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Wave propagating in multilayers composed of piezo electric and piezo magnetic layers

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ABSTRACT

In this paper, a study of effective parameters and wave properties of a slab of an artificial material comprised of alternating piezomagnetic and piezoelectric layers is presented. This kind of composite structure features new functionalities including effective magneto-electric coupling nonexistent in either constituent layer. In the first section, the equations of propagation of hybrid elasto-electro-magnetic waves in the equivalent homogeneous medium are derived by using a double scale method based on the periodical homogeneization. The wave length is considered to be much greater than the layer spatial periodicity and electromagnetic retardation is not taken into account. In the second section, dispersion relations for the hybrid waves travelling in a slab with previously established effective parameters are obtained. It was shown that although all three components, mechanic, electric and magnetic, contribute to the overall oscillatory behavior, the wave is predominantly elastic. At the same time, such composite media demonstrate double tunability, electric via the piezoelectric phase and magnetic through the piezomagnetic one, and can be regarded as novel functional materials.

1. Introduction

The amount of studies on piezoelectric materials and on piezomagnetic materials has drastically increased during the two latest decades [1]. Developing smart materials or multifunctional structures keeps getting more and more interesting for many applications. The electronics takes benefit from mechanical properties of some crystals through the piezoelectric effect. Moreover, piezomagnetic materials also present an interesting coupling: a magnetic field can be generated by a mechanical strain and vice versa. Direct coupling between electric field and magnetic field can occur in natural materials, known as intrinsic multiferroics. They are relatively few and the effect in them is too weak to make it of any interest to practical applications. At variance with the natural multiferroics, the composite materials made of ferroelectric and ferromagnetic phases can generate huge magnetoelectric responses allowing for technological applications in various domains such as data storage, mechanical devices, magnetic sensors, high frequency signal treatment. This field belongs to the large domain of metamaterials possessing properties that cannot be found naturally. Table 1.

The magnetoelectric effect (ME), even though not existing in each constituent phase, can be large in the composite. The shape plays a major role. The ME effect in the composite results from the combination of the piezomagnetic and piezoelectric effect localized in non-overlapping spatial domains. It is schematized by the formula [2]:

$$\text{Magnetic electric effect} = \frac{\text{Magnetic field}}{\text{Mechanical strain}} \times \frac{\text{Mechanical strain}}{\text{Electric field}}$$

Deriving the effective properties allows for controlling the response of smart structures to external influences. In this paper, the longitudinal waves in a periodic stack consisting of piezoelectric layers and of piezomagnetic layers, propagating along the direction normal to the layers are studied. The paper is organized in the following way.

Firstly, the basic equations for composites made of piezoelectric and piezomagnetic phases are reminded and the effective elastic, piezoelectric, piezomagnetic and magnetoelectric coefficients are derived thanks to the Sanchez-Lene-Dumont's method for homogenization of a periodic medium, [3–5].

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Table 1
Material constants for $CoFe_2O_4$ and $BaTiO_3$.

Parameter	$BaTiO_3$ (phase piezoelectric)	$CoFe_2O_4$ (phase piezomagnetic)
$\rho(kg/m^3)$	5.3×10^3	5.8×10^3
$C_{1111}(Pa)$	166×10^9	286×10^9
$C_{3333}(Pa)$	162×10^9	269.5×10^9
$C_{1133}(Pa)$	78×10^9	170.5×10^9
$C_{1313}(Pa)$	43×10^9	45.3×10^9
$e_{333}(C/m^2)$	18.6	
$e_{311}(C/m^2)$	−4.4	
$e_{113}(C/m^2)$	11.6	
$q_{333}(N/Am)$		699.7
$q_{311}(N/Am)$		580.3
$q_{113}(N/Am)$		550
$\kappa_{11}(F/m)$	11.2×10^{-9}	0.08×10^{-9}
$\kappa_{33}(F/m)$	12.6×10^{-9}	0.093×10^{-9}
$\mu_{11}(Ns^2/C^2)$	5×10^{-6}	157×10^{-6}
$\mu_{33}(Ns^2/C^2)$	10×10^{-6}	157×10^{-6}

Secondly, the dynamics of the composite medium is studied: an equation allowing for evaluating the eigen frequencies is derived. The aim of the calculation is to provide the dispersion law [6].

Thirdly, the eigen frequency equation is numerically solved with the parameters of $BaTiO_3$ and of $CoFe_2$ O_4. Several volume fractions of $BatiO_3$ are considered. Brillouin spectroscopy is the most appropriate candidate for experimental verification of theoretical predictions and numerical results obtained in this paper. This powerful and versatile technique, usually referred to as BLS (Brillouin Light Scattering), is based like Raman spectroscopy on inelastic scattering of laser light by thermally excited phonons, gives direct access to the dispersion characteristics of the probed elastic or magnetic waves in a considerable range of temporal and spatial frequencies. Thus high-precision measurements of the Doppler frequency shift in the backscattered light caused by the propagating phonons with the help of sophisticated multi-pass Fabry Perot interferometers can be carried out in a frequency range of 3–300 GHz [7] with their wave vector varying from 0.2 to 20 μm^{-1}. The latter is related to the angle of incidence θ by the following expression: $k = 4\pi \sin \theta/\lambda$ where λ=514.5 nm is the wave length of the Argon laser (for example). If the spatial period of the composite medium is small compared to the probed wave length then the variation of the frequency *versus* the wave vector allows for evaluating the parameters of the effective medium.

An interested reader can find more details in Ref. [8]. In the case of an isotropic opaque slab whose thickness is much larger than the laser wave length, the elastic wave evidenced by this technique is the Rayleigh mode whose angular frequency ω is obtained from the relation

$$C_{1111}\left(2C_{2323} - \rho\left(\frac{\omega}{k}\right)^2\right)^4 = 16C_{2323}^3\left(C_{2323} - \rho\left(\frac{\omega}{k}\right)^2\right) \times \left(C_{1111} - \rho\left(\frac{\omega}{k}\right)^2\right)$$

where C_{ijkl} are the elastic constants and ρ is the mass of the unit volume.

It is to mention that at least two alternative experimental methods provide the dynamic properties: picosecond acoustic technique [7] and ultrasonic immersion test [9].

2. Presentation of the piezoelectric and piezomagnetic materials and notations

We consider a three-dimensional piezoelectric-piezomagnetic heterogeneous body with natural reference configuration the open subset $\boldsymbol{\Omega}$ of $\mathbb{R}^3$. We denote by $\mathbf{e}_1$, $\mathbf{e}_2$, $\mathbf{e}_3$ the canonical basis of $\mathbb{R}^3$ and by (x_1,x_2,x_3) the associated cartesian coordinates. The body is assumed to be infinite in the directions $\mathbf{e}_1$ and $\mathbf{e}_2$. It has a constant thickness 2 h in the $\mathbf{e}_3$ direction and is filled with periodically layered piezomagnetic and piezoelectric material as shown in (Fig. 1). The layers are stacked along the direction $\mathbf{e}_1$, and supposed perfectly bounded.

The constitutive equations in the piezoelectric-piezomagnetic composites in linear approximation can be written by direct notation for tensors as [10]:

$$\begin{aligned} \boldsymbol{\sigma} &= \mathbf{C}\boldsymbol{\varepsilon} - \mathbf{e}^T\mathbf{E} - \mathbf{q}^T\mathbf{H} \\ \mathbf{D} &= \mathbf{e}\boldsymbol{\varepsilon} + \boldsymbol{\kappa}\mathbf{E} + \boldsymbol{\alpha}\mathbf{H} \\ \mathbf{B} &= \mathbf{q}\boldsymbol{\varepsilon} + \boldsymbol{\alpha}^T\mathbf{E} + \boldsymbol{\mu}\mathbf{H} \end{aligned} \quad (1)$$

where **E**, **D**, **B**, and **H** are electric field vectors, electric displacement, magnetic induction and magnetic field vectors, respectively. $\boldsymbol{\sigma}$, $\boldsymbol{\varepsilon}$, the stress, strain second rank tensor respectively. **C**, **e**, **q**, denote the fourth-rank elastic stiffness tensor, the third-rank piezoelectric tensor, the third-rank piezomagnetic tensor respectively. $\boldsymbol{\kappa}$, $\boldsymbol{\mu}$ and $\boldsymbol{\alpha}$ are the second-rank dielectric, the second-rank magnetic permeability, the magnetoelectric second-rank tensors, respectively. The superscript T means the transpose of the tensor. Since we are interested in the materials without any natural coupling between electric and magnetic fields we suppose $\boldsymbol{\alpha}$=0 for both constituent phases. Thus, for the piezoelectric phase in the composite, $\mathbf{q} = 0$:

$$\boldsymbol{\sigma} = \mathbf{C}\boldsymbol{\varepsilon} - \mathbf{e}^T\mathbf{E}, \quad \mathbf{D} = \mathbf{e}\boldsymbol{\varepsilon} + \boldsymbol{\kappa}\mathbf{E}, \quad \mathbf{B} = \boldsymbol{\mu}\mathbf{H}, \quad (2)$$

and for the piezomagnetic phase in the composite, $\mathbf{e} = 0$ and $\boldsymbol{\alpha} = 0$:

$$\boldsymbol{\sigma} = \mathbf{C}\boldsymbol{\varepsilon} - \mathbf{q}^T\mathbf{H}, \quad \mathbf{D} = \boldsymbol{\kappa}\mathbf{E}, \quad \mathbf{B} = \mathbf{q}\boldsymbol{\varepsilon} + \boldsymbol{\mu}\mathbf{H}. \quad (3)$$

We assume that the coefficients of these tensors admit the usual symmetry properties [11]:

$$C_{ijkl} = C_{jikl} = C_{ijlk} = C_{klij}, \quad e_{kij} = e_{kji}, \quad q_{kij} = q_{kji}, \quad \kappa_{ij} = \kappa_{ji}, \quad \mu_{ij} = \mu_{ji}.$$

The material is supposed to be isotropic in the plane perpendicular to e_3 axis and polarized in this direction. Consequently the non zero coefficients in the tensors **C**, **e**, **q**, $\boldsymbol{\kappa}$, $\boldsymbol{\mu}$ are:

$$C_{1111} = C_{2222}, \ C_{3333}, \ C_{1133} = C_{2233}, \ C_{2211} = C_{1313} = C_{2323}, \ C_{1212}. \quad (4)$$

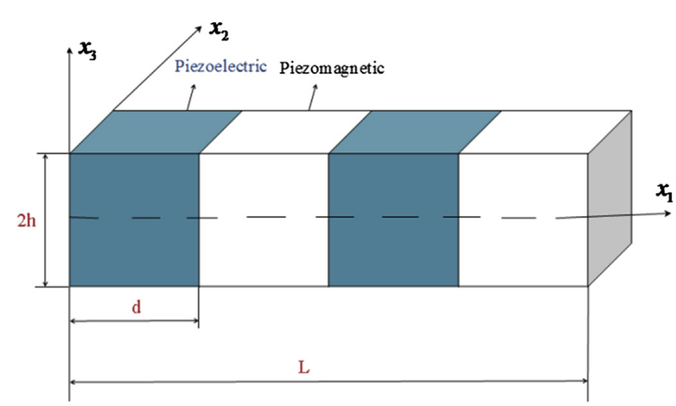

Fig. 1. Multilayer consisting of piezo electric and piezo magnetic layers.