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POLARITON DISPERSION IN NOVEL NANOCOMPOSITE SUPERLATTICE SYSTEM

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ABSTRACT: In a series of works K. Navaneethakrishnan et al.[Physica E **31**, 209(2006)] have investigated the possibility of acoustic polaritons in a novel superlattice system consisting of piezoelectric materials. In the present work, Silver Nanoparticles is added to these dielectric superlattices systems(Ag-$LiNbO_3$/Ag-$LiTaO_3$). The behavior of the polariton dispersion as a function of filling factor of silver nanoparticles concentration are investigated systematically. The significance of the polariton modes are analysed. New modes on the polaritonic gap, where the propagation of electromagnetic wave is forbidden, are obtained in the system due to the presence of silver nanoparticles (NPs).

1. INTRODUCTION

Plasmonic materials like metal nanostructures are currently being used to build novel devices to confine [1], guide [2, 3], or modify light [4] on a nanometer scale. Our aim is to use metal nanoparticles (NPs) completely embedded in an optical nonlinear dielectrics instead of a normal dielectric superlattice. This will result in an even higher enhancement of nonlinear effects due to the increased confinement of light compared to metallic films .

In this study, we investigated silver NPs embedded in Lithium niobate and Lithium Tantalate superlattice system (Ag-$LiNbO_3$/Ag-$LiTaO_3$). Lithium niobate and Lithium Tantalate are the most important materials for integrated optical devices due to its huge nonlinear optical coefficients [5]. Silver is a widely used plasmonic material with a Surface Plansmon Resonance (SPR) in the visible range [6]. Our aim is to study the influence of the silver NPs on the nonlinear optical properties of lithium niobate and Lithium Tantalate with varying silver NP concentration.

2. THEORY

Composite materials with noble metal nanoparticles are very attractive for a development of new optical devices. Nanoparticles are distributed randomly but homogenously in dielectric matrix. Let us assume that nano-particles have spherical form with radius about some nanometers, i.e. particle size is much smaller than wavelength and penetration depth of electromagnetic wave in metal. Linear and nonlinear optical properties of these materials are determined by Plasmon resonance of metal nanoparticles and dielectric matrix.

$\varepsilon_m(\omega)$ is a dielectric permittivity of nanoparticles material, **f** is a filling factor of nanoparticles, i.e. their volume fraction, We

can find the bulk metallic dielectric permittivity with Drude approximation in the following way:

$$\varepsilon_m(\omega) = \varepsilon_0 - \frac{\omega_p}{\omega(\omega + i\gamma)} \quad (2)$$

where ε_0 is a constant (ε_0 = 5 for Ag), $\boldsymbol{\omega_p}$ is a plasma frequency (ω_p = 9 eV for Ag), $\boldsymbol{\gamma}$ is a relaxation constant (γ =0).

For distinctness, further we will consider silver as a material of nanoparticles. The dielectric constant for $LiNbO_3$ is given by

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{(\varepsilon_0 - \varepsilon_\infty)\omega_{TO}^2}{\omega_{TO}^2 - \omega^2 - i\omega\gamma} \quad (3)$$

where $\boldsymbol{\omega_{TO}}$ is the frequency of the transverse optical phonons[7], $\boldsymbol{\varepsilon_\infty}$ and $\boldsymbol{\varepsilon_0}$ are the high frequency and static dielectric constants respectively. Here $\boldsymbol{\gamma}$ is the damping factor.

The dielectric function of the material (Ag-$LiNbO_3$) is given by

$$\varepsilon_A(\omega) = \varepsilon(\omega)\frac{(2-f)\varepsilon_m(\omega) + f\varepsilon(\omega)}{f\varepsilon_m(\omega) + (2-f)\varepsilon(\omega)} \quad (4)$$

Similarly, the dielectric function of the material (Ag-$LiTaO_3$) is given by

$$\varepsilon_B(\omega) = \varepsilon(\omega)\frac{(2-f)\varepsilon_m(\omega) + f\varepsilon(\omega)}{f\varepsilon_m(\omega) + (2-f)\varepsilon(\omega)} \quad (5)$$

The study of excitations propagating in this type of SL produces new results. 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 novel SL. In this work, assuming alternating layers of A and B medium of thickness d_1 and d_2 stacked along the z-direction. Several authors [8] have derived the following dispersion relation for TM modes assuming the electromagnetic boundary conditions, namely, the electrostatic potentials and the electric displacement field perpendicular to each interface are continuous:

$$1+\left(\frac{\varepsilon_B(\omega)\alpha_1}{\varepsilon_A(\omega)\alpha_2}\right)^2 + 2\left(\frac{\mathfrak{E}_B(\mu)\sim_1}{\mathfrak{E}_A(\mu)\sim_2}\right)\left(\frac{\cosh(\alpha_1 d_1)\cosh(\alpha_2 d_2) - \cos(qL)}{\sinh(\alpha_1 d_1)\sinh(\alpha_2 d_2)}\right) = 0$$

For the semiconductor SL (μ_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 $\alpha_i^2 = k_x^2 - \frac{\omega^2}{c^2}\mathfrak{E}_i$, where k_x is the component of the wave vector in the X-direction for TM modes[9].

3. RESULTS AND DISCUSSIONS

The phonon polariton dispersion of the novel superlattices consisting of Nanocomposite medium of $LiNbO_3$ with Ag as A medium and Nanocomposite medium of $LiTaO_3$ with Ag as B medium are analysed for various cases. The Polariton dispersion at the centre of the Brillion zone of the A medium is analyzed. When we make the nanoparticles concentration as zero, we get the usual polariton dispersion of the bulk medium as in Fig.1.

When the nanoparticles concentration is 0.1, in addition to the usual two modes of propagation, a third mode also appears due to the presence of silver nanoparticles. We also observe that there is a drastic change occurs in all the three modes. The initial values of the usual modes shifts to higher values. The initial value of the upper mode shift from 46.7 THz ie., the longitudinal optical phonon frequency of A medium to higher values like 973.22 THz. The origin of lower mode shift from zero to the transverse optical phonon frequency of the medium (ω_{TO}) The middle mode starts with the frequency of 140 THz ,

slowly increases and gets a constant value of 911THz as shown in Fig.2. As the concentration of the nanoparticles increases there is no appreciable change in the lower and the upper modes, but the middle mode move towards a constant values. At f=0.5, the middle mode ranges from 325 THz to 707THz as shown in Fig. 3. When the concentration increases again at f=0.9 the middle mode appears to be a constant mode at 540 THz. When we analyse the polariton dispersion of Ag-$LiNbO_3$/Ag-$LiTaO_3$ nanocomposite superlattice system with the nanoparticles concentration f=0.1, eight modes of propagation are obtained. Here, the lower two modes becomes straight lines and has a constant value ie., μ_{TO} of $LiTaO_3$ and $LiNbO_3$ The next two modes represents the interfacial modes, finally merge. The next higher mode represents the conventional upper mode of the polariton dispersion. The next three higher modes purely represents the plasmonic behavior of metal nanoparticles as shown in Fig. 4. We found these changes are due to the presence of metal nanoparticles. Fig. 5 clearly shows the tuning of middle mode with the metal nanoparticles concentration. As the concentration increases, the curve nature of the mode becomes a straight line.

CONCLUSIONS

The polariton dispersion of both the bulk nanocomposite medium and the novel nanocomposite superlattice medium are analysed in detail. It is concluded that the straight line behavior of the propagation mode reflects the presence of metal nanoparticles. As the concentration of metal nanoparticles increases the polariton behavior turns to plasmonic behavior. This type of tuning in both bulk and superlattice system can be applied to improve the available technologies especially in the field of communication and hence to invent the devices that have potential uses across several industrial sectors.

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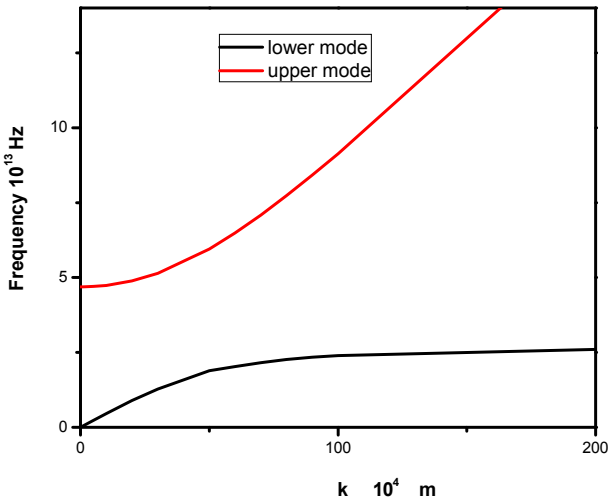

Figure 1- Dispersion of $LiTaO_3$-Ag, when the nanoparticles concentration f=0

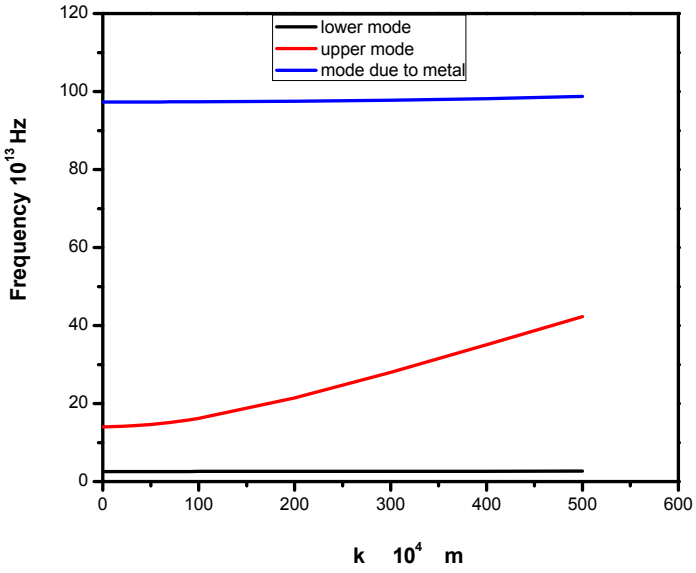

Figure 2- Dispersion of $LiTaO_3$-Ag, when the nanoparticles concentration f=0.1

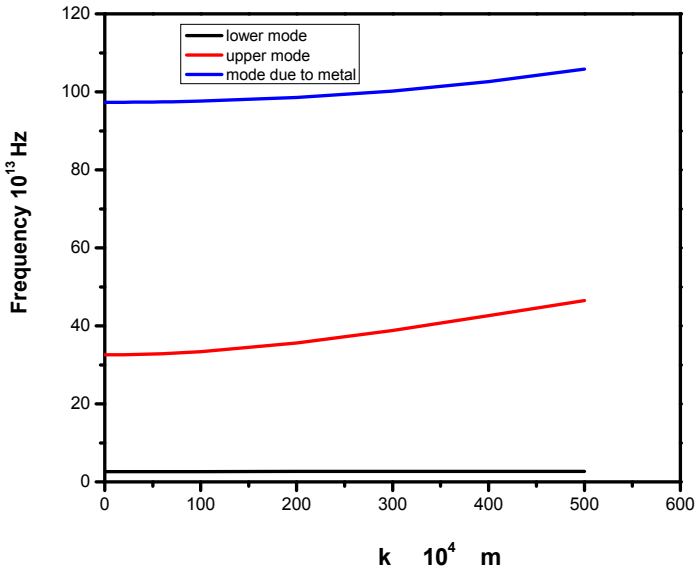

Figure 3- Dispersion of $LiTaO_3$-Ag, when the nanoparticles concentration f=0.

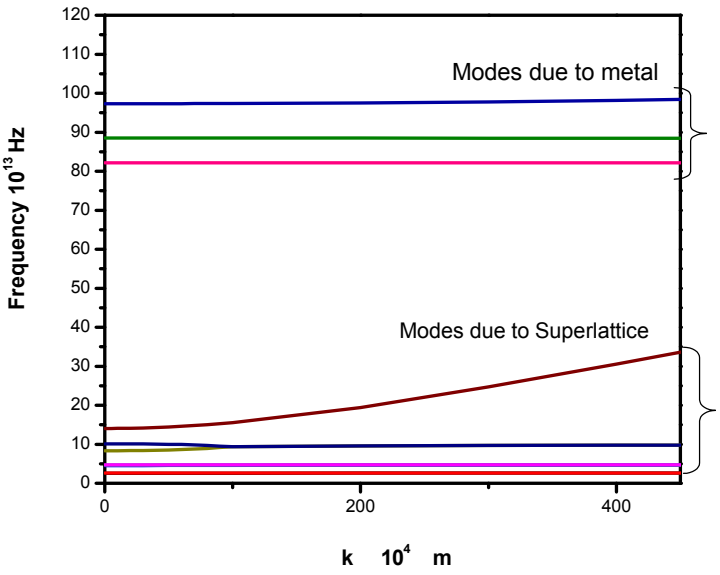

Figure 4- Dispersion of Ag-$LiNbO_3$/Ag-$LiTaO_3$ superlattice system when the nanoparticles concentration f=0.1 and $d_1=d_2=50$Å

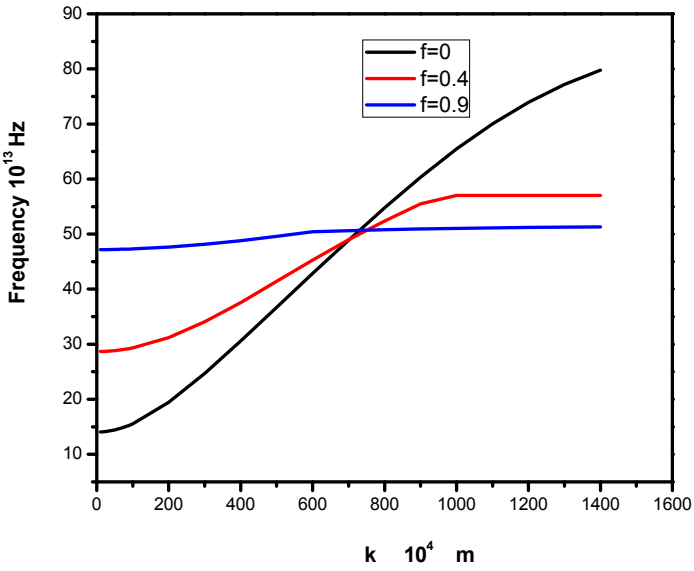

Figure 5- The tuning of middle mode with the concentration of metal nanoparticles