Investigations on Nonlinear Polariton Dispersion in Ferroelectric Superlattice System

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Abstract- **Superlattices have drawn considerable attention in the recent years. In this work, the behaviour of polaritons in a quantum well superlattice system is analysed both at the centre and at the edge of the brillouin zone using $LiNbO_3$/ $LiTaO_3$ as an example. The significance of the polariton modes are analysed. New modes due to nonlinearity on the polaritonic gap, where the propagation of electromagnetic wave is forbidden, are obtained in the system as suggested by some recent literature. The variation of frequency with the thickness is also studied.**

Keywords: Phonon polariton; photonic gap; $LiNbO_3$ and $LiTaO_3$; nonlinear
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INTRODUCTION

We consider the coupling of the phonons and electromagnetic photons. When the crystal superlattices is illuminated by light, a transverse electromagnetic field is stimulated, and transverse oscillations of long wavelength optical phonons will be influenced particularly, when the photon frequency ω=kc and the transverse phonon frequency ω_t $(\sim 10^{13}\ s^{-1})$ are close to each other, the coupling will be very strong, the spectra of photons and phonons will change drastically, and polaritons will be generated [1-6].

When light propagates through matter it will induce motion of the charged particles. In a dielectric medium the charges are bound together and will start to oscillate in the applied electric field; they form oscillating electric dipoles. The oscillating dipoles add up to a macroscopic polarization which is used to describe the response of the material. For larger amplitudes the motion of the particles will be distorted and nonlinear terms will be important [7,8]. The importance of the induced polarization can be understood from the fact that any oscillating dipole also emits radiation, at the frequency of oscillation, and thus modifies the optical field that induced the polarization.

When the effect of nonlinear interactions cannot be ignored, it is necessary to discuss their effects on the polaritons. Recently nonlinear effects on polaritons in isotropic crystals and uniaxial crystals [1,9] were discussed. The nonlinear effects introduce additional modes in the polaritonic gap. Here, the effect on nonlinear interactions of phonon polaritons in $LiNbO_3$/ $LiTaO_3$ superlattices is discussed. The various modes of polariton dispersion is analysed in detail.

THEORY

The dependence of the frequency ω on the wave vector k of an electromagnetic wave in a crystal with a dielectric function $\varepsilon_1(\omega)$ is determined by a dispersion relation. For an infinite isotropic crystal, Maxwell's equations together with the constitutive relations lead to

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the polariton dispersion relation [10]

$$\frac{c^2k^2}{\omega^2} = \varepsilon_1(\omega) = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)\omega_{TO}{}^2}{\omega_{TO}{}^2 - \omega^2} \qquad (1)$$

where c is the velocity of light in vacuum, ε_s the static dielectric constant, ε_∞ the high frequency dielectric constant and ω_{TO} the transverse optical phonon frequency. There is a photonic gap between ω_{TO} and ω_{LO} within which no electromagnetic radiation can pass through. Recently it has been shown [1] that for noncentrosymmetric crystals, the dielectric function, is modified to

$$\varepsilon_i(\omega) = \varepsilon_1(\omega) + 4\frac{f^2 b_{12}{}^4 g E_0^2(\omega)}{(\omega^2 - \omega_{TO}^2)^4 \omega_{TO}^2 \varepsilon_0} \qquad (2)$$

if nonlinear effects are included. Here i refers to A or B medium. In the above equations,

$$b_{12} = b_{21} = \left[\frac{(\varepsilon_s - \varepsilon_\infty)}{4\pi}\right]^{1/2} \omega_{TO},$$

$$b_{11} = -\omega_{TO}{}^2 ; b_{22} = \frac{\varepsilon_\infty - 1}{4\pi};$$

$$f = \frac{\omega_{TO}{}^2}{d} ; g = \frac{\omega_{TO}{}^2}{d^2}$$

; and d is the lattice parameter[7]. All these parameters are available for the important materials like $LiNbO_3$, and $LiTaO_3$ which are noncentrosymmetric crystals.

The study of excitations propagating in SL produces new results. Typically the thickness of an individual layer lies in the range 100-5000 Å. If one constituent, material A, always has thickness d_1, and the second, material B, always has thickness d_2, one has built a periodic structure known as a SL. In this work, assuming alternating layers of $LiNbO_3$, and $LiTaO_3$ as A and B medium of thickness $d_1$and d_2 stacked along the z-direction. Several authors [10] have derived the following dispersion relation for TM modes assuming the electromagnetic boundary conditions, namely, the electrostatic,c potentials and the electric displacement field perpendicular to each interface are continuous:

$$1+\left(\frac{\varepsilon_B(\omega)\alpha_1}{\varepsilon_A(\omega)\alpha_2}\right)^2 +2\left(\frac{\varepsilon_B(\omega)\alpha_1}{\varepsilon_A(\omega)\alpha_2}\right)$$
$$\left(\frac{\cosh(\alpha_1 d_1)\cosh(\alpha_2 d_2) - \cos(qL)}{\sinh(\alpha_1 d_1)\sinh(\alpha_2 d_2)}\right) = 0$$

For the semiconductor SL ($\mu_v = 1$) consisting of alternating layers of materials A and B, the dielectric functions are taken as in equation (2).

Here ,L = d_1+ d_2 is the SL period and q is the component of the wave vector along the SL axis and $\alpha_i^2 = k_x^2 - \frac{\omega^2}{c^2}\varepsilon_i$, where k_x is the component of the wave vector in the X-direction for TM modes.

RESULTS AND DISCUSSION

The behavior of phonon polaritons with electric field E=1x10^6 v/m, of $LiNbO_3$ / $LiTaO_3$ quantum well superlattice system is studied. The numerical values of the physical parameters used in the calculations are easily available for the materials $LiNbO_3$ and $LiTaO_3$ [11]. The dispersion relation given in Eq. (3) for the SL including the nonlinear effect is solved numerically and the results are plotted. We get eight modes. In a normal superlattice system usually five polariton modes are obtained. Here, with nonlinearity the additional three modes are obtained in the polaritonic gap as shown in Fig. 1. Among the three modes, the two modes are due to two sublattices of the superlattice and the other mode is an interfacial mode.

In Fig.2, at the brillouin zone edge ie., at $q = \frac{\pi}{L}$, the modes due to nonlinearity show constant value. Mode multiplicity occurs in the photonic band gap. The upper mode is shifted to the order of 10^{16} Hz as in the other superlattice system. At , $q = \frac{\pi}{4L}$ we found the similar behavior of the polariton mode as in the brillouin zone edge except the mode multiplicity. Here the mode multiplicity does not occur. Two separate modes at constant value occur in the polaritonic gap as shown in Fig.3.

The frequency of various modes are also analysed with the thickness. When the thickness of the one layer of the superlattice increases, the frequency of the upper mode decreases and finally gets the constant value as shown in Fig.4 and Fig.5 for various k values. The value of the frequency of other modes gets a constant value with the increase in thickness.

CONCLUSION

The behaviour of polaritons in a quantum well superlattice system is analysed including nonlinear effects at the brillouin zone edge and at the centre. The presence of the various modes in the photonic gap is the new feature introduced by nonlinearity. It is found that the frequency is in the decreasing order when the thickness of the superlattice gets increases. The presence of new frequency modes shows the propagation of electromagnetic radiation in the polaritonic gap which may be exploited in optical communications.

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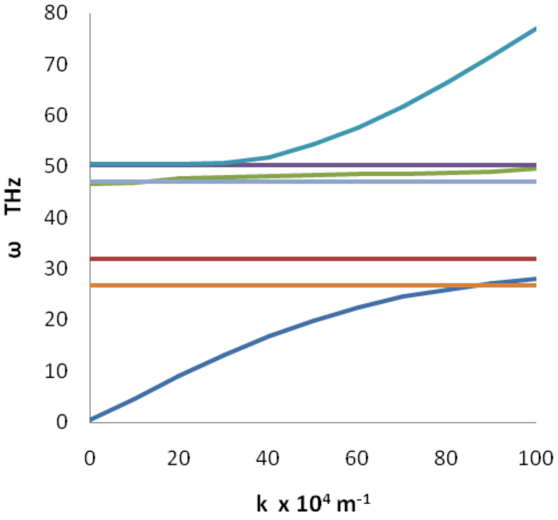

Fig.1. Polariton dispersion in ferroelectric superlattice with nonlinearity when q=0

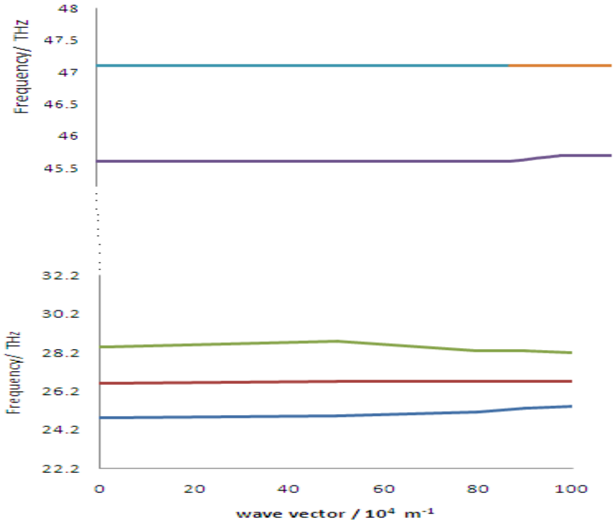

Fig. 2. Polariton dispersion in ferroelectric superlattice with nonlinearity (d_1=100 A° and d_2=100 A° when $q = \frac{\pi}{L}$

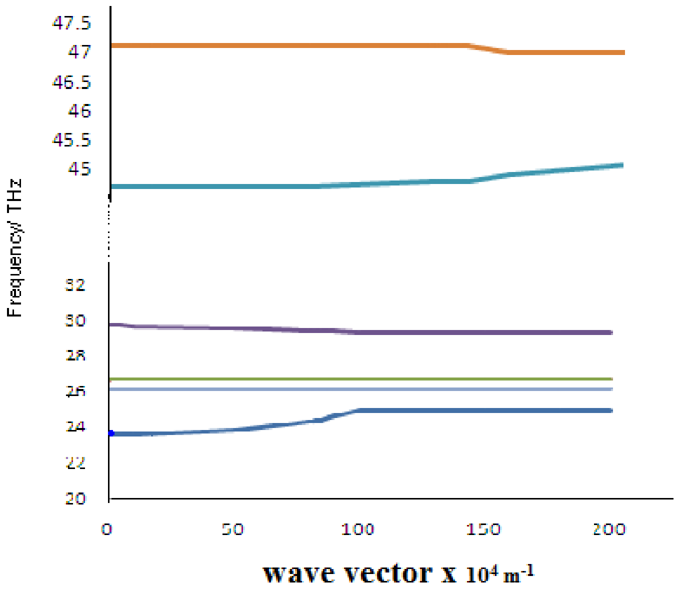

Fig. 3. Polariton dispersion in ferroelectric superlattice with nonlinearity (d_1=100 A° and d_2=100 A° when $q = \frac{\pi}{4L}$

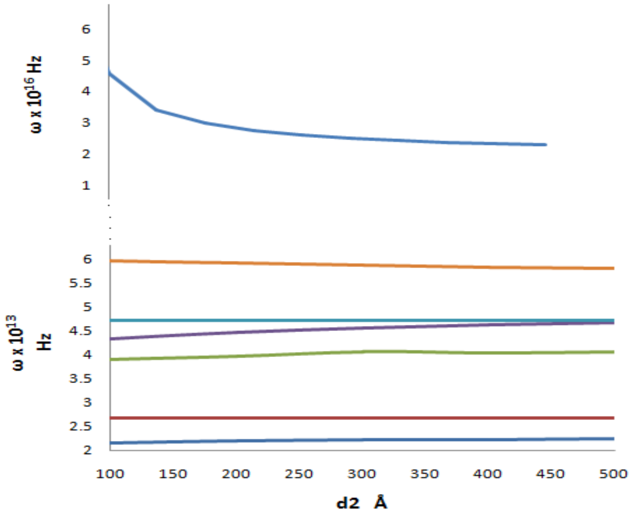

Fig. 4. Polariton dispersion in ferroelectric superlattice for k=0, at the Brillouin zone center

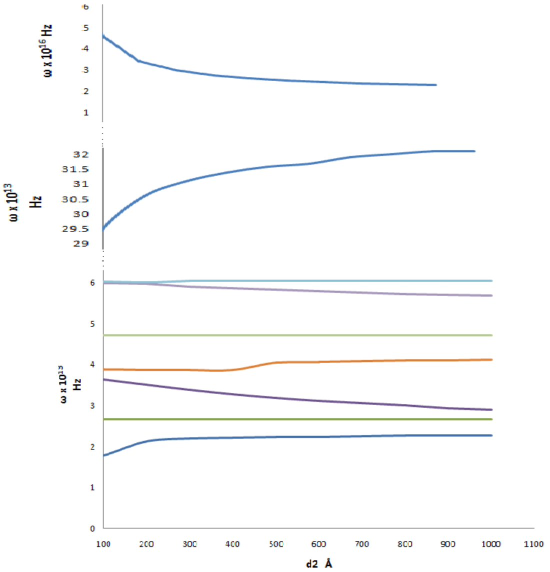

Fig. 5. Polariton dispersion in ferroelectric superlattice for k=400, at the Brillouin zone center

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