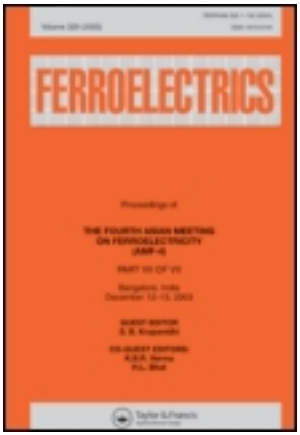

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Fabrication of the Ionic-Type Phononic Crystal and its Long-Wavelength Optical Properties

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The ionic-type phononic crystal (ITPC) is composed of two kinds of ferroelectric or piezoelectric media with a periodic superlattice structure. Through the piezoelectric effect, there is the coupling between the vibration of the superlattice and the electromagnetic (EM) wave that is similar to the coupling between the lattice vibration and the EM wave in ionic crystal. The ITPC thus exhibits interesting long wavelength optical properties, such as microwave absorption, dielectric abnormality and polariton excitation that exist originally in a crystal.

Keywords: Ionic-type phononic crystal; Optical properties; Polariton

INTRODUCTION

One of the most fruitful concepts in solid-state physics is that of the electronic band structure of crystals. As such, one would also expect to find band structures in studies of classical waves in a periodic superlattice. Since the first demonstration of photonic band structure in a periodic dielectric medium, i.e., photonic crystal [1], there has been growing interest in these artificial dielectric composites not only because of their applications such as manipulating light in specific path and novel laser geometries, but also due to interesting quantum electrodynamics effects [1, 2]. The concept can also be extended to sound waves propagating in a periodic elastic medium, i.e., phononic crystal [3]. Phenomena such as Anderson localization [4] and possible applications

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such as acoustical filter or transducer [3] can also be realized. Recently more and more research attentions have been paid on this topic.

In real crystals, interactions exist between electrons, photons and phonons that result in the coupling effects. The infrared light absorption and polariton excitation are resulted from the coupling between lattice vibration and electromagnetic (EM) wave in an ionic crystal, thus similar optical properties may be expected in a specific phononic crystal due to the coupling of vibration of the superlattice with EM waves.

In this work, we proposed a new notion of "ionic-type phononic crystal" (ITPC). The fundamental equations of coupled motion in ITPC were then deduced. Some novel characteristics of ITPC such as infrared light absorption and polariton excitation were demonstrated.

THEORETICAL DEDUCTION

The concept of ITPC is based on normal phononic crystal. Besides the well know plane wave method [5] and transfer matrix technique [6], there is a simple model for calculating the dispersion relation of a 1-Dimensional (1-D) phononic crystals that is similar to the 1-D atom chain model in crystals. We demonstrated that each block of a 1-D phononic crystal could be treated as a light spring with two identical mass dots at the boundaries if neglecting the high-order oscillation mode. The equivalent mass is $m^* = \rho Al/2$, the equivalent elastic moduli is $c^* = \pi^2 c/4 = \pi^2 \rho v^2/4$, and the equivalent force constant is $\beta^* = \pi^2 v^2 \rho A/4l$, where ρ, A, l, v are the density, cross-section area, thickness, and sound velocity of the plate, respectively. Thus the 1-D phononic crystal, a periodic combination of plate A and plate B, can be viewed as a 1-D diatomic chain. The mass of each "atom" is $m = m_A^* + m_B^*$ and the force constants are β_A^* and β_B^*, respectively. The dispersion relation is then easily to be obtained as:

$$\omega_\pm^2 = \frac{\beta_A^* + \beta_B^*}{m} \pm \frac{1}{m}\sqrt{\beta_A^{*2} + \beta_B^{*2} + 2\beta_A^*\beta_B^* \cos\left[k(l_A + l_B)\right]} \qquad (1)$$

where ω_+, ω_- correspond to the optic branch and acoustic branch, respectively. k is the wave vector. At the edge of the Brillouin zone, a band gap appears, which agrees well with the result from other methods.

Since the 1-D phononic crystal can be viewed as a "diatomic chain". Let's consider a special composite combined with two kinds of

ferroelectric media with their spontaneous polarization aligned in opposite direction as shown in Figure 1. Obviously, the boundaries of the neighboring domains are charged boundaries with two different charges. Since the domain boundary can be viewed as not only the concentration of mass but also the charge center, this special phononic crystal can be viewed as a 1-D "ions chain" and is thus termed ITPC.

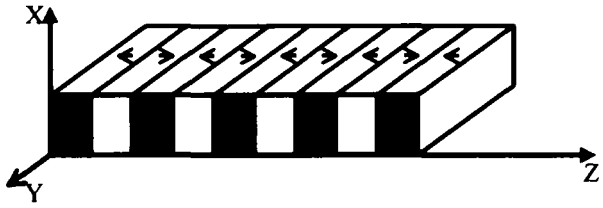

FIGURE 1: Schematic diagram of an ionic type phononic. The arrows represent the orientation of the spontaneous polarization.

In an ITPC, two kinds of ions constitute dipoles whose relative motion can be influenced by an EM field, especially that of a microwave. Because the wave vector of a microwave is much smaller than the width of Brillouin zone, the microwave interact only with optic branch phonons at the center of the Brillouin zone, giving rise to some typical long wavelength optical properties. However, in ITPC, the relative motion is actually caused by the piezoelectric effect, which means that vibrations of superlattice can interact with EM waves even if the phononic crystal is comprised of two kinds of piezoelectric blocks.

In piezoelectric media, the fundamental piezoelectric equations are:

$$\begin{cases} \sigma = cS - e\mathbf{E} & (2) \\ \mathbf{P} = eS + \varepsilon_0(\varepsilon - 1)\mathbf{E} & (3) \end{cases}$$

where S is strain, σ is stress, ε is original dielectric constant, c is the elastic constant and e is piezoelectric coefficient. As we know, the fundamental equations for studying the coupling between the lattice vibration and the EM wave are the Huang's equations. [7] One would ask if there is any relation between the Huang's equations and the piezoelectric equations. For simplicity, let's choose the simplest case in which the ITPC was composed of two kinds blocks with the same thickness and elastic properties. The only difference between the neighboring domains is that their poling directions are aligned

oppositely. Because the piezoelectric coefficient is a 3rd-order tensor, it changes its sign from negative domains to positive domains just the same as the nonlinear optical coefficient [8, 9]. The motion of domain boundaries with positive and negative charges is defined as $\mathbf{U}_+$ and $\mathbf{U}_-$, respectively. Under long wave approximation, the motion of each primitive cell can be viewed as identical. Thus we obtained the equations that describe the relative motion of domain boundaries:

$$\begin{cases} \ddot{\mathbf{W}} = -\dfrac{\pi^2 v^2}{l^2}\mathbf{W} + \dfrac{2e}{\sqrt{\rho l}}\mathbf{E} & (4) \\ \mathbf{P} = \dfrac{2e}{\sqrt{\rho l}}\mathbf{W} + \varepsilon_0(\varepsilon - 1)\mathbf{E} & (5) \end{cases}$$

where $\mathbf{W} = \dfrac{\sqrt{\rho}}{2}(\mathbf{U}_+ - \mathbf{U}_-)$, l is the domain thickness.

Compared Eq. 4, Eq. 5 with Huang's equations, it is easy to find that they have the same format, which means that the Huang's equations and the piezoelectric equations have close relation in physics. From Eq. 4, Eq. 5 and the Maxwell equations, the following results were obtained:

1. The eigenfrequency of transverse vibration without the coupling of the EM field is $\omega_{T0} = \omega_0 = (-b_{11})^{1/2}$, while the eigenfrequency of longitudinal wave is $\omega_{L0} = \left(-b_{11} + \dfrac{b_{12}^2}{\varepsilon_0 + b_{22}}\right)^{1/2}$, where $b_{11} = \dfrac{-\pi^2 v^2}{l^2}$, $b_{12} = \dfrac{2e}{\sqrt{\rho l}}$, $b_{22} = \varepsilon_0(\varepsilon - 1)$. The ratio of ω_{L0} and ω_{T0} is described by the Lyddane-Sachs-Teller (LST) relationship:

$$\frac{\omega_{L0}}{\omega_{T0}} = \left[\frac{\varepsilon(0)}{\varepsilon(\infty)}\right]^{1/2} \quad (6)$$

where $\varepsilon(0)$ and $\varepsilon(\infty)$ are the dielectric constants at low frequency and high frequency, respectively, comparing with the eigenfrequency of ITPC. They can be determined as $\varepsilon(\infty) = \varepsilon$, $\varepsilon(0) = \dfrac{-b_{12}^2}{b_{11}\varepsilon_0} + \varepsilon$.

2. When an EM wave propagates in an ITPC, the electric field stimulates a long wavelength optic branch vibration and then causes the intensive attenuation of the electric energy at a specific frequency. The absorption power is related to the imaginary part of the dielectric

constant. By including a damping part $-\gamma\dot{W}$ into the right side of Eq. 4, where γ is a phenomenological damping constant, we have:

$$\varepsilon''(\omega) = \frac{b_{12}^2 \omega\gamma}{\varepsilon_0\left[(\omega^2 + b_{11})^2 + \omega^2\gamma^2\right]} \tag{7}$$

There is a strong absorption at $\omega = \left(-b_{11}\right)^{1/2} = \omega_{T0}$ that is equivalent to the infrared absorption in ionic crystals but in different frequency band.

3. Near the eigenfrequency of ITPC, the electromagnetic wave interacts with the mechanical vibration strongly, thus the transverse mode is neither bare photon mode nor bare optic branch phonon mode in this very narrow range of k-values. It is called polariton mode. The corresponding energy quantum is called polariton. [7, 10] Our results show that the polariton also exists in an ITPC just as in a ionic crystal.

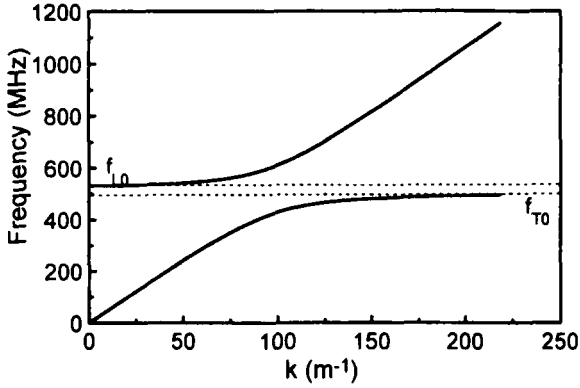

FIGURE 2: The calculated polariton dispersion curve of a LN ITPC with the period of 7.2μm. There is a frequency gap between f_{L0} and f_{T0} where the propagation of electromagnetic waves were compressed.

Figure 2 shows the calculated polariton dispersion curve of an $LiNbO_3$ (LN) ITPC with the period of 7.2μm by taking $\gamma = 0$, which makes ε and therefore k real. The eigenfrequencies of the transverse wave and longitudinal wave are $f_{T0} = 500MHz$, $f_{L0} = 532MHz$. From this figure, there is a frequency gap where dielectric constant is negative. The corresponding refractive index becomes imaginary. The incident

radiation with these frequencies will be reflected. However, this gap does nothing with the stop band in ordinary photonic crystals.

EXPERIMENTS AND DISCUSSIONS

For testing and verifying the predictions above, a LN ITPC was fabricated with the growth striation technique. [9] The crystal doped with 0.5wt% yttrium was grown along the Z-axis by using the Czochralski method. A special asymmetric temperature field caused a periodic temperature fluctuation on the solid-liquid-interface, which resulted in a periodic yttrium distribution along the growing direction. This concentration distribution built up a periodic space-charge-field (SCF). When the paraelectric to ferroelectric phase transition took place, the periodic ferroelectric domain structure was produced by the SCF. [9] By controlling proper technical parameters, an ITPC with the period of 7.2μm was fabricated. The crystal was then Y-cut into a thin sample with the thickness of 1.7mm. A pair of Ag electrodes (2.0mm×2.0mm) were deposited on the surfaces for the experiments.

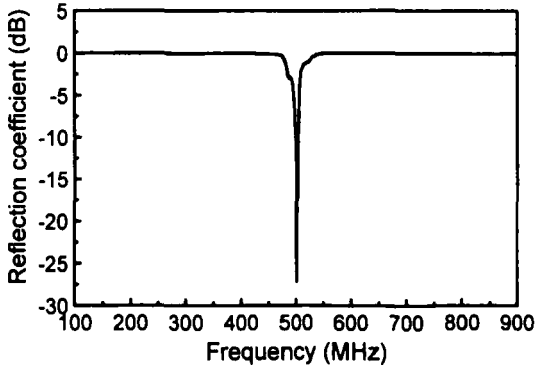

FIGURE 3: The measured reflection coefficient of a LN ITPC in the microwave band. The minim of the reflection coefficient indicates that there is a strong microwave absorption peak at 502 MHz.

The microwave reflection coefficient of the ITPC was measured to simulate the situation when a microwave beam propagates in the sample. Under this circumstance, the electric field was applied on the sample

simultaneously (k=0) which coincides with the long wavelength approximation used above. Figure 3 shows the reflection coefficient as a function of frequency. There is a strong absorption peak at 502MHz, very close to the theoretical value $f = f_{T0} = 500\,MHz$.

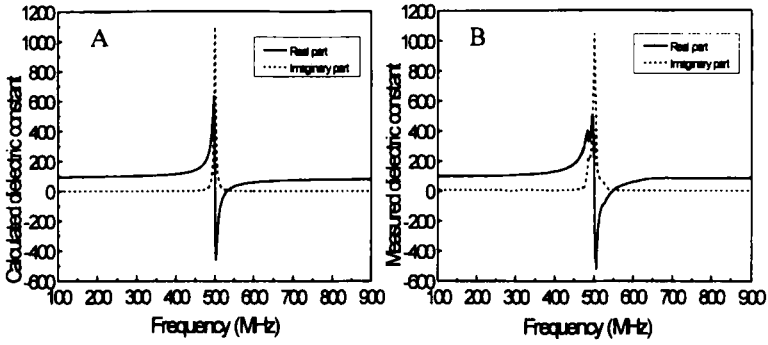

FIGURE 4: The dielectric constant curves of a LN ITPC. The solid lines correspond the real part and the dashed lines correspond the imaginary part. **(A)** is the calculated result by choosing proper damping (γ=0.01ω_{T0}) and **(B)** is the measured dielectric constant.

For demonstrating the polariton excitation in ITPC, the dielectric constant in microwave band was measured. The results were shown in Figure 4, which was compared with the theoretical results by choosing proper damping. (γ=0.01ω_{T0}) The dielectric constant changed severely near ω_{T0}, which is obviously caused by the superlattice in ITPC. In theory, one can obtain the desired dielectric constant in the microwave band since the structure can be designed intentionally, which is very useful for some devices. Much information of the ITPC can be obtained from the dielectric constant curve. The measured f_{T0}, f_{L0}, $\varepsilon(0)$ and $\varepsilon(\infty)$ are 502MHz, 547MHz, 99.88 and 88.02, respectively. They all roughly match the theoretical predictions. The deviation of f_{L0} may do something with the domain thickness fluctuation. The LST relationship was also proved, which is $\frac{\omega_{L0}}{\omega_{T0}} = 1.09$, only a little deviation to $\left[\frac{\varepsilon(0)}{\varepsilon(\infty)}\right]^{1/2}$ (1.07). The absorption peak in Figure 3 is at the same position of the peak of the

imaginary part of dielectric constant just as prediction. There is a gap between ω_{T0} and ω_{L0} where $\varepsilon < 0$ and incident electromagnetic waves will be strongly reflected. All of the phenomena above show that there is really the polariton mode in ITPC.

Obviously, the optical properties of the ITPC have many technical applications. Various acoustic and microwave devices such as new transducers, oscillators, modulators, and coherent microwave sources based on this artificial material can be constructed. Because of the homogeneous feature of the LN ITPC, the width of the phononic band gap is zero. One would expect that perhaps there would be some more novel properties if the ITPC were made with two kinds of media since it combines the phononic band structure and optical properties together. Furthermore, another coupling in real crystals is the interaction between phonons and electrons, which influences the crystal's conductive properties. In phononic crystals, coupling between the motions of phonons and electrons is also possible. In general, one can try to simulate various physical processes existing in real crystals with phononic crystals. This fact implies that phononic crystals are sure to have significant physical and technical values.

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