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Effect of external perturbations on phonon-polariton modes and photonic band gap in piezoelectric crystal

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ABSTRACT

The behavior of polariton dispersion as a function of superlattice period and temperature in a novel piezoelectric superlattice (PSL) by using Lithium Niobate is analyzed theoretically. By implementing the temperature coefficients of each acoustic and optical parameters, the dielectric permittivity is determined. The modes are shifted and the polaritonic gap decreases with temperature. The transmission properties of a one-dimensional novel photonic crystal having novel piezoelectric superlattice as one of the layers and air as another layer have been investigated by means of transfer matrix method. The photonic band gaps can be tuned by altering the thicknesses of the layers, incidence angle, the number of periods and temperature. When the thickness of the PSL layer changes from µm to mm, the photonic band gap is found to be shifted from THz to GHz region. The evolution of these results provides a guideline for designing optoacoustic devices, filters, and sensors.

1. Introduction

The study of the periodic structure results in many important concepts, such as the Brillouin zone, band structure etc. In a real crystal, the periodic potential leads to the band gap, where the electrons are prohibited from moving freely [1]. In a Photonic Crystal (PC) with periodic modulation of dielectric constants [2,3], photons can be described in terms of photonic band gap (PBG) structure, in order to control the propagation of light. It is important for applications such as suppressing spontaneous emission, manipulating light in a specific path and creating novel laser geometries [2–4]. Recently, interest in a PC, a periodic elastic composite is known as phononic crystal has grown [5–8]. The structure modulation may be extended to quasiperiodic or aperiodic or two-dimensional structures [9–11]. The modulation parameters of band gap are density, elastic constants, piezoelectric coefficients etc. If two or more parameters may be modulated together, which could result in some coupling effects.

The coupling between lattice vibrations (transverse optical phonons) and electromagnetic (EM) waves (photons) in an ionic crystal results in infrared absorption and polariton excitation, which causes the opening of the polaritonic band gap in which the propagation of EM waves is forbidden. The phenomenon in the coupling of phonons and photons has been found in both bulk and superlattice (SL) systems [12]. In the case of piezoelectric crystals through the electromechanical coupling, the photon can also couple with the longitudinal acoustic phonons giving rise to polariton behavior in the low-frequency region [13,14].

The novel PSL is composed of periodically reversed frequency domains which can be fabricated by the crystal growth technique [15] or electric poling method [16]. In the PSL, it has been shown that the transverse polarization induced by the longitudinal wave couples strongly with EM radiation, resulting in the creation of new type of polaritons, which do not exist in ionic crystals. Since the $LiNbO_3$ (LN) has high electromechanical constant, the excitation of polariton was shown to be possible. This property makes it possible to control and propagate the flow of both phonons and photons simultaneously and new opto-acoustic devices might be developed. LN and $LiTaO_3$ (LT) crystals have been used to study optical excitation and detection of phonon-polaritons. It finds application in a variety of polaritonic devices such as waveguides, resonators, and gratings [17]. In this study, both the polariton dispersion at the Brillouin zone (BZ) center and the PBG is analyzed for LN crystals.

The dielectric, elastic and piezoelectric constants are the most important parameters for the piezoelectric crystals. Piezoelectric coefficients reflect the material sensitivity of the piezoelectric effect. The temperature dependent piezoelectric constants for many crystals such as the LT [18], YCOB [19] and NdCOB [20] have been studied. However, the temperature range of their applications is limited by their phase transition. The hydrostatic pressure dependence of the linear and nonlinear piezoelectric constants for LN and LT are already

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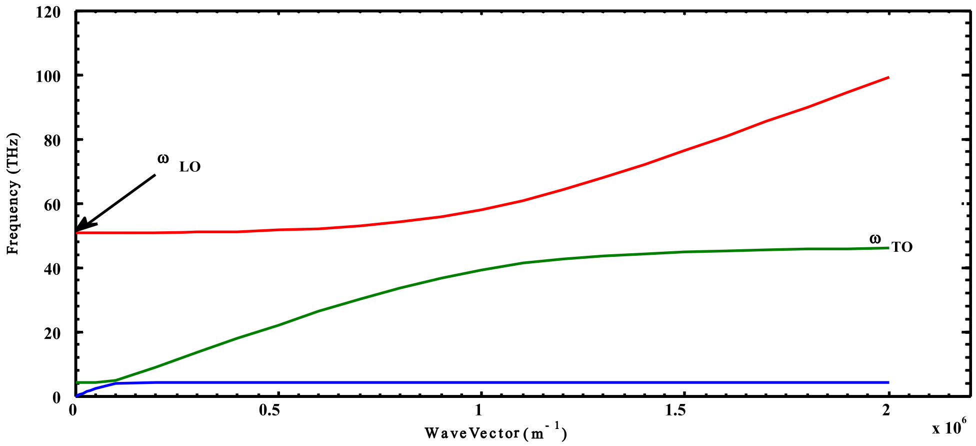

Fig. 1. Polariton dispersion for a superlattice period of 100 Å at 300 K.

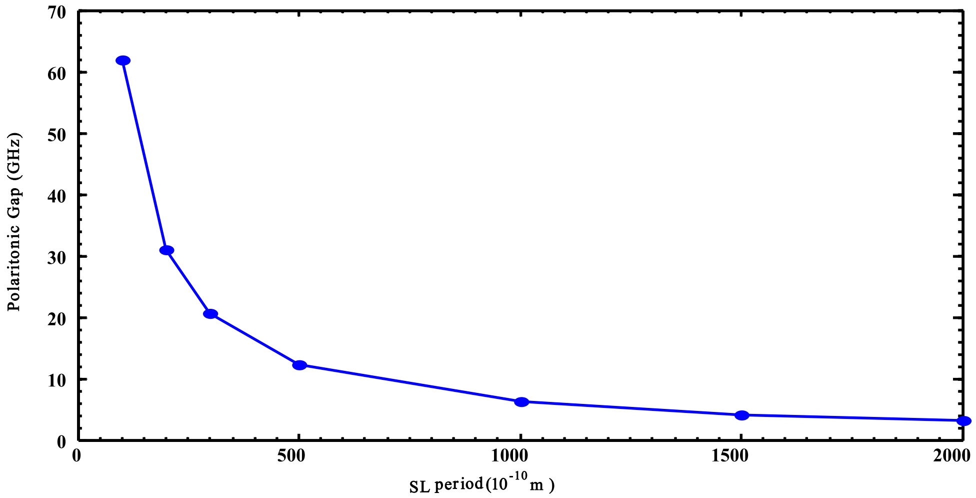

Fig. 2. Variation of polaritonic gap for different SL period.

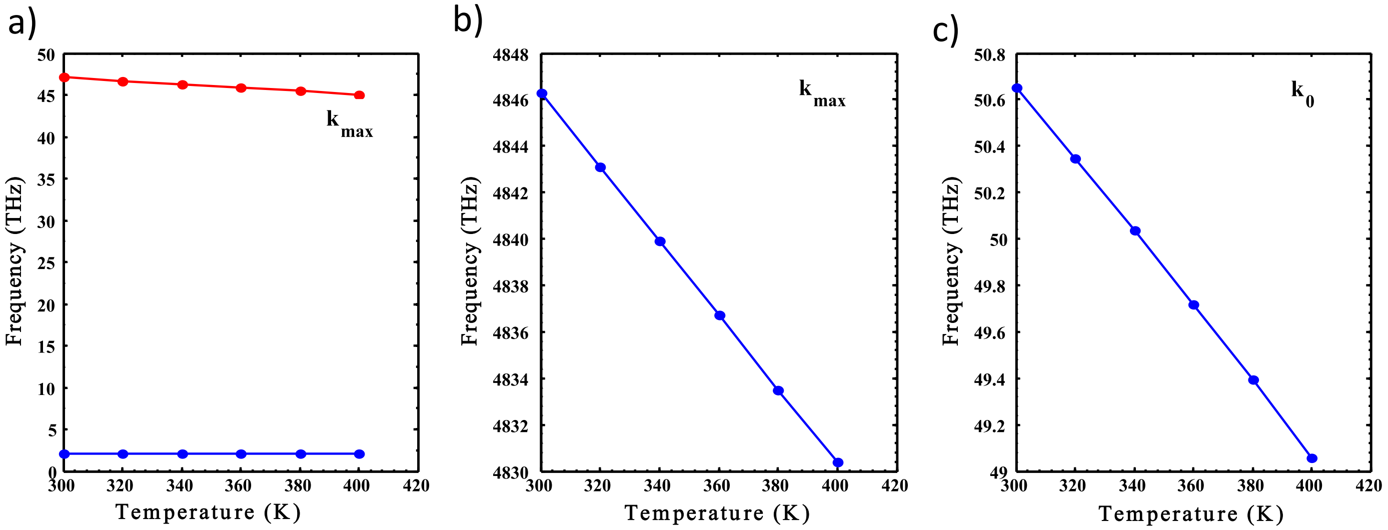

Fig. 3. Variation of phonon frequency with temperature a) lower and middle mode and b) upper mode at k_{max} and c) upper mode at k=0.

studied at pressures from 0.05 to 2.8 GPa [21]. LN and LT crystals are excellent materials for mobile phones, piezoelectric sensors, and optical applications. Especially, they have widely used in surface acoustic wave (SAW) devices for their low acoustic losses. Since only a narrow region of the BZ is available in optical experiments, $0 < k < 10^4$ cm^{-1}, only the long wavelength phonons become important in polariton studies. In the case of SL, an additional ingredient turns out to be BZs associated with the SL period.

In the first part of the present study, the behavior of polaritonic gap as a function of SL period and the temperature is analyzed for LN novel PSL. In the second part, it is assumed that the PC consists of novel PSL and air as the layers. The variation of PBG is analyzed by varying