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ELASTIC NONLINEARITY AND DOMAIN WALL MOTION IN FERROELASTIC CRYSTALS

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Abstract—Nonlinear interactions between elastic waves and ferroelastic domain walls offer the possibility of setting up and electronically controlling periodic domain gratings for application as tunable diffraction gratings, acoustic wave filters and surface acoustic wave transducers. Estimates of the practicality of using this control mechanism are presented for neodymium pentaphosphate.

Ferroelastic materials have the unique character of exhibiting easily switchable elastic, electrical and optical properties and have, for this reason, attracted the attention of device-oriented physicists. Gadolinium molybdate (GMO), an improper ferroelectric with moderate piezoelectric coupling and pronounced optical birefringence, has been the principal object of these investigations. Applications considered include electrooptic memories and displays,[1] optical shutters and fine line sources,[2] electronically variable surface acoustic wave (SAW) delay lines,[3] and analogue memory devices.[4] In these devices ferroelastic domain wall motion and switching is produced by applying voltages to suitably configured electrodes on the crystal. Domain wall motion may also be induced by application of an appropriate static stress to the crystal. Indeed, for a pure ferroelastic, such as neodymium pentaphosphate (NPP), this is the only switching mechanism available.[5,6,7] For NPP it is estimated that a shear stress on the order of $10^5 N/m^2$ would be sufficient to displace a domain wall.

Stripe domain patterns have been observed in both GMO[1] and NPP,[5] with individual domain widths as small as 10 μm.[6] Because of the switchable optical birefringence and elastic stiffness inherent in ferroelastic domains, these stripe patterns or arrays offer the interesting possibility of realizing switchable and latching optical diffraction gratings, acoustic wave filters and SAW transducers. The latching feature of such devices arises from the remarkable stability of ferroelastic domains, once the electrical or mechanical switching signal has been removed. In these applications, it is necessary to ensure that the stripe domain pattern is strictly periodic, a condition that is not automatically realized.[1,5] The concept presented here involves use of a periodic <u>internal</u> static stress for this purpose and also for switching the period of the domain pattern. The internal stress is to be generated by rectification of a standing acoustic wave, a process whereby elastic nonlinearities excite stresses at harmonics of the excitation frequency and also at zero frequency.[8,9,10] An order of magnitude estimate is easily made of the acoustic intensity required to generate by this process the switching stress cited above. The efficiency of this mechanism is enhanced by the fact that ferroelastics exhibit larger than normal third and fourth order elastic constants.[11,12,13] For an assumed third order constant on the order of $10^{12} N/m^2$ a strain of 10^{-4} would be required to reach the domain switching stress. In an elastic resonator with a volume of 0.01 cm^3, a frequency of 1 MHz and a quality factor of 10^4, this corresponds to an input power of 30 mW.

Neodymium pentaphosphate is an ideal material for this type of experiment because of its low threshold stress. It is of monoclinic symmetry in the ferroelastic state, having 13 second order and 32 third order elastic constants. Two types of domain walls exist, oriented perpendicular to the 1 or 3 crystal axes respectively.[5,6] Both are switched by a $\sigma_{13} \equiv \sigma_5$ shear stress, with the 3-oriented wall moving more readily. Optimal interaction of a plane elastic wave with a domain wall of this orientation requires wave propagation along the 3-axis. In a monoclinic crystal the wave types allowed for this propagation direction are quasishear (qs) and quasilongitudinal ($q\ell$) polarized in the 13 plane, and pure shear polarized normal to this plane. Consequently, either the qs or the $q\ell$ wave is a candidate for domain wall interaction.

If the 1 and 3 components of elastic displacement for waves polarized in the 13 plane are taken as $\bar{u} + u$ and $\bar{w} + w$, where the barred quantities are solutions to the linearized elastic equations, development of the nonlinear analysis to terms of second order in the displacement gradients[8] leads to the nonlinearly coupled equations

$$c_{55}u_{,33} + c_{35}w_{,33} - \rho_0\ddot{u} = -\left(P'_5\right)_{,3} \qquad 1(a)$$

$$c_{35}u_{,33} + c_{33}w_{,33} - \rho_0\ddot{w} = -\left(P'_3\right)_{,3} \qquad 1(b)$$

where subscripts following a comma designate spatial derivatives and

$$P'_5 = \frac{1}{2}(c_{35} + c_{555})(\bar{u}_{,3})^2 + \frac{1}{2}(c_{35} + c_{335})(\bar{w}_{,3})^2 + c_{355}(\bar{u}_{,3})(\bar{w}_{,3}) \qquad 2(a)$$

$$P'_3 = \frac{1}{2}(c_{333} + 3c_{33})(\bar{w}_{,3})^2 + \frac{1}{2}(c_{355} + 3c_{33})(\bar{u}_{,3})^2 + c_{335}(\bar{u}_{,3})(\bar{w}_{,3}) \qquad 2(b)$$

are the 5 (or 13-shear) and 3 (or 33-longitudinal) terms in the quadratic part of the first Piola-Kirchoff stress tensor. Equations (1) and (2) describe the generation of second harmonic and static elastic displacements by a high intensity elastic wave. To picture this, consider first the case of a traveling elastic wave. The quadratic terms in Eq. (2) reduce, then, to a sinusoid with second harmonic time and space variations and a spatially uniform zero frequency stress. In Eq. (1) the sinusoids act as source terms generating second harmonic displacements (SHG).[14] The uniform zero frequency stress relaxes to a static strain in a medium of finite length, an effect that has recently been observed experimentally.[15] For a standing elastic wave the quadratic terms in Eq. (2) produce, in addition to the second harmonic stresses, a zero frequency stress with periodic spatial variations related to the elastic wavelength. It is proposed to use this static stress distribution to order and tune periodic gratings of ferroelastic domains in NPP. It has been estimated that, for NPP, c_{335} is approximately ten times larger than the other constants in Eq. (2), with a value on the order of 10^{13} N/m^2.[12] This reduces the acoustic power requirement estimated above by a factor of 10. Since the combinations of elastic constants in Eq. (2) are the same for rectification and for SHG, we are preparing to confirm this estimate by acoustic SHG along the 3-axis in NPP. A new method,[17] based on an extension of the laser heterodyne probe technique[18] to second harmonic generation, will be used rather than the standard capacitive probe detection scheme.[19]

Since ferroelastic domain walls are most easily introduced into thin platelets the geometry chosen for resonant elastic wave interactions with a domain wall is as shown in Figure 1. The figure illustrates the spectrum of extensional, flexural and width shear vibrations calculated by the method described in Reference 20. All three types of resonant mode generate the required 13 shear stress, but the flexure mode family has been selected for further investigation because of the strength of its shear component and the relative simplicity of its spectrum. Figure 2 shows a prototype composite resonator using a lithium niobate driver to excite the nonpiezoelectric NPP flexure resonator.

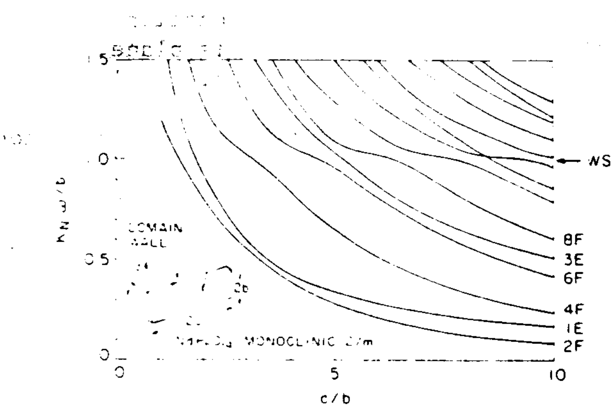

FIGURE 1 Theoretical frequency spectrum of extensional, flexural and width shear modes in a thin NPP plate resonator.

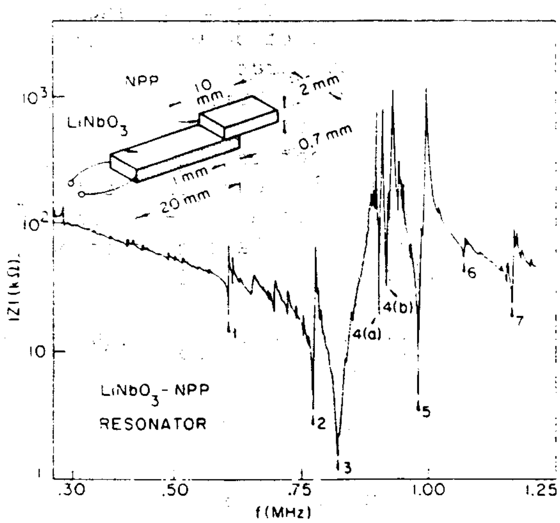

FIGURE 2 Measured frequency spectrum of composite resonator. The numbered lines represent resonances of the lithium niobate driver. Splitting of line 4 indicates coupling to the NPP, as does the series of resonances between lines 1 and 2.

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