Tunable and absolute electromagnetic vacuum in two-dimensional photonic-band-gap Based on multiferroic materials
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In the past years, the concepts of solid state physics have been brought to bear on electromagnetism and Maxwell’s equations. In analogy to the case of electron waves propagating in a crystal, light waves traveling in artificially periodic dielectric structures have been described in terms of photonic bands with possible frequency gaps, where the propagation of electromagnetic (EM) waves is prohibited. There has been widespread interest in structural long-range order and Bloch waves for studying magnetic orders. In analogy to the case of electron waves propagating in a crystalline state, a photonic band gap (PBG) can be defined by two wave vectors in a reciprocal lattice. In this letter, we propose forming a tunable and absolute PBG in a multiferroic photonic-band-gap material made of TbMnO₃ crystals arranged in a square lattice. The a-axis dielectric constant of TbMnO₃ at terahertz frequencies is about 9 (Ref. 7) and the real part ε₀ of the a-axis dielectric constant is about 28 (Ref. 11) as shown in the inset. In our frequency range with a 24-GHz width, the variation of the dielectric constant is less than 1%, so we assume its real and imaginary parts not to be dispersive under a ESMF.

Figure 1 shows the magnetodielectric effect of a TbMnO₃ crystal at the temperature 12 Kelvin (K). After applying the 8 Tesla (T) ESMF parallel to the c axis of TbMnO₃, the real part ε′ and imaginary part ε″ of the a-axis dielectric constant clearly change. This is due to the corresponding electromagnon change of the dielectric constant in the antiferromagnetic-order transition of Tb spins, which is from a modulated antiferromagnetic/ferroelectric (AFM/FE) phase to a canted-antiferromagnetic (CA-AFM) phase, as shown in the inset. In our frequency range with a 24-GHz width, the variation of the dielectric constant with the frequency is less than 1%, so we assume its real and imaginary parts not to be dispersive under a ESMF.
The multiferroic photonic-band-gap material we propose is made of TbMnO$_3$ crystal cylinders arranged in a square lattice (lattice parameter $a$) with air as the background, as shown in the inset of Fig. 2. For simplicity without losing generality, the PBG system’s axis is parallel to the extension direction of the cylinders (the $c$ axis of TbMnO$_3$ and the direction of the applied ESMF), and the EM waves propagate along the $b$ axis of TbMnO$_3$. The TE-mode photonic band structure is shown in Figure 2, where the cylinder radius is 0.4$a$. When the ESMF is 0 T, three PBGs are clear and their center frequencies are 0.155, 0.270, and 0.385, respectively, as shown in Figure 2, where the cylinder radius is 0.4$a$. When the ESMF is 0 T, three PBGs are clear and their center frequencies are 0.155, 0.270, and 0.385, respectively, as shown in the right panel of Fig. 2. We find that when the value of the lattice parameter ($a$) is changed, the first PBG is centered at almost the same position and the photonic structures are nearly same, showing a scale-length invariant behavior. We, therefore, conclude that the first PBG is dominated by Bragg scattering. When an 8-T ESMF is applied (the left panel of Fig. 2), most smooth bands become pointed except the photonic structure around the first PBG. The center frequency of the first PBG is moved up by 0.01 and the PBG width is almost unaltered. All of this shows that the ESMF only has little effect on the first PBG and the photonic band structure nearby. Our results are in agreement with recent experimental and theoretical results that show a tiny shift in frequency of Bragg-dominating PBGs in response to an ESMF. The center frequency of the second PBG shows its relation to some electric modes of TbMnO$_3$ crystals for EM absorption. The third PBG for absolute and tunable PBG is discussed below.

Figure 3 shows the corresponding TM-mode photonic band structure. Two gaps appear with center frequencies of 0.220 and 0.395. The first gap is rather wide (right panel of Fig. 3). By applying the 8-T ESMF, the first gap is reduced by 97.5% and even remains. This shows that the gap originates from antiferromagnetic resonances, i.e., magnetic modes, because the ESMF can only rearrange the antiferromagnetic order.

To clarify the tunable and absolute gap, Fig. 4 shows TE- and TM- mode photonic band structures without the ESMF, which constitute the fundamental result of this work. No bands intervene between the frequency 0.39 and 0.40. The absolute gap appears with the moderate width 5% of the center frequency, which has contributions from the third TE-mode gap and the second TM-mode gap. Despite the mode difference, the similar band shape nearby shows that the absolute PBG is dominated by the same resonance. Noticeably, the absolute PBG is closed by applying the ESMF, as shown in the left panel of Figs. 1 and 2. Because the ESMF moves the Bragg-dominating gap, we conclude that the absolute gap is not related to such large-scale geometric resonance. To highlight the possible resonance type, we present the EM intensity distribution of the PBG bottom or top at the high symmetry point $\Gamma$ in the upper inset of Fig. 4. Both TE- and TM- mode EM waves are effectively confined within the cylinder. The intensity of EM waves at the gap top distributes as a circle, which has higher symmetry than the four-leaf-clover shape at the gap bottom. Also, the intensity was strongly enhanced in the center of the circle or ‘leaf.’ For an individual cylinder without the ESMF (the magnetic permeability defaulted as 1), the Mie resonance formulations for the scattered and internal fields subject to an incident plane wave are simplified as: 

$$H^{\text{out}} = \sum_{-\infty}^{\infty} a_n H_n(kp)e^{-in\varphi}, \quad H^{\text{int}} = \sum_{-\infty}^{\infty} b_n J_n(\sqrt{\epsilon}kp)e^{-in\varphi},$$ 

for TE mode,
FIG. 4. (Color online) Absolute gap of the band structure without the external static magnetic field. The dashed lines are the TE-mode photonic band structure and the dotted lines are the TM-mode one. The upper insets show the electromagnetic intensity distribution of the gap bottom or top at the high-symmetry point Γ, which indicates that the absolute and tunable PBG is due to the Mie resonance. That is, the tunable and absolute gap is related to the EM absorption of a single cylinder of the TbMnO$_3$ crystal itself. The lower inset shows the gap-to-midgap-frequency ratio as a function of radial contrast in an external static magnetic field of 80 Tesla.

for TM mode,

$$
E^{\text{ext}} = \sum_{-\infty}^{\infty} a_n H_n(k\rho)e^{-\imath n\phi},
$$

$$
E^{\text{int}} = \sum_{-\infty}^{\infty} b_n J_n(\sqrt{\epsilon}k\rho)e^{-\imath n\phi},
$$

where $\rho$ and $\phi$ are the cylindrical coordinates with the origin at the cylinder center, $x \equiv 0.4ak = 0.4c_0/\epsilon$, $x_1 = \sqrt{\epsilon}x$, $k$, and $\omega$ are the wave vector and the angular frequency, respectively, $J_n(x)$ and $H_n(x)$ are the nth order Bessel function and Hankel function of the first kind, respectively, and the prime denotes a derivative with respect to the argument. The Mie resonance of these gaps corresponds to divergence of the amplitude coefficients for the scattered and internal fields, i.e., the vanishing denominator of $a_n$ or $b_n$. The intensity distributions in the inset of Fig. 4 are the same as those features of a cylinder described by the Mie resonance formulation. Therefore, all of this shows that the tunable and absolute gap originates from the first or high-order Mie resonance. That is, the tunable and absolute gap is related to the EM absorption of a single cylinder of the TbMnO$_3$ crystal itself.\textsuperscript{[5,16]} The manganese spins of TbMnO$_3$ at 12 K without the ESMF are in a modulated AFM/FE phase. The refractive index of the TbMnO$_3$ cylinders, ~4.9, is larger than that of the surrounding air. Thus, TbMnO$_3$ cylinders constitute a series of potential barriers to prohibit the propagation of EM waves, corresponding to strongly localized photon states. That is, the photonic states are spatially inside the cylinders and fully inhibited; other photons of transporting EM waves cannot take up these energy states, and propagation of EM waves inside the cylinder is forbidden and located. Pimenov \textit{et al.} have shown that an 8-T ESMF can induce a transition of Tb spins to a CA-AFM phase at 12 K, and the antiferromagnetic order is rearranged and the magnetic permeability modulated. More importantly, the electromagnons’ contribution to the $a$-axis dielectric constant can be suppressed during the magnetic structure transition, and as a result, the imaginary part of the $a$-axis dielectric constant is decreased by more than a factor of two and the real part is reduced by about 2.\textsuperscript{[9]} Therefore, the absorption of cylinder as an attractive potential decreases, and so does the potential barrier surrounding the cylinder. It is then possible for the third TE-mode gap to close. At the same time, the absolute PBG is turned off. The lower inset of Figure 4 schematically shows the photonic band structure with different radius-to-lattice ratios. The absolute and tunable gap opens only in cylinders with 0.4a radius, as the arrow indicates. Despite different cylindrical radii, the ESMF has almost the same effect on the first TE-mode PBG.

In summary, we investigated the possibility of a tunable and absolute PBG in a 2D square-lattice structure using the magnetodielectric effect of magnetic transition in a multiferroic TbMnO$_3$ crystal.

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\textsuperscript{[16]} C. F. Bohren and D. R. Huffman, \textit{Absorption and Scattering of Light by Small Particles} (Wiley, New York, 1983).