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One-way electromagnetic waveguide using multiferroic Fibonacci superlattices

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ABSTRACT

The multiferroic Fibonacci superlattices (MFSs) are composed of single-phase multiferroic domains with polarization and magnetization according to the rule of Fibonacci sequence. We propose to construct a one-way electromagnetic waveguide by the MFSs. The forbidden band structures of the MFSs for the forward and backward electromagnetic waves are not completely overlapped, and an obvious translation between them occurs around the fixed point $\bar{\omega} = 1$ with broken time-reversal and space inversion symmetries (TRSIS), which indicates the existence of one-way electromagnetic modes in the MFSs. Transmission spectrum is utilized to present this property and to indicate further one-way electromagnetic modes lying within the polaritonic band gap. The maximum forbidden bandwidth (divided by midgap frequency) of 5.4% for the backward electromagnetic wave (BEW) is found, in which the forward electromagnetic wave (FEW) can pass. The functions of one-way propagation modes and polaritonic band gap integrated into the MFSs can miniaturize the one-way photonic devices. The properties can also be applied to construct compact microwave isolators.

1. Introduction

The one-way electromagnetic waveguide has attracted considerable attention [1], which possesses the property that electromagnetic waves can propagate only one-way in the range of certain frequency, while the opposite directional propagation modes are prohibited. There have been many theoretical [2–6] and experimental [7,8] studies with respect to one-way propagation modes, since they are predicted by Raghu and Haldane [2]. A variety of physical systems have been explored which involve photonic crystals with plasmonic [4], gyromagnetic [5,7], honeycomb magnetic [8], as well as optical waveguide isolators [3]. Owing to TRSIS breaking by magneto-optical and magnetic domains in a two-dimensional (2D) photonic crystal waveguide [3], the FEW and BEW for a given frequency have different group velocities. A 2D gyromagnetic photonic crystal [5] breaks time-reversal symmetry, resulting in the formation of electromagnetic chiral edge states (CESs), which can travel only in one direction and avoid the influence of disorderly scattering. A plasmonic metal under a static magnetic field integrated with photonic crystal can be constructed as a one-way electromagnetic waveguide [4]. The self-guiding electromagnetic CESs along the zigzag edge of a honeycomb magnetic photonic crystal are also experimentally observed [8].

From above comprehensive understanding, the constitution of generally unidirectional waveguide requires the integration of two functions, including the one-way propagation modes and photonic band-gap (PBG), and the former must lie within the frequency region of the latter in order to against disorderly backscattering, thus electromagnetic energy can always propagate towards a single direction. The unidirectional edge states [5,8] or the asymmetric bulk modes [3] are utilized to act as the propagation modes. Asymmetric modes in nonreciprocal spectrum indicate that there are two different propagation modes of electromagnetic waves for a given frequency. The waveguide systems for the realization of the nonreciprocal spectrum are generally made of ferromagnetic or dielectric materials [1] with appropriate arrangements, so that the TRSIS are broken. The occurrence of one-way waveguide essentially requires TRSIS breaking as well, the one-way propagation modes can be generated in the systems without time-reversal symmetry [5], and the formation of photonic bandgap requires no space-inversion symmetry [9]. Multiferroic [10] material can achieve TRSIS breaking because of their unique properties, which have several different ferroelectric properties in the same phase, such as ferroelectricity, ferromagnetism and ferroelasticity. The coexistence of electric and magnetic order parameters results in TRSIS breaking [11]. The multiferroic materials are usually also provided with piezoelectric and piezomagnetic

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properties, thereby strong couplings among electric polarization, magnetization and lattice strain [12,13] can be found. The lattice strain of multiferroic compounds can be induced by piezoelectric effect, and their magnetization can be affected as a result of magnetoelectric effect when an electric field is applied on such materials, similarly, an applied magnetic field can manipulate lattice strain and electric polarization as well. Several existing multiferroic materials, such as $BiFeO_3$, $Bi_2FeCr_2O_6$ and $BiCrO_3$, the values of their piezoelectric, piezomagnetic and magnetoelectric coefficients have been estimated on the basis of the first-principles calculations [14]. The corresponding coefficients of $Ga_{2-x}Fe_xO_3$ [15,16] have also been experimentally determined. It is a typical multiferroic material with ferrimagnetic ordering and has a ferrimagnetic transition temperature of $T_c = 260\text{–}345$ K [16]. Its thin films show ferrimagnetism at room temperature [15].

Although many studies [17–25] on modulated quasi-periodic superlattices have been carried out, they are composed by pure ferroelectric, ferromagnetic or multiferroic domains. In the multiferroic superlattices [26], the ferroelectric and ferromagnetic domains are arranged alternately along the x-axis, with periodic reversal of the electric polarization and magnetization, so they are modulated by both piezoelectric and piezomagnetic coefficients, and the coupled polaritonic band structures are discussed in detail. Electromagnetic waves propagating in MFSs has rarely been investigated up to now. In this paper, the $GaFeO_3$ compound is chosen as a suitable candidate of the MFSs because of availability of its relatively complete material parameters and its high transition temperature compared with other multiferroic materials. The experimental configuration we consider is illustrated in Fig. 1. The ferroelectric and ferromagnetic domains with magnetization along the $+z$-axis and electric polarization along the $+y$-axis are marked as A, and the domains with conversely polarization and magnetization are labeled as B. The stacking rule for defining the Fibonacci sequences is $S_l = S_{l-2}S_{l-1}$ for $l \geq 2$, with $S_0 = B, S_1 = A$, and S_l denotes the lth generational sequence. The number of layers is given by F_l, which follows the recursive rule $F_l = F_{l-1} + F_{l-2}$, and F_l is a Fibonacci number, with $F_1 = F_0 = 1$. The blocks of A and B are arranged along the x-axis according to the corresponding concatenation rule. The quasi-periodic piezoelectric superlattices cause the bulk acoustic phonon dispersion in the brillouin zone to be folded, the intersection and hybridization among the folded phonon branches and photon branch yields symmetrical polaritonic band structure. Different from those superlattices, the band structures of the MFSs are asymmetrical with respect to the FEW and BEW due to TRSIS breaking. Furthermore, a one-way propagation mode of electromagnetic wave for a given frequency may be obtained.

The rest of this paper is organized as follows: in Section 1, the brief descriptions of piezoelectric, piezomagnetic and magnetoelectric effects on the MFSs are presented, and the experimental setting for them is sketched. In Section 2, the corresponding fundamental dynamic equations for them are given. The band structures and transmission spectra are numerically computed and the corresponding results are analyzed. Particularly, the one-way electromagnetic waveguide using the MFSs is fully discussed. Our conclusion is given in Section 3.

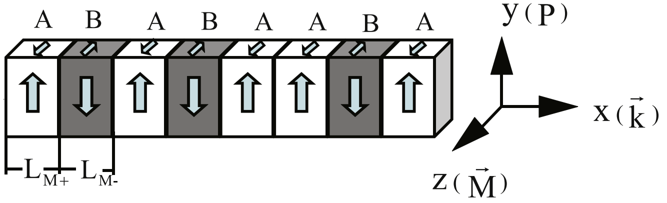

Fig. 1. The schematic diagram of a multiferroic Fibonacci superlattice with the generation of $l = 5$. L_{M+} and L_{M-} denote the domain thicknesses. The arrows in the y-axis denote the electric polarization of domains and the arrows in the z-axis denote the magnetization of domains. The electric field, magnetic field, and vibrational displacement are taken as y-axis, z-axis and x-axis, respectively.

2. Dynamical equations and numerical results

The experimental settings of the MFSs are different from those of the pure piezoelectric or piezomagnetic superlattices, which require the largest piezoelectric or piezomagnetic coefficient [21] to be utilized, resulting in the largest electromechanical or magneto-mechanical transducer effects. The MFSs should be modulated simultaneously by piezoelectric and piezomagnetic coefficients through appropriately arranging multiferroic domains. The magnetic point group of $GaFeO_3$ is $m'2'm$ [27] near room temperature. Its spontaneous polarization and magnetization are along the y-axis and z-axis, respectively, and all its parameters are available, which constitute the necessary conditions as a candidate material for the MFSs with the Fibonacci sequence S_5 (8 layers) displayed in Fig. 1. It has a considerable electromechanical coefficient and a still small magneto-mechanic transducer coefficient.

The longitudinal dimension of the MFSs is much larger than that of the transverse. Thus the MFSs can be regarded as a one-dimensional system. For a transverse-electric–magnetic (TEM) plane wave traveling through the MFSs, which lacks the longitudinal electric and magnetic field components, the coupling equations [26] among electric field, magnetic field and lattice displacement are written as follows:

$$\begin{aligned}\left(\frac{\omega L}{2\pi c_s}\right)\bar{E}_y(\bar{x},\omega) = &-i\alpha_1\frac{\partial}{\partial\bar{x}}\bar{H}_z(\bar{x},\omega)\\ &-\beta_1\left(\frac{\omega L}{2\pi c_s}\right)\theta_1(\bar{x})\frac{\partial}{\partial\bar{x}}\bar{u}_x(\bar{x},\omega)\\ &-\gamma_1\theta_1(x)\theta_2(x)\left(\frac{\omega L}{2\pi c_s}\right)\bar{H}_z(\bar{x},\omega),\end{aligned} \tag{1}$$

$$\begin{aligned}\left(\frac{\omega L}{2\pi c_s}\right)\bar{H}_z(\bar{x},\omega) = &-i\alpha_2\frac{\partial}{\partial\bar{x}}\bar{E}_y(\bar{x},\omega)\\ &-\beta_2\left(\frac{\omega L}{2\pi c_s}\right)\theta_2(\bar{x})\frac{\partial}{\partial\bar{x}}\bar{u}_x(\bar{x},\omega)\\ &-\gamma_2\theta_1(x)\theta_2(x)\left(\frac{\omega L}{2\pi c_s}\right)\bar{E}_y(\bar{x},\omega),\end{aligned} \tag{2}$$

$$\begin{aligned}\left(\frac{\omega L}{2\pi c_s}\right)^2\bar{u}_x(\bar{x},\omega) = &-\frac{\partial^2}{\partial\bar{x}^2}\bar{u}_x(\bar{x},\omega)\\ &+\frac{\partial}{\partial\bar{x}}[\theta_1(\bar{x})\bar{E}_y(\bar{x},\omega)]+\frac{\partial}{\partial\bar{x}}[\theta_2(\bar{x})\bar{H}_z(\bar{x},\omega)].\end{aligned} \tag{3}$$

The above dimensionless equations describe dynamical properties for electromagnetic waves propagating in the MFSs. ω indicates frequency, $L = L_{M+} + L_{M-}$ is the sum of A and B domains. $c_s = \sqrt{K_{11}/\rho}$ is the sound velocity in $GaFeO_3$ compound, ρ denotes its density. The nonzero dimensionless functions $\bar{E}_y(\bar{x},t) = \bar{d}_{21}E_y(x,t)$, $\bar{H}_z(\bar{x},t) = \bar{T}_{31}H_z(x,t)$, $\bar{u}_x(\bar{x},t) = 2\pi u_x(x,t)/L$ denote transverse electric field, transverse magnetic field and lattice displacement, respectively. $\bar{x} = x2\pi/L$ is a dimensionless variable. The step-functions $\theta_i(\bar{x}) = \pm 1$ $(i = 1, 2)$ describe the modulation of a superlattice, $\theta_1(\bar{x}) = \pm 1$ denotes the domains with magnetization along the $\pm z$ axis, and $\theta_2(\bar{x}) = \pm 1$ represents the polarization along the $\pm y$ axis. The three groups of dimensionless parameters of above equations fully describe the dynamical properties of the MFSs. $\alpha_1 = \bar{d}_{21}/c_s\epsilon_0\bar{\epsilon}\bar{T}_{31}$ and