Propagation of Shear Horizontal Waves in Laminated Composites Based on Different Orientation Poled 0.72Pb(Mg\(_{1/3}\)Nb\(_{2/3}\))O\(_3\)-0.28PbTiO\(_3\) Single Crystals

WANG Yu-Ling(王玉玲)\(^1, 2\), ZHANG Rui(张锐)\(^1\)*, SUN En-Wei(孙恩伟)\(^1\), SONG Wei(宋伟)\(^1\), CAO Wen-Wu(曹文武)\(^1\)*

\(^1\)Condensed Matter Science and Technology Institute, Harbin Institute of Technology, Harbin 150080
\(^2\)Department of Physics, Daqing Normal University, Daqing 163712

\(^3\)Materi\(als\) Research Institute, The Pennsylvania State University, University Park, Pennsylvania 16802, USA

(Received 7 June 2013)

The propagation characteristics of shear horizontal waves in [001]\(c\), [011]\(c\), and [111]\(c\) direction polarized 0.72Pb(Mg\(_{1/3}\)Nb\(_{2/3}\))O\(_3\)-0.28PbTiO\(_3\) (PMN-0.28PT) piezoelectric single crystals/polymer periodic laminated composites are studied by the global matrix method. The numerical results show that the piezoelectric effect has significant influence on the bandgaps width of the composite structure containing [011]\(c\), and [111]\(c\), poled PMN-0.28PT, but little effect on the band structure of the system containing [001]\(c\), poled single crystal. In addition, the first bandgap (FBG) width of the composite structure depends strongly on the filling directions when the filling fraction of PMN-0.28PT is larger than 0.5, and its FBG starting frequency displays no distinct difference among the three polarization directions at all filling fractions. The reported results provide valuable guidelines for designing filters and transducers made of composite structures containing relaxor-based ferroelectric single crystals.

PACS: 63.22.Np, 72.80.Tm, 73.20.At

In this work, we employ the global matrix method to calculate the shear horizontal (SH) wave propagation inside the composite structures of relaxor-based PMN-0.28PT ferroelectric single crystals. The influences of piezoelectric effect on the SH wave transmission spectrum are investigated with the PMN-0.28PT single crystal being poled along [001]\(c\), [011]\(c\), and [111]\(c\), respectively. Also, the band structure of the laminated structure is studied at various filling fractions of PMN-0.28PT single crystals. The obtained result is useful for the better understanding of SH wave band structures and provides guidelines for the development of high-efficiency electric-acoustic devices.

In our calculations, the linear piezoelectric relations, quasi-stationary approximation for electric potential and Cartesian coordinates are utilized. Figure 1 shows the periodic laminated structure of PMN-0.28PT and polymer, alternating in the X direction, which is embedded in two semi-infinite piezoelectric media. The SH wave propagates in the X and Y plane, and vibrates along the Z direction. The main crystallographic axes X, Y, and Z of the single crystals are parallel to the following pseudo-cubic directions: X→[100]\(c\), Y→[010]\(c\), Z→[001]\(c\) for the [001]\(c\) polarized case, X→[011]\(c\), Y→[100]\(c\), Z→[011]\(c\) for the [011]\(c\) polarized case, and X→[110]\(c\), Y→[11\(\bar{1}\)]\(c\), Z→[111]\(c\) for the [111]\(c\) polarized case.

The general elastic wave equations in a piezoelectric medium are:

\[
\frac{\partial^2 u_i}{\partial x_i x_1} - \frac{\partial^2 \varphi}{\partial x_i x_k} = \rho \frac{\partial^2 u_i}{\partial t^2},
\]

\[
\frac{\partial^2 u_i}{\partial x_i x_1} - \frac{\partial^2 \varphi}{\partial x_k x_1} = 0, \quad i, j, k, l = 1, 2, 3, \quad (1)
\]

*Supported by the National Basic Research Program of China under Grant No 2013CB632900, the National Natural Science Foundation of China under Grant No 50602009, Program of the Ministry of Education of China for New Century Excellent Talents in University under Grant No NCET-06-0045, Postdoctoral Science Research Developmental Foundation of Heilongjiang Province under Grant No LBH-Q06008.

**To whom correspondence should be addressed. Email: ruizhang_ccmst@hit.edu.cn; dzk@psu.edu
© 2013 Chinese Physical Society and IOP Publishing Ltd

096301-1
where \( u_i \) is the mechanical displacement in the \( i \) direction, \( \varphi \) is the electrical potential function, \( \rho \) is the mass density of the medium, \( c_{ijkl} \) are the components of the elastic stiffness tensor at constant electric field, \( e_{ijk} \) are the components of piezoelectric constant tensor, \( \varepsilon_{ik} \) are the components of dielectric permittivity tensor at constant strain.

For the SH wave obliquely incident into the laminated structure, the mechanical displacement vectors \( u \) and the scalar electric potential \( \varphi \) can be expressed as:

\[
u_{ij} = (A_j e^{ik_y(x-x_i)} + B_j e^{-ik_y(x-x_i)})e^{i(k_yy-\omega t)},
\]

\[
\varphi_j = [A_j' e^{ik_y(x-x_j)} + B_j' e^{-ik_y(x-x_j)}] + \frac{\varepsilon_j}{\varepsilon} (A_j e^{ik_y(x-x_j)} + B_j e^{-ik_y(x-x_j)})e^{i(k_yy-\omega t)},
\]

where \( k_j \) and \( k_y \) are the wave vectors along the \( X \) and \( Y \) directions in the \( j \)th layer, respectively; \( k_j \) can be further expressed as \( k_j = [(\omega/\varepsilon_j)^2 - k_y^2]^{1/2} \) with \( \omega \) being the angular frequency, and \( v_j = [(e + e_2^2/\varepsilon)/\rho]^{1/2} \) is the \( \text{SH} \) wave velocity. \( A_j, A_j', B_j, B_j' \) in \( (2) \) and \( (3) \) are the continuous functions of \( x \) and \( y \) along with a length \( L \), which is embedded in the piezoelectric single crystal. The recording the piezoelectric effect has a significantly different \( \text{SH} \) wave transmission in the composite of PMN-0.28PT single crystal or piezoelectric ceramic.

For PMN-0.28PT single crystals poled along [001] \( _c \), [011] \( _c \), and [111] \( _c \) directions, \( k_{15} \) has drastically different piezoelectric properties due to their different domain pattern symmetries.\(^{[13]} \) We investigate the influence of piezoelectric effect on the \( \text{SH} \) wave transmission spectrum in the composite structure, which has 2 cells with 1 mm length. Figure 2 shows its band structure at the filling fraction of 0.2, where the solid line and the dotted line denote the \( \text{SH} \) wave transmission spectra with and without the piezoelectric effect, respectively. The transmission spectra have completely overlapped profile in both the cases for the composite structure consisting of [001] \( _c \) poled PMN-0.28PT single crystal, which indicates that the piezoelectric effect has no influence on the \( \text{SH} \) wave propagation in the composite.

PMN-0.28PT single crystals poled along [001] \( _c \), [011] \( _c \), and [111] \( _c \) directions, which is stiffened because of the piezoelectric effect.\(^{[21]} \) In PMN-0.28PT single crystals poled along [001] \( _c \) and [111] \( _c \) directions, \( k_{15} \) is much larger considering the piezoelectric effect.\(^{[13]} \) As a result, a significantly different \( \text{SH} \) wave transmission of the piezoelectric ceramic/polymer composite is associated with the \( \text{SH} \) wave transmission spectrum of the dielectric permittivity tensor.\(^{[11]} \) The electromagnetic coupling constant \( k_{15} \) of the piezoelectric material is closely associated with the elastic constant \( c_44 \), which is stiffened because of the piezoelectric effect.\(^{[21]} \) In PMN-0.28PT single crystals poled along [001] \( _c \), and [111] \( _c \) directions, \( k_{15} \) is much larger considering the piezoelectric effect.\(^{[13]} \) As a result, a significantly different \( \text{SH} \) wave transmission spectrum in the composite containing [001] \( _c \) (Fig. 2(b)) and wider bandgaps manifested in the laminated structure containing [111] \( _c \) poled PMN-0.28PT (Fig. 2(c)). These results are different from that of the piezoelectric ceramic/polymer composite system even though the filling fraction in both the situations are small.\(^{[7]} \) The electromagnetic coupling constant \( k_{15} \) of the piezoelectric material is closely associated with the elastic constant \( c_44 \), which is stiffened because of the piezoelectric effect.\(^{[21]} \) In PMN-0.28PT single crystals poled along [001] \( _c \), and [111] \( _c \) directions, \( k_{15} \) is much larger considering the piezoelectric effect.\(^{[13]} \) As a result, a significantly different \( \text{SH} \) wave transmission spectrum in the composite containing [001] \( _c \) (Fig. 2(b)) and [111] \( _c \) (Fig. 2(c)) poled PMN-0.28PT is produced by the strong piezoelectric effect. Since \( k_{15} \) of [001] \( _c \) poled PMN-0.28PT is smaller compared with that of the piezoelectric ceramic,\(^{[7]} \) the piezoelectric effect has no influence on the \( \text{SH} \) wave propagation in the composite.
structure with a larger filling fraction of 0.7. The structures, where they have 3 cells with 1 mm length. SH wave transmission spectrum of the [001]c poled PMN-0.28PT based composite structure shows no obvious difference with and without the piezoelectric effect. Critical filling fraction of about 0.7 for [001]c, poled single crystal as shown in Fig. 3(a), which is similar to the single crystal, and about 0.8 for [011]c and [111]c poled case of 0.2 filling fraction. This is also correlated with the small $\varepsilon_{15}$ of [001]c poled PMN-0.28PT.$^{[13]}$ In the composite structure containing [011]c and [111]c poled PMN-0.28PT, a distinctly enlarged bandgap shows significant difference when the filling fraction is width is observed in Figs. 3(b) and Fig. 3(c), because of strong shear piezoelectricity in these two polarized single crystals. Also, we find another significant impact on the piezoelectric effect on the band structure at larger filling fraction by comparing the SH wave propagation in the composites at the filling fractions of 0.2 and 0.7, i.e., the piezoelectric effect plays a more important role in larger filling fraction.

Fig. 2. The transmission spectrum for SH waves normal incident to the periodic laminated composites based on different polarized directions PMN-0.28PT single crystals at the filling fraction of 0.2: (a) [001]c, (b) [011]c, (c) [111]c. The solid line and the dotted line denote the SH wave transmission curves with and without the piezoelectric effect.

Fig. 3. The transmission spectrum for SH waves normal incident to the periodic laminated composites based on different polarized directions PMN-0.28PT single crystals at the filling fraction of 0.7: (a) [001]c, (b) [011]c, (c) [111]c. The solid line and the dotted lines denote the SH wave transmission curves with and without the piezoelectric effect.

Figures 4 and 5 show the effects of filling fraction on the SH wave propagation in the three composite structures, where they have 3 cells with 1 mm length. The first bandgap (FBG) width of SH waves normal incident to the periodic laminated composites based on different polarized directions PMN-0.28PT single crystals at various filling fractions. Inset: the SH wave transmission spectrum at the filling fraction of 0.8.

Figure 4 displays the FBG starting frequency of the composite structure with various filling fractions. The starting frequency under the three poling directions exhibits a gradual decrease with the filling fraction up to 0.6, and then displays an increasing trend. The results in Figs. 4 and 5 indicate that the single crystal polarization direction contributes strongly to the bandgap width of the composition structure, mainly by affecting the FBG.

In summary, we have used the global matrix...
method to investigate the SH waves transmission spectra in the composite structure consisting of relaxor-based ferroelectric single crystal PMN-0.28PT and polymer. The comparison of the band structure with and without piezoelectric effect indicates that the piezoelectric effect has significant contribution for SH wave propagation in the composite structures containing [011]c and [111]c poled PMN-0.28PT, but little influence for [001]c polarized crystal. The starting frequencies at various filling fractions have no distinct difference in the three cases, while the FBG width of the structure containing [111]c poled PMN-0.28PT is the largest among the three cases when the filling fraction is larger than 0.5. These theoretical results could provide valuable instructions for the design of acoustic filters and ultrasonic transducers.

References


096301-4