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Piezoelectricity induced defect modes for shear waves in a periodically stratified supperlattice

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ABSTRACT

Properties of shear waves in a piezoelectric stratified periodic structure with a defect layer are studied for a superlattice with identical piezoelectric materials in a unit cell. Due to the electro-mechanical coupling in piezoelectric materials the structure exhibits defect modes in the superlattice with full transmission peaks both for full contact and electrically shorted interfaces. The results show an existence of one or two transmission peaks depending on the interfacial conditions. In the long wavelength region where coupling between electro-magnetic and elastic waves creates frequency band gaps the defect layer introduces one or two defect modes transmitting both electro-magnetic and elastic energies. Other parameters affecting the defect modes are the thickness of the defect layer, differences in refractive indexes and the magnitude of the angle of the incident wave. The results of the paper may be useful in the design of narrow band filters or multi-channel piezoelectric filters.

1. Introduction

The piezoelectric, piezomagnetic and combined magneto-electric effects in periodic structures can significantly influence the frequency band gap structures which appear due to the periodic modulation of the physical parameters and result from the Bragg reflection [1–8]. It has been shown that phononic bandgaps can be achieved in a piezoelectric structure that is homogeneous but is formed by simply periodically reversing the sign of the piezoelectric tensor [9,10]. This gives certain advantages over other types of tunable materials in terms of wide range of applications in smart materials and structures. Thin film piezoelectric layered structures, for example, have been extensively used in high frequency, high performance, small size, low cost, low energy consumption technologies.

In periodic structures made from materials with coupled response effects, other mechanisms such as acousto-optic coupling can also create band gaps. A piezoelectric or piezomagnetic superlattice made of a periodically domain-inverted dielectric crystal with periodically modulated piezoelectric or piezomagnetic coefficients but a homogeneous refractive index, can be considered as a one dimensional diatom ionic crystal with positive and negative ions arranged periodically [11]. Coupling between transverse lattice vibrations and electro-magnetic waves in an ionic crystal can lead to phonon polariton coupling with possible stop bands in the infrared region [12]. Analogously, piezoelectric and piezomagnetic periodic structures with the periodicity of the lattice expanded from an atomic scale to microns can exhibit similar coupling and resonant band gap structure in the microwave region [13–18]. This coupling between the electromagnetic wave and the superlattice vibration takes place in the long wavelength region where the superlattice can be considered as a deep subwavelength artificial material. Using the long wavelength approximation it has been shown that the piezoelectric superlattice exhibits a new type of polariton, in which the

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resonance frequency is determined by the period of the superlattice, and negative effective permittivity occurs near the high frequency side of the resonance [19,20]. Theoretical and experimental work has suggested that a different type of polariton is also possible in a piezoelectric superlattice, that is coupling of electro-magnetic waves with longitudinal superlattice vibrations [21].

While the long-wave approximation only reveals the phonon-photon polariton at high acoustic frequencies in the middle of the Brillouin zone the analytical solution shows that coupling of photons and phonons is possible also at optical frequencies in the whole Brillouin zone [22,23]. It also reveals a phonon-polariton gap in a piezoelectric phononic crystal with a unit cell made of different constituent materials. The similarities and differences between artificial superlattices and real lattices suggests rich physics in artificial microstructures and gives a possibility to control and manipulate both photons and phonons simultaneously [21,24].

In order to control frequency band structures, including the location and bandwidth of stop bands, tunable periodic structures can be designed by introducing defect layers into the structure, changing the geometry and altering the elastic characteristics of these inclusions [25]. When the periodicity is broken by introducing appropriate defects, localised defect modes will appear within band gaps, which lead to the selective transmission of acoustic and electromagnetic waves.

For one-dimensional piezoelectric phononic crystals the control of defect modes is of great interest in tunable filters [26,27]. A number of interesting results include a new type of omnidirectional gap that is found in one-dimensional photonic crystals composed of permittivity or permeability-negative materials, where the spectral position of the defect mode is almost independent of incident angles and nearly invariant with the scaling [28]. Using a nematic liquid crystal as a defect layer an electrical tuning of defect modes in a one-dimensional periodic structure has been demonstrated in Ref. [29]. The polaritonic band structures and transmission spectra of piezoelectric-modulated superlattices are investigated in Ref. [24]. The properties of band gap materials have been already used in designing various devices such as band filters, perfect mirrors and microcavity lasers.

Because of the potential applications, it is of great interest to investigate the defect modes in piezoelectric superlattices. Due to the magneto-elastic coupling the piezoelectric periodic structures become sensitive to boundary conditions between interfaces demonstrating new and exciting features. This makes even the one dimensional problem diverse, including situations such as defect modes in a periodic structure with cells composed of identical but oppositely polarised piezoelectric material, commonly referred to as superlattice, with full contacts between interfacial layers and in a periodic structure with identical elements in the unit cell separated by electrically shorted interfaces. Bragg resonances, the presence of trapped modes and slow waves and the defect mode in a piezoelectric finite width waveguide consisting of layers separated by electrically shorted interfaces is considered in Ref. [30]. Although shorted interfaces make the structure act as a periodic phononic crystal with frequency band gaps even if the unit cell has identical elements and the same polarisation, the superlattice with these interfaces does not produce band gaps. The reflection of an electro-elastic wave is caused by the equipotential condition at the interfaces and only one coupled electro-elastic wave propagates in the system. At high frequencies the piezoelectricity does not affect the wave propagation.

The problem is more interesting in a periodic superlattice with full contact interfaces. The system in this case is described by two coupled electro-acoustic waves and exhibits a very interesting acousto-optic resonance (phonon-polariton) at high acoustic frequencies which cannot be observed in the previous problem. A question arises how phonon-polariton band gaps caused by this coupling will be affected by a defect layer and whether a defect mode can be observed in the long wavelength region. To the best of our knowledge very little work is done on the property of defect modes for phonon polariton resonances. The dynamic setting for Maxwell's equation, where both the optical effect and the effect from the rotational part of the electric field are taken into account, makes it possible to investigate this problem as well.

2. Statement of the problem

We investigate the reflection/transmission properties of a finite stack of transversely isotropic hexagonal piezoelectric crystal (6 mm) periodically stratified piezoelectric crystal with a defect layer and with the crystallographic axes directed along the Oz direction (Fig. 1). The defect layer with width a_3 is introduced in such a way that the periodic structure has a mirror symmetry about it. On each side of the defect layer the periodic structure consists of a stack of n cells each containing a pair of layers ($j = 1, 2$) made of oppositely polarised identical piezoelectric material and lengths a_1 and a_2 ($\beta = a_1 + a_2$) and one additional layer a_1 (Fig. 1).

We start by writing the equations of motion, Maxwell's equations and constitutive relations for piezoelectric martials. Due to the piezoelectric effect these equations couple through the constitutive equations as follows.

$$\mathrm{div}(\boldsymbol{\sigma}) = \rho\frac{\partial \mathbf{u}}{\partial t}, \quad \mathrm{curl}(\mathbf{E}) = -\frac{\partial \mathbf{B}}{\partial t}, \quad \mathrm{curl}(\mathbf{H}) = \frac{\partial \mathbf{D}}{\partial t}, \tag{1}$$

$$\boldsymbol{\sigma} = \mathbf{c} : \mathbf{S} - \mathbf{e}\cdot\mathbf{E}, \quad \mathbf{D} = \mathbf{e} : \mathbf{S} + \boldsymbol{\varepsilon}\cdot\mathbf{E}, \quad \mathbf{B} = \boldsymbol{\mu}\cdot\mathbf{H}, \tag{2}$$

where $\boldsymbol{\sigma}$, $\mathbf{S}$, $\boldsymbol{\varepsilon}$ and $\boldsymbol{\mu}$ are the stress, strain, dielectric permittivity and magnetic permeability second rank tensors, $\mathbf{e}$ is the piezoelectric third rank tensor, $\mathbf{c}$ is the fourth rank elasticity tensor, ρ is the density, **D, E, B** and **H** are electric displacement, electric field, magnetic induction and magnetic field vectors and **u** is the displacement vector, dot corresponds to the tensor contraction