Electrically tunable photonic crystals with nonlinear composite materials

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Based on nonlinear composite materials, we exploit theoretically a class of electrically tunable one-dimensional double-layer photonic crystals (PCs), namely, composite-dielectric and composite-composite PCs. For such PCs, extensive and precise tunability of photonic band gaps can be readily achieved by choosing appropriate pump ac or dc electric fields. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2809389]

Photonic crystals (PCs) are attractive optical materials for controlling and manipulating the flow of light or electromagnetic waves. They are of particular importance in electromagnetism (especially optics and photonics), where they are promising for a variety of optical and microwave applications, such as some types of beam steerers, modulators, band-pass filters, lenses, microwave couplers, and antenna radomes. The main attraction of the PCs is the existence of forbidden band gaps in their transmission spectra. To achieve suitable band gaps, there are great efforts to obtain tunability of the band gaps.[1–3] Suh *et al.*[1] introduced a mechanically tunable photonic structure for tuning the band gaps. Busch and John[2] predicted the tunability of photonic crystal structures by infiltrating liquid crystals (LCs) into an opal structure. This work was soon followed by experimental demonstration of temperature tuning of photonic band gap in LC-infiltrated PC structure.[4] In a word, the tunability depends on either electric permittivities or magnetic permeabilities, which can be adjusted by external electric or magnetic fields, respectively. Consequently, the electromagnetic spectrum of the PCs can be altered over a wide range by using external fields.[5]

Composite materials (or composites for short) are materials made by combining two or more constituent materials with significantly different physical or chemical properties, which gives the composites unique properties. If small metallic particles are introduced into a dielectric host, the third-order nonlinearity (Kerr-type nonlinearity) of composites can be enhanced significantly.[6–8] This enhancement arises from those of component materials through local field and resonant scattering effects,[8–10] both of which are sensitively dependent on the microstructure of composites. For a nonlinear component material, the local constitutive relation between local electric field **E** and displacement field **D** is given by

$$\mathbf{D} = [\epsilon + \chi^{(3)}|\mathbf{E}|^2]\mathbf{E}, \tag{1}$$

where ϵ is a (spatially dependent) dielectric permittivity and $\chi^{(3)}$ is (also spatially dependent) third-order Kerr nonlinear susceptibilities.[11,12] In the quasistatic approximation, the system can be regarded as one with effective dielectric permittivity $\bar{\epsilon}$ and effective third-order nonlinear susceptibility $\bar{\chi}^{(3)}$, which are defined by the spatial average of **D**,

$$\langle \mathbf{D} \rangle = [\bar{\epsilon} + \bar{\chi}^{(3)}|\mathbf{E}_0|^2]\mathbf{E}_0. \tag{2}$$

Here, $\mathbf{E}_0$ is the external pump electric field vector. So far, one has proposed various methods for calculating the effective linear or nonlinear responses, based on effective medium theories including the Maxwell-Garnett approximation (MGA).[8,12,13]

In the present work, we propose to use nonlinear composite microstructures to achieve another class of PCs (Fig. 1) by using pump dc or ac electric fields to tune the band structures. The idea relies on the fact that the dielectric permittivity of composite materials can be altered by applying an external pump electric field because of the third-order nonlinearity as mentioned above. To exemplify this idea, we theoretically calculate the band structures, viz., dispersion relation, of PCs with composite microstructures under pump electric fields.

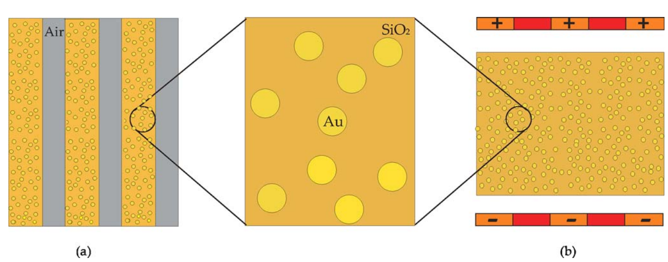

FIG. 1. (Color online) Schematic view of one-dimensional PCs composed of (a) a nonlinear composite microstructure and linear common dielectric medium, e.g., air and (b) a nonlinear composite material subjected to the application of spatially periodic nonzero (indicated by the symbols, + and −) and zero pump electric fields. The composites in both cases can be prepared with nonlinear nanoparticles (e.g., gold) randomly dispersed in linear dielectric (e.g., silica), as shown in the middle panel.

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For one-dimensional PCs with N layers, the photonic band structures can be easily calculated in the transfer matrix method. The dispersion relation for double-layer PCs,[14]

$$\cos(kd) = \cos(k_1 d_1)\cos(k_2 d_2) - \frac{1}{2}\left(\frac{k_1}{k_2} + \frac{k_2}{k_1}\right)\sin(k_1 d_1)\sin(k_2 d_2), \quad (3)$$

where d means the lattice constant, $d_{1(2)}$ the thickness of corresponding layers, and $d = d_1 + d_2$. k represents the Bloch wave vector and $k_{1(2)} = \sqrt{\epsilon_{1(2)}}\omega/c$ denotes the local wave vector. Here, $\epsilon_{1(2)}$ stands for the dielectric permittivity of media in the corresponding layers, ω the frequency of light or electromagnetic waves (probe electromagnetic field), and c the speed of light in free space.

Next, we consider a composite layer in which nonlinear nanoparticles are randomly embedded in a linear host. The nonlinear nanoparticles possess nonlinear dielectric permittivity $\tilde{\epsilon}_p$ as

$$\tilde{\epsilon}_p = \epsilon_p + \chi_p^{(3)}|\mathbf{E}_p|^2 \approx \epsilon_p + \chi_p^{(3)}\langle|\mathbf{E}_p|^2\rangle, \quad (4)$$

where ϵ_p denotes the field-independent linear dielectric permittivity, $\chi_p^{(3)}$ the third-order nonlinear susceptibility of the nanoparticles, $\mathbf{E}_p$ the local electric field inside the nanoparticles, and $\langle\cdots\rangle$ the volume average of $\cdots$. Then, the effective response ϵ_1 of the layer can be given by the Maxwell-Garnett approximation as beneath,[8,15,16]

$$\frac{\epsilon_1 - \epsilon_m}{\epsilon_1 + 2\epsilon_m} = p\frac{\tilde{\epsilon}_p - \epsilon_m}{\tilde{\epsilon}_p + 2\epsilon_m}, \quad (5)$$

where ϵ_m represents the linear dielectric permittivity of (linear) host and p the volume fraction of nonlinear nanoparticles in the layer. The volume-averaged local electric field $\langle|\mathbf{E}_p|^2\rangle$ is given by[12,17]

$$\langle|\mathbf{E}_p|^2\rangle = \frac{9|\epsilon_m|^2}{|(1-p)\epsilon_p + (2+p)\epsilon_m|^2}\mathbf{E}_0^2. \quad (6)$$

In the following numerical calculations, nonlinear nanoparticles and linear host are taken to be Au and SiO_2, respectively. Here, we should mention that, if nonlinear metallic nanoparticles are chosen, e.g., Au, the pump electric fields acting upon the composite material should be an ac field with a high enough frequency. On the other hand, if nonlinear dielectric nanoparticles such as polymer are used instead, the pump fields can either be a dc or an ac field.

Now, we investigate one-dimensional double-layer PCs, which consist of one layer of composite materials and the other layer of common dielectric [see Fig. 1(a)]. For model calculations, we investigate Au:SiO_2 (one layer with effective dielectric response ϵ_1) versus air (the other layer with dielectric permittivity ϵ_2) in this work. The so-called Au:SiO_2 layers are actually composed of Au nanoparticles which are randomly embedded in the SiO_2 host, with volume fraction of Au nanoparticles $p=0.15$. For model calculations, the dielectric permittivity of SiO_2 is taken to be $\epsilon_m = 2.25\epsilon_0$. The probe electromagnetic field can be much weaker in strength than the pump ac electric field. In this regard, the dispersion (and loss) of the (much weaker) probe electromagnetic field can be neglected. On the other hand, the proposed PC is operated at microwave frequencies where the loss can be neglected due to large skin depth at the frequency range. So, here we take the value for $\epsilon_p = -9.97\epsilon_0$,[11,12] which is a real frequency-independent constant. The value for ϵ_p corresponds to a pump field produced by a laser source at 620 nm.[12] We should remark that the actual value does not change our qualitative results originating from field-induced nonlinearity. Throughout this work, ϵ_0 denotes the dielectric permittivity of free space.

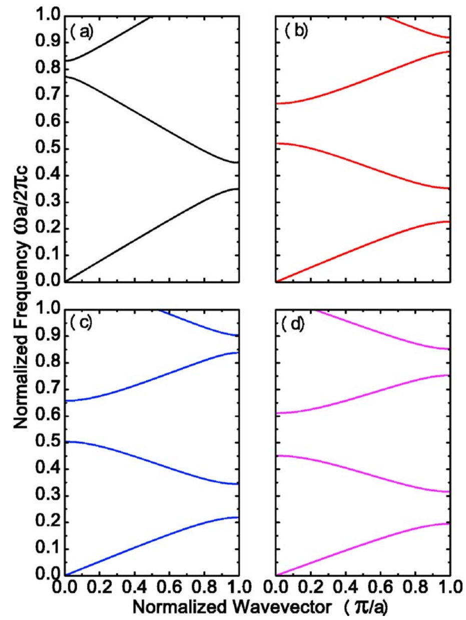

FIG. 2. (Color online) Calculated photonic band structures of (a) SiO_2/air, (b) Au:SiO_2/air under zero pump ac field, $\chi_p^{(3)}E_0^2=0$, (c) Au:SiO_2/air under nonzero pump ac field, $\chi_p^{(3)}E_0^2=0.2\epsilon_0$, and (d) Au:$SiO_2$/air under nonzero pump ac field, $\chi_p^{(3)}E_0^2=0.6\epsilon_0$, for a one-dimensional PC [Fig. 1(a)]. Parameters: $d_1=d_2=0.5a$. Here, a is the lattice constant.

The existence of the Kerr nonlinearity of the composites enables an extensive tunability of band structures for such one-dimensional double-layer PCs by applying pump electric fields. Figure 2 shows the band structures of this kind of PC under different pump fields (throughout this work, we use $\chi_p^{(3)}E_0^2$ to indicate the strength of an external controlling pump electric field E_0). We find that the pump electric field has a great effect on the widths of the band gaps, viz., their widths become narrower compared to the case of the zero pump field. The reason is easily understood. When the pump electric field is strengthened, the effective dielectric permittivity of each composite layer grows monotonically. This originates from the third order nonlinearity, which leads to a significantly increasing refractive-index contrast between consecutive composite and dielectric layers. In Fig. 3, the width of the first gap is also shown. It is evident that the gap changes increasingly sharp, along with the increase of the magnitude of a pump electric field. Moreover, the pump electric field makes an apparent shift of the positions of forbidden gaps toward the lower frequencies (redshift). As a result, more photonic band gaps come to appear accordingly. Apparently, we can obtain the tunable PCs just by adjusting external pump electric fields.

On the other hand, based on such a composite microstructure, we also propose to fabricate another kind of PCs [see Fig. 1(b)]. Figure 1(b) schematically shows the structure where nonzero and zero pump electric fields are periodically arranged, which is just the structure investigated in Fig. 4(b). If spatially periodic pump fields are applied on such a composite material due to the variation of the permittivity ad-

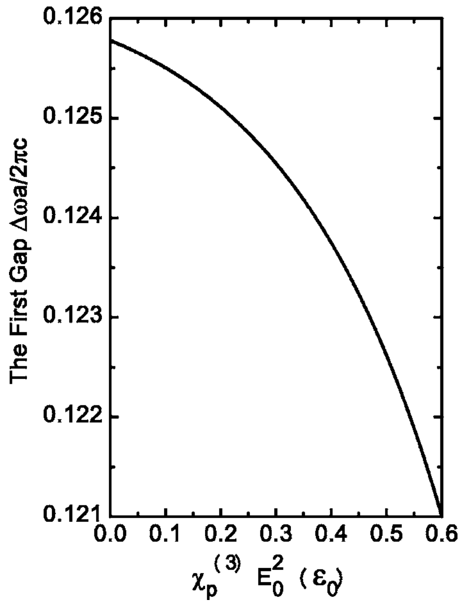

FIG. 3. The first band gap of a one-dimensional PC [Fig. 1(a)] composed of composite microstructures, as a function of the external pump ac electric field. Parameters: $d_1 = d_2 = 0.5a$.

justed by the pump fields, this media might behave as a one-dimensional double-layer PC (Ref. 18) [see Fig. 4(b)]. For comparison, Fig. 4(a) also displays the result of the same composite medium, which is not subjected to any external pump electric field at all. Apparently, the system corresponding to Fig. 1(b) has photonic band gaps indeed, as shown in Fig. 4(b). We should claim that, to achieve such a PC, the zero pump electric field in Fig. 1(b) can also be replaced by another different nonzero pump field. In this sense, the dielectric contrast between two consecutive layers becomes more free to be manually adjusted.

Herein are some comments. We have demonstrated to control photonic band gaps by field-induced nonlinearity.

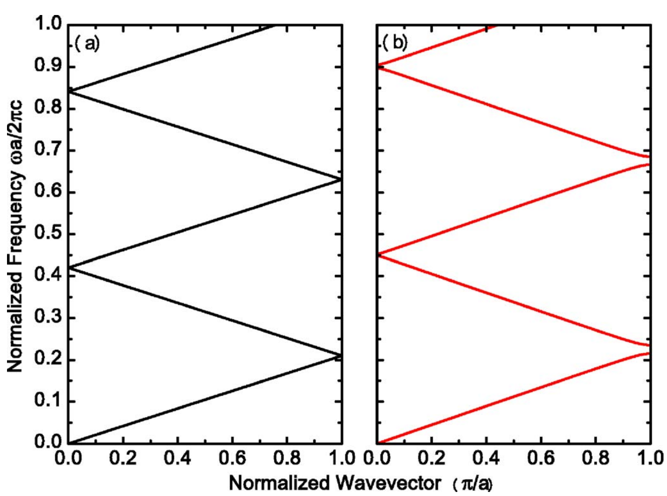

FIG. 4. (Color online) Photonic band structure of a one-dimensional PC [Fig. 1(b)] composed of a Au:SiO_2 composite material under the application of spatially periodic pump ac electric field E_0, for (a) $\chi_p^{(3)} E_0^2 = 0$ (zero pump ac field) and (b) $\chi_p^{(3)} E_0^2 = 0.6\epsilon_0$ (nonzero pump ac field). Parameters: $d_1 = d_2 = 0.5a$.

The nonlinear response obtained from metal-dielectric composites can be both fast and appreciable. We have used the MGA in the present work to gain some insights toward field-induced nonlinearity. In theory, the asymmetrical MGA is much simpler, and alternatively, the symmetrical Bruggeman-type effective medium approximation may be used as well, especially for metals at higher volume fractions.

In fact, the composite materials can also be fabricated with others, such as dielectric nanoparticle coated by a nonlinear dielectric nanoshell, to get a large nonlinearity enhancement[19,20] and thus a desired dielectric permittivity with a broad tunable range.

To conclude, we have proposed another class of PCs, which possesses electrically tunable photonic band structures. Our proposal is based on the fact that the effective refractive index of nonlinear composite microstructures has an electric-field dependence due to the existence of third-order nonlinear responses.

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