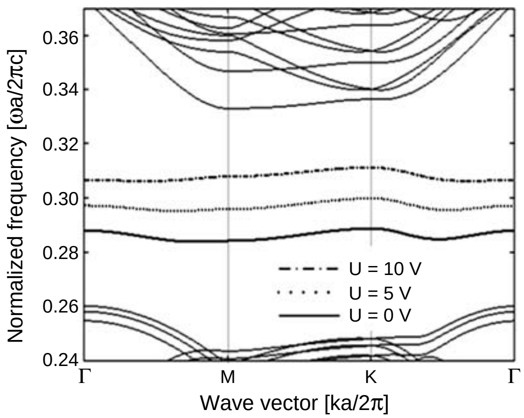

Fig. 7. Modulated band diagram of photonic crystal waveguide. The three lines correspond to the different applied voltages of 0 V (solid line), 5 V (dotted line), and 10 V (dash-dotted line).

respectively, corresponding to the guided mode cutoff wavelength shift by approximately 0, 46.7, and 93 nm. By tuning the voltage more exactly, a more refined mode shift can be obtained. It is concluded that the wavelength shift is nearly linearly increased with the applied modulating voltage increasing. Modulation sensitivity is about 9.34 nm/V. The flexible dynamic tuning of the slow mode can meet the requirements for the use of optical buffer in all-optical network in principle.

Shifts of the photonic crystal band and guided mode caused by refractive index variation can be applied to tune light transmission in the photonic crystal structures by changing the voltage dynamically and externally with low power. The external controlled guided mode shift can be conveniently utilized for slow mode selection and slow light cutting off or turning on. For a multiple wavelength system, by tuning the external voltage exactly, one can select the slow mode which should be delayed or stored.

In order to provide a clear understanding of the modulation property of the structure proposed, the light propagation of continuous wave (1550 nm) transmitted within this CPCRA at both 0 V and 5 V has been respectively simulated. The simulation results by finite-difference time-domain (FDTD) are shown in Fig. 8. For example, at 0 V, the light with wavelength 1550 nm is on the guided mode which can propagate in the coupled resonator optical waveguides in PCs (Fig. 8**a**) [15]. When applying a voltage of 5 V, it cannot transmit along the coupled resonator optical waveguides any more (Fig. 8**b**). Because the device goes into strong cutoff at this wavelength (1550 nm), this causes the light to be reflected back out of the CPCRA at the input. The simulation results show the effective control of the propagation of light with the changing of applied voltage distinctly. So, for a fixed single frequency, by tuning the voltage to change the guided mode frequency, one can control the turning on or turning off slow mode. This is critical technology in external, dynamical and controllable optical delay lines, all-optical buffers and storages.

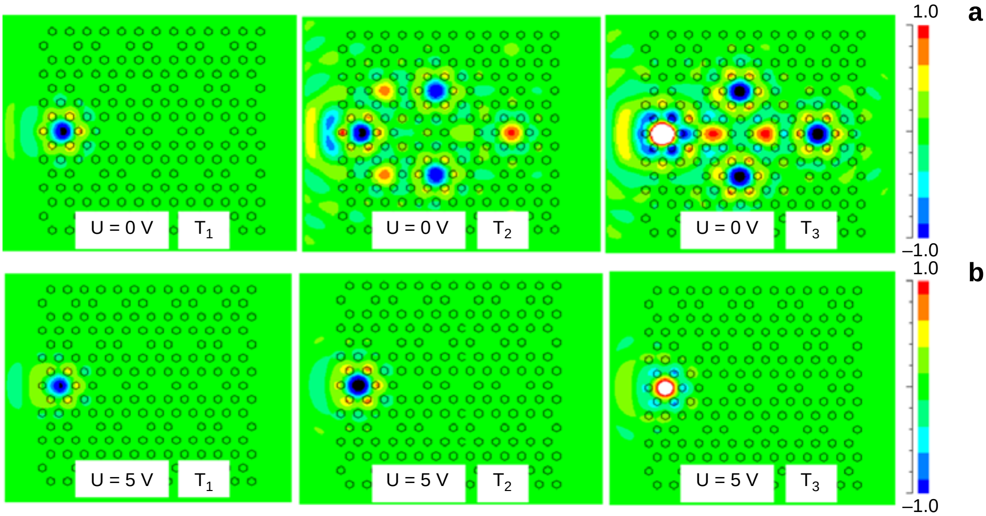

Fig. 8. Simulations of light propagation through the CPCRA with different applied voltages. T_1, T_2 and T_3 represent different times throughout the light propagation. U = 0 V (**a**), U = 5 V (**b**).

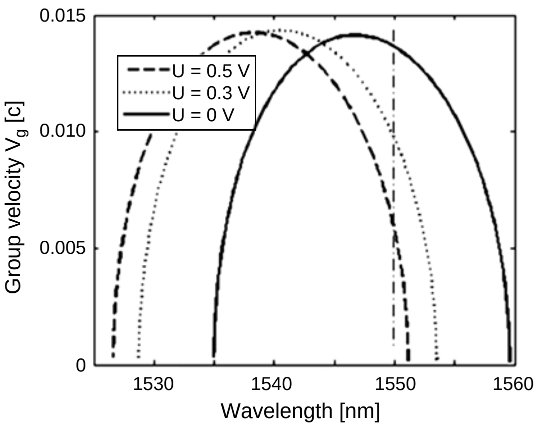

Fig. 9. The variation of group velocity of guided mode versus normalized frequency. The three lines correspond to the different applied voltages of 0 V (solid line), 0.3 V (dotted line), 0.5 V (dashed line).

Figure 9 illustrates the group velocity of the guided mode with three different applied voltages. It shows that the variation of modulating voltage controls the transmission of the guided mode. In addition, for an identical frequency of guided mode under transmission (1550 nm, as the dash-dotted vertical line shows), the group velocity will decrease greatly with the increase of the applied voltages. This type of behavior clearly provides the capability of group velocity modulation at determinate frequency by changing the modulating voltage dynamically and externally, which corresponds to the tuning of the storing time of light for real application.

Generally, the storage time T_s of a buffer is defined as,

$$T_s = L / v_g \tag{7}$$

where L is the length of CPCRA and v_g is the group velocity of light transmission. Equation (7) shows that the storage time is direct ratio to the length of delay line, but inverse ratio to the group velocity. We just make the hypothesis that the length of CPCRA discussed in this paper is 7.97 μm, and the group delay can be determined as Fig. 10 shows. In the vicinity of band edge, the group delay approaches 200 ps.

We calculated the group delay when different modulating voltages are applied to the structure corresponding to the group velocity tuning in Fig. 9, as shown in Fig. 11. For the wavelength of 1550 nm, we can see a group delay of the guided mode to

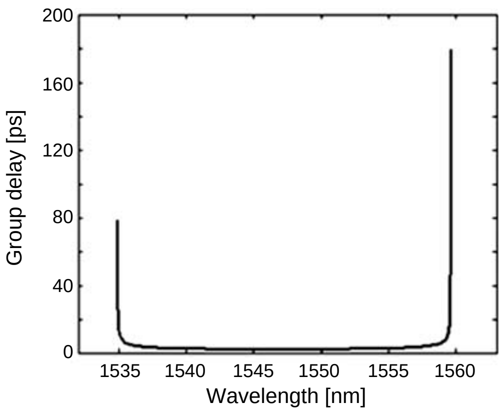

Fig. 10. Calculated group delay of the guided mode versus the wavelength along the propa-gation direction *ΓM*.

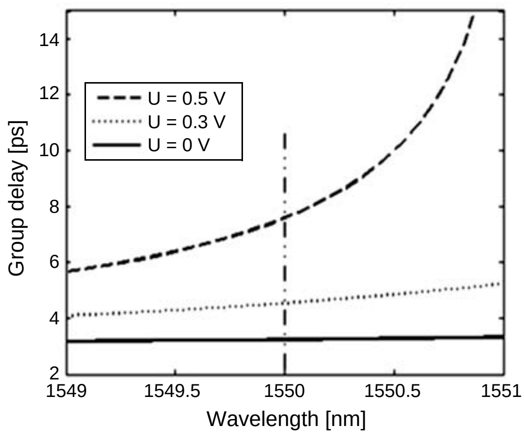

Fig. 11. The variation of group delay of guided mode as applied voltage increased. The three lines correspond to the different applied voltages of 0 V (solid line), 0.3 V (dotted line), 0.5 V (dashed line).

increase sharply as the modulating voltage increases. When modulating voltage is 0 V, 0.3 V and 0.5 V, the group delay is about 3.1 ps, 4.3 ps and 7.6 ps, respectively. So, for a certain frequency of guided mode under transmission, the flexible tuning of slow mode can not only be utilized for slow light selection, but also to manipulate the storing time of slow light in optical delay lines, all-optical buffers or optical storages.

4. Conclusions

We have designed a novel ultrafast electro-optic slow light modulator based on 2D coupled photonic crystal resonator arrays (CPCRAs). The structure supports flat guided mode in all crystal directions, which refers to an ultra low group velocity of $10^{-3}c$. Employing the polymer as substrate material and local field effect induced by the slow light transmission gives rise to the fast electro-optic tuning of the slow mode in a wide frequency range with low modulating voltage in this structure. The wavelength shift modulation sensitivity is about 9.34 nm/V. The flexible tuning of slow mode can not only be utilized for slow light frequency selection, but also to manipulate the storing and releasing of slow light pulses with a given frequency in optical delay lines, all-optical buffers or optical storages. The study presented here can be extended to 3D coupled resonator arrays, as well as to other types of resonators, including those not based on photonic crystals.

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