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Simultaneous microwave photonic and phononic band gaps in piezoelectric–piezomagnetic superlattices with three types of domains in a unit cell

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ABSTRACT

A novel phoxonic crystal using the piezoelectric (PMN-PT) and piezomagnetic ($CoFe_2O_4$) superlattices with three types of domains in a unit cell (PPSUC) is present, in which dual microwave photonic and phononic band gaps can be obtained simultaneously. Two categories of phononic band gaps, originating from both the Bragg scattering of acoustic waves in periodic structures at the Brillouin zone boundary and the electromagnetic wave-lattice vibration couplings near the Brillouin zone center, can be observed in the phononic band structures. The general characteristics of the microwave photonic band structures are similar to those of pure piezoelectric or piezomagnetic superlattices, with the major discrepancy being the appearance of nearly dispersionless branches within the microwave photonic band gaps, which show an extremely large group velocity delay. Thus, the properties may also be applied to compact acoustic-microwave devices.

1. Introduction

The phoxonic crystal (PxC) [1] as a promising artificial material for optomechanical systems and acoustic-optical devices, possessing the property that dual photonic band gaps (PtBGs) and phononic band gaps (PnBGs) can coexist simultaneously, has attracted great attention during the past decade. Generally, the PtBGs and PnBGs are the most significant features for photonic and phononic crystals, respectively. Photonic crystals [2] are periodic composites composed of two or more materials with different dielectric constants, where electromagnetic waves undergo periodic Bragg scattering from the Brillouin zone boundaries, giving rise to the PtBGs. As a result, the PtBGs are referred to as frequency ranges over which propagation of electromagnetic waves is prohibited. Similarly, phononic crystals [3–10] are also the appropriate propagation medium exhibiting a periodic modulation of mechanical properties. The propagation of elastic waves in a specific wavelength range can be prohibited due to superposition of Bragg and Mie resonant scattering as well [11]. A symbiotic relationship between the PtBGs and the PnBGs is not necessarily true, and the existence of the PtBGs in a periodic structure does not necessarily mean that the PnBGs are also present in such a structure and vice versa. The design and fabrication of hypersonic phononic crystals [4] with lattice parameters of approximately 1 μm, operating in the radio-frequency regime, open a new pathway towards achieving the PxCs. The existing research on the PxCs has focused on obtaining the PtBGs and PnBGs simultaneously and on improving the interaction between photons and phonons.

Up to now, a variety of PxCs have been investigated which involve one-dimensional nanobeam structures [12–16], two-dimensional periodic structures [17–21], as well as a three-dimensional metallodielectric structure [22]. Comprehensively, the basic constituents of the PxCs are usually elastic and dielectric materials. They are arranged periodically along a certain direction, a plane, or the three-dimensional space so that the PxCs are generated. The periodical modulation of elastic and dielectric constants in the PxC can lead to the formation of the PtBG and PnBG simultaneously, and the changes of lattice symmetry can also induce the modification of the phoxonic band gaps, which result in the convenient manipulation of photons and phonons and in the enhancement of the acoustic-optical interaction. Besides, the PxC has a significant

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slow-wave delayed effect, similar to that of the photonic crystal waveguides [23,24], the strong dispersion in the vicinity of the photonic band edge can be used to generate slow-light effect. The slow-down factor $n_g = c(dk/d\omega)$ and delay-bandwidth product (DBP), as important physical parameters, are used to evaluate the performance of the slow-wave devices, and n_g defines the ratio of group velocity in medium with respect to that in vacuum. The DBP is utilized to stipulate the frequency range with sizeable time-delay, and is also a good indicator reflecting the buffering capacity of data information [24].

Piezoelectric or piezomagnetic superlattices can also be used as the candidate devices with a significant group velocity delay effect since the dispersion branch in the neighborhood of photonic band edge is flat. Until now, many studies on the superlattices have been carried out, which involve the experimental synthesis of the ionic-type phononic crystal [25] in microwave band, polariton [26–29], velocity dispersion of plate acoustic waves [30], magnetoelectric coupling in piezoelectric/magnetostrictive heterostructures [31], magnetoelastic response [32], as well as surface phonon polaritons [33,34]. The ionic-type phononic crystal [25] with the minimum modulation period of 7.2 μm has been synthesized and the ferromagnetic $La_{0.7}Sr_{0.3}MnO_3$ layers [32] with thicknesses of $d = 1.5$–13 nm have been obtained, which can provide the prerequisites for the synthesis of piezoelectric or piezomagnetic superlattices with higher operating frequencies.

From comprehensive understanding above, although there have been many theoretical and experimental investigations on the PxCs so far, the research with regard to dual microwave photonic and phononic band gaps of the PPSUC is still rare. The PPSUC is characterized by the piezoelectric domains with electric polarization along $\pm y$-axis and the piezomagnetic domain with magnetization along $+z$-axis and is shown in Fig. 1. Sound waves are generated and strengthened via the piezoelectric or piezomagnetic effects when electromagnetic waves incident on the PPSUC. There are several key points regarding the PPSUC that need to be emphasized, as follows. (1) Dual microwave photonic band gaps (MPtBGs) and PnBGs can be obtained by the transfer matrix method and the Bloch theorem. (2) As expected, there is a class of PnBG deriving from the Bragg scattering at the Brillouin zone boundaries. Nevertheless, the other PnBG originating from coupling between electromagnetic waves and lattice vibrations may also be present in the center of the Brillouin zone. (3) The PnBGs and the MPtBGs can be adjusted by changing the thickness ratio of the piezomagnetic domain to the piezoelectric domain when one of the two piezoelectric domains in a unit cell is given. (4) The extremely flat dispersion branches can appear periodically in the MPtBGs and show strong slow-wave delayed effect in this structure. (5) The maximum slow down factor of group velocity with a sample length of 1 cm around 10 GHz (21 GHz) in this structure can reach 70 521 (691 064) for the first (second) channels with $L_{P+} = 2L_{M+} = 2L_{P-} = 1.343$ μm and is far more than that of the similar structure [35]. In addition, the sense of forward and backward directions can be flipped easily by using an external magnetic field.

The rest of this paper is organized as follows: In Sec. 2, the brief descriptions of piezoelectric and piezomagnetic effects on the PPSUC are presented, and the experimental setting for them is sketched and the corresponding fundamental dynamic equations for piezoelectric and piezomagnetic domains are given, respectively. In Sec. 3, the microwave photonic and phononic band structures in the PPSUC are numerically computed by the transfer matrix method and the MPtBGs and the PnBGs are analyzed. Particularly, the relationship between the relative bandwidth of the PnBGs and the relative thickness distribution of three types of domains in a unit cell, and the slow-wave delayed effect obtained from the extremely flat dispersion branch locating within the MPtBGs are fully discussed. Our conclusion is given in Sec. 4.

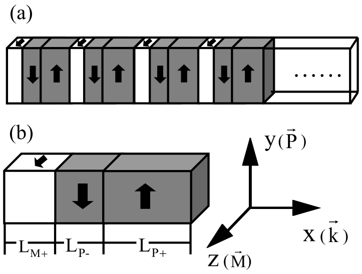

Fig. 1. A schematic diagram of (a) quasi-one-dimensional piezoelectric and piezomagnetic superlattices with three types of domains in a unit cell and (b) its minimum period. The white blocks refer to the ferromagnetic domains and the gray blocks denote the ferroelectric domains. Lattice displacement u_x and wavevector k are along x-axis, the magnetic field H_z and magnetization M_z are along $\pm z$-axis, and the electric field E_y and polarization P_y are along $\pm y$-axis. L_{M+}, L_{P+} and L_{P-} represent the thicknesses for piezomagnetic domain, piezoelectric domains with polarization along $\pm y$-axis, respectively.

2. The experimental configuration and dynamical equations

In this paper, we consider the piezoelectric–piezomagnetic superlattices with three types of domains in a unit cell as shown in Fig. 1. The transverse dimension of the superlattices is much smaller than the longitudinal dimension. Therefore, they can be treated as one-dimensional modulated structures. A ferromagnetic $CoFe_2O_4$ compound is selected as the piezomagnetic domain, and a ferroelectric PMN-PT compound is selected as the piezoelectric domain. Such choice is mainly based on the low lattice mismatch [36], low leakage current [37], and large magneto-electric effect between the piezoelectric and piezomagnetic domains. As in the situation in Fig. 1(b), there are three different types of domains in a minimum period, which includes the ferromagnetic domain with magnetization along z-axis and both ferroelectric domains with polarization along $\pm y$-axis, respectively, and are arranged repeatedly along x-axis, causing the PPSUC to be constructed. Such treatment is mainly based on the following considerations: (1) This structure ensures the use of a large transverse piezoelectric coefficient of PMN-PT and a large piezomagnetic coefficient of $CoFe_2O_4$, so that the maximum magneto-electric effect can be achieved; (2) This structure also ensures that periodic modulation of elastic constants and densities can be implemented, and the microwave photonic and phononic band structures can be generated simultaneously; (3) There exist periodically extremely flat dispersion branches within the MPtBGs in the microwave photonic band structure, which are fundamental to the significant slow-wave delayed effect.

Consider a plane electromagnetic wave impinging on the surface of the PPSUC, its propagation wavevector is perpendicular to the domain wall, which is coupled with the longitude acoustic wave along the x-axis. The dynamical properties of ferroelectric domains of the PPSUC are determined by the coupled Maxwell equations and lattice vibration equations.

$$\frac{\partial}{\partial x} E_y(x,t) = -\frac{\partial}{\partial t} B_z(x,t), \tag{1}$$

$$\frac{\partial}{\partial x} H_z(x,t) = -\frac{\partial}{\partial t} D_y(x,t), \tag{2}$$

$$\rho^e \frac{\partial^2}{\partial x^2} u_x(x,t) = \frac{\partial}{\partial x} Z_1(x,t). \tag{3}$$

$E_y(x,t)$, $H_z(x,t)$ and $u_x(x,t)$ refer to transverse electric field, magnetic field, and longitudinal lattice displacement, respectively. The electric displacement along y-axis, the magnetic induction along z-axis, and the stress component along x-axis are represented by $D_y(x,t)$, $B_z(x,t)$, and $Z_1(x,t)$, respectively. The symmetries of piezoelectric tensors manifest that the electric field and magnetic