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Optimization of magnetoelectricity in multiferroic fibrous composites

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ABSTRACT

We propose a method to optimize the effective magnetoelectric voltage coefficient of fibrous composites made of piezoelectric and piezomagnetic phases. The optimization of magnetoelectricity is with respect to the crystallographic orientations and the volume fraction for the two materials. We show that the effective in-plane ($\alpha^*_{E,11}$) and out-of-plane ($\alpha^*_{E,33}$) coupling constants can be enhanced many-fold at the optimal orientation compared to those at normal orientation. For example, we show that the constants are 101 and 5 times larger for the optimal orientation of $CoFe_2O_4$ fibers in a $BaTiO_3$ matrix of the optimized volume fraction compared to the normal orientation, while they are 43 and 5 times larger for $BaTiO_3$ fibers in a $CoFe_2O_4$ matrix. The predictions are in good agreement with the finite element analysis.

1. Introduction

Magnetoelectric (ME) materials, which show a polarization induced by an applied magnetic field, or conversely, a magnetization induced by an applied electric field, have been the focus of recent research due to their coupling between the electric and magnetic fields. This make them particularly appealing and promising for a wide range of applications, such as ME data storage and switching, magnetic field detectors, and amplification and frequency conversion between the electric and magnetic fields (Fiebig, 2005). However, the ME effect in single phase materials is rather weak or cannot be observed at room temperature (Astrov, 1960; Rado and Folen, 1961). Composite materials, on the other hand, offer an alternative option for improvement of the ME coupling, as explained in recent reviews by Eerenstein et al. (2006) and Nan et al. (2008). This much stronger ME effect could be realized in a composite made of piezoelectric and piezomagnetic/magnetostrictive phases using product properties: an applied magnetic field creates a strain in the piezomagnetic/magnetostrictive material which in turn creates a strain in the piezoelectric material, resulting in an electric polarization.

A variety of models have been proposed to predict the effective magnetoelectroelastic moduli of the multiferroic composite. The estimates of the effective properties of ME composites are usually obtained by various approximate mean-field models (Nan, 1994; Benveniste, 1995; Wu and Huang, 2000). The exact solutions for local fields are available for simple microstructures such as a single ellipsoidal inclusions (Huang and Kuo, 1997; Li and Dunn, 1998a), periodic arrays of circular/elliptic fibrous ME composites (Kuo, 2011; Kuo and Pan, 2011) and laminates (Srinivas et al., 2001; Bichurin et al., 2003), etc. A homogenization method was employed for calculating the effective properties of periodic ME fibrous composites (Aboudi, 2001; Camacho-Montes et al., 2009), while numerical methods based on the finite element analysis have also been developed to address ME composites with more general microstructures (Liu et al., 2004; Lee et al., 2005). However, much of this theoretical development limits itself to the situation where the poling direction (magnetic axis) of the piezoelectric (piezomagnetic) material is either normal to or along the layer (fiber) direction. Further, many of these works assume transverse isotropy or uniaxial symmetry.

In the work of Li and Dunn (1998b), they used Eshelby's pioneering approach to study the fields in and around inclusions and inhomogeneities in *anisotropic* solids exhibiting

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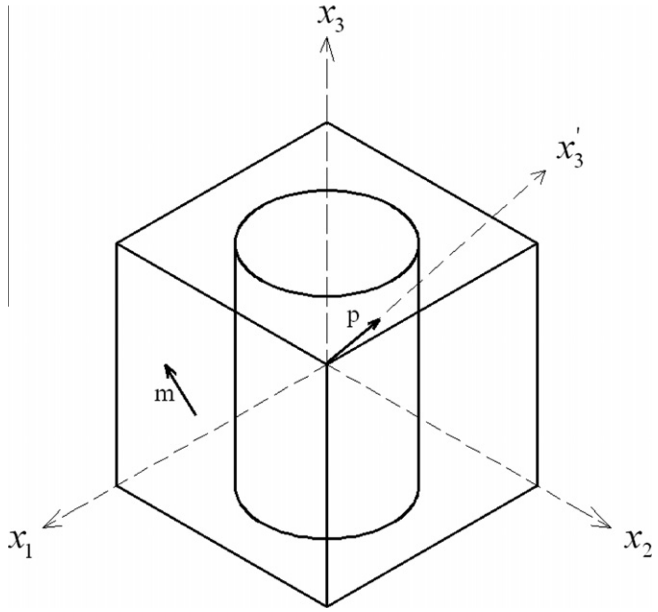

Fig. 1. The fibrous composite configurations.

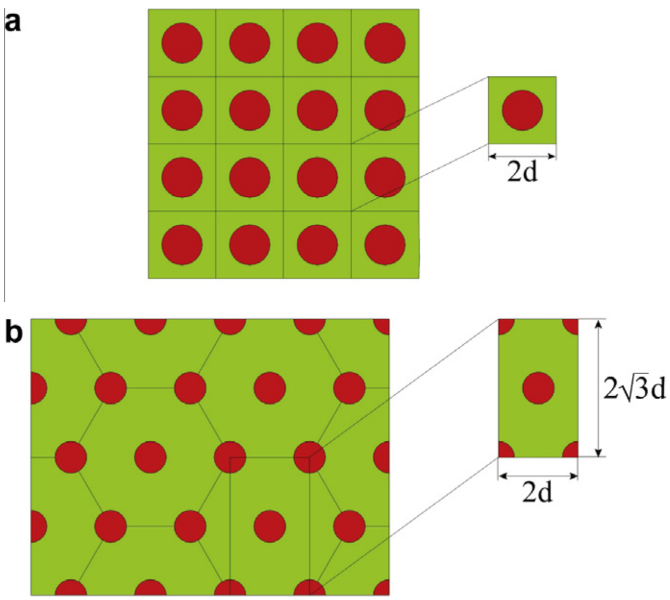

Fig. 2. A schematic representation of a unit cell. (a) A square array. (b) A hexagonal array.

full coupled-field behavior. Later, Li (2000a) developed a numerical algorithm to evaluate the magnetoelectroelastic Eshelby's tensor for the general material symmetry and ellipsoidal inclusion shape. Recently, experiments by Yang et al. (2006) and Wang et al. (2008) showed that single crystals are attractive and the effective ME coefficient of the laminate can depend sensitively on the crystallographic orientation of the material. Srinivas et al. (2006) developed a mean-field Mori–Tanaka model to calculate the ME coupling of matrix-based multiferroic composites, emphasing the effects of shape and orientation distribution of second phase particles. In addition, Kuo et al. (2010) proposed a simple framework to optimize the effective magnetoelectric response of a piezoelectric-magnetostrictive bilayer. The essence of the concept is that the induced electric field in the piezoelectric phase could be increased if the *orientation* and *volume fraction* of the piezoelectric layer can be carefully chosen. They have used it to show that, for anisotropic materials as in single crystals, the optimal ME response is obtained for non-trivial orientations.