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GENERATION OF PLASMON-POLARITONS IN EPSILON-NEAR-ZERO POLARITONIC METAMATERIAL

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Abstract. In this paper, we study the generation of plasmon-polaritons in the epsilon-near-zero nanorod polaritonic metamaterial by using nonlocal effective medium approximation (EMT). The results indicate that the nonlocal EMT is the simplest and most accurate approach to describe the characteristics of plasmon-polaritons at the epsilon-near-zero regime ($\varepsilon \approx 0$) in the polaritonic metamaterial. In contrast, the Maxwell-Garnett effective medium approximation is considered to be the most general method to study the generated plasmon-polaritons in metamaterials. An additional plasmon-polariton is found in the polaritonic metamaterial through the nonlocal EMT, which could not be found with the Maxwell-Garnett EMT. A flat longitudinal wave-number of the excited plasmon-polariton occurs in the angle of incident light ranging from –20 to 20°, leading to the collinear group-velocity vectors, and its energy will be carried in one direction. The findings can be used in some applications in optical communication.

Keywords: polaritonic metamaterials, epsilon-near-zero metamaterials, cylindrical composite mediums, optical nonlocality

1 Introduction

Terahertz (THz) radiations have received a lot of interest due to their application prospects in optoelectronic devices. Terahertz electromagnetic waves can be used for potential applications in security and sensing [1], tissue imaging [2], communications [3], and even astronomy [4]. These waves have been insufficiently explored until recently. One of the main reasons is the scarcity of THz sources. Because standard materials in the visible spectrum used for THz manipulation components, such as polarizers, filters, beam splitters, and collimators, do not possess suitable properties in the THz region, polaritonic metamaterials can overcome this obstacle. The unique and exotic electromagnetic properties of the metamaterials (like all-angle negative refraction [5], electromagnetic cloaking, and backward radiation [6]) associated with metallic spatial features of polaritonic materials can create dynamic quasiparticle force fields and manipulate waves in the THz domain. The polaritonic metamaterials have strong positive and negative permittivity [7]. This property can make them a perfect replacement of either metals or high index dielectrics in the THz regime.

In the THz domain (long-wavelength approximation), the spacial dispersion is negligible [8-10]. The properties of polaritonic metamaterials are well described by the Maxwell-Garnett (MG) effective medium theory (EMT) [11-13]. The effects of spatial dispersion are considered when the polaritonic rods in the structure of the polaritonic metamaterial are perpendicular to the interface [14]. In this work, we consider the features of plasmon-polariton generation on polaritonic metamaterials in the case of epsilon-near-zero (ENZ) permittivity. In this regime, metamaterials are strongly affected by optical nonlocality [15-19]. We demonstrate theoretically that, in the optical ENZ regime, the spatial dispersion qualitatively changes the optical properties of polaritonic metamaterials and leads to the existence of additional transverse-magnetic-polarized waves that are not described by using the MG EMT.

2 Light beam transformation in polaritonic metamaterials

We consider the polaritonic metamaterials (PMM) made of polaritonic cylindrical rods periodically embedded into the dielectric template matrix, as illustrated in Fig. 1. Polaritonic metamaterials border on external conventional isotropic medium with dielectric permittivity ε (for example, by air when ε = 1). The rod with radius *R* is oriented along the *z*-direction, and the spacing between the cylinders (lattice constant) is *a*.

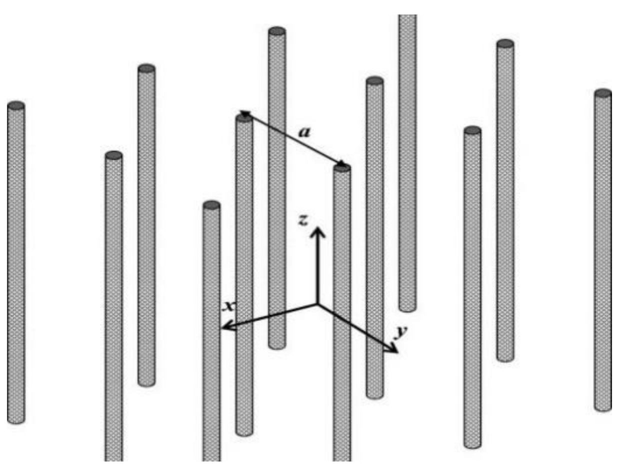

Fig. 1. Medium formed by long thin cylindrical rods arranged in a square lattice

In the approximation of the MG EMT, this metamaterial can be considered as a uniaxial uniform medium characterized by the permittivity tensor $\widehat{\varepsilon} = diag\{\varepsilon_t^{MG}, \varepsilon_t^{MG}, \varepsilon_l^{MG}\}$ [20]:

$$\varepsilon_t^{MG} = \varepsilon_d \cdot \frac{\varepsilon_r (N+1) + \varepsilon_d (1-N)}{\varepsilon_d (N+1) + \varepsilon_r (1-N)}, \tag{1a}$$

$$\varepsilon_l^{MG} = \varepsilon_r N + \varepsilon_d (1-N), \tag{1b}$$

where ε_t^{MG} and ε_l^{MG} are the transverse and longitudinal main effective permittivities of the tensor; $N = \pi r^2/a^2$ is the inclusion factor; and ε_d and ε_r are the permittivity of the dielectric host matrix and the rods. The permittivity of polaritonic cylindrical rods is given by the Lorentz formula [21]:

$$\varepsilon_r = \varepsilon_\infty \left[1 + \frac{\left(\omega_L^2 - \omega_T^2\right)}{\left(\omega_T^2 - \omega^2 + i\omega\gamma\right)} \right], \tag{2}$$

where ε_∞ is the bulk dielectric permittivity of polaritonic cylinders; ω (2πc/λ) is the cyclic frequency of optical radiation; ω_T and ω_L are the constants; γ is the damping constant.

Let us consider two different sets of polaritonic metamaterial samples. They are $LiTaO_3$ cylindrical rods in the air host ($LiTaO_3$/Air) and $LiTaO_3$ cylindrical rods in polypropylene $(C_3H_6)_n$ host ($LiTaO_3/(C_3H_6)_n$) with a permittivity of 2.2. The rods have a radius (*R*) of 0.1 μm, a lattice constant (*a*) of 2 μm, and *N* of $7.854.10^{-3}$. For lithium tantalate oxide $LiTaO_3$: $\omega_T/2\pi$ = 26.7 THz, $\omega_L/2\pi$ = 46.9 THz, $\gamma/2\pi$ = 0.94THz, and ε_∞ =13.4 [20]. From Eqs. (1) and (2), we can obtain the spectral dependence of permittivities of two polaritonic metamaterials samples. Fig. 2 shows our calculated results for the dependence of the real and imaginary parts of transverse and longitudinal permittivities of $LiTaO_3$/Air and $LiTaO_3/(C_3H_6)_n$ on the wavelength.

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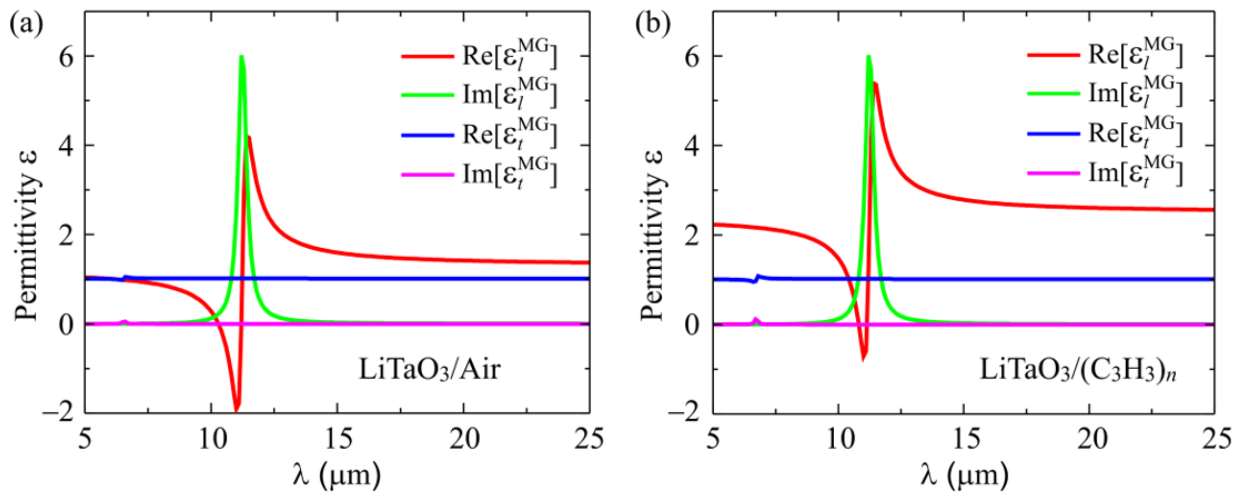

Fig. 2. Real (Re) and imaginary (Im) parts of transverse ε_t and longitudinal ε_l permittivities as a function of wavelength λ of polaritonic metamaterials made of polaritonic cylindrical rods periodically with radius *R* of 0.1 μm embedded into air host matrix $LiTaO_3$/Air (a) and polypropylene host matrix $LiTaO_3/(C_3H_6)_n$ (b)

From Fig. 2, we can see that, in the wavelength range from 5 to 25 μm, the value of Re[ε_t] is around 1 for $LiTaO_3$/Air and Re[ε_t] around 2 for $LiTaO_3/(C_3H_6)_n$. For $LiTaO_3$/Air near the wavelength of 10.3 μm, the real part of the effective longitudinal permittivity has a very small negative value, then the ENZ regime of type I is achieved. For the $LiTaO_3/(C_3H_6)_n$, the ENZ regime type I is realized when the wavelength equals 10.8 μm.

Previous studies [15-19] indicate that the materials made of cylindrically symmetric interference structures exhibit strong optical nonlocality near the ENZ regime. The effective permittivity ε_t is related to the plasmonic oscillations perpendicular to the axis of the cylindrical rod (transverse modes) [11]. In this work, the region under consideration with strong nonlocal effective permittivity ε_l is located outside of the transverse mode region; therefore, ε_t can be well described by Maxwell-Garnett's theory without considering the nonlocal properties. Previous experimental work on polaritonic rod metamaterials are analyzed with the present nonlocal dispersion relations as follows [22]

$$\varepsilon_l^{non} = \varepsilon_d + \frac{\varepsilon_d}{\dfrac{\varepsilon_d}{N(\varepsilon_r - \varepsilon_d)} - \dfrac{k_0^2 - \left(k_z^{non}\right)^2}{k_p^2}}, \qquad (3)$$

where k_p is the plasma wave number, $k_p = \frac{1}{a}\sqrt{2\pi.\left(0{,}5275 + \ln\left(\frac{a}{2\pi R}\right)\right)^{-1}}$,

and k_{non} is the longitudinal (along the *z*-axis) wave number with nonlocal dispersion.

Let us now consider a *p*-polarized light beam (TM mode), an incident light on the interface separating two semi-infinite media: an isotropic dielectric medium with permittivity ε_1 and a polaritonic metamaterial, and this metamaterial has an optic axis perpendicular to the interface boundary and parallel to the *z*-axis. In the framework of the effective medium approximation, the dispersion equation can be written in the form

$$\frac{q^2}{\varepsilon_l^{MG}} + \frac{\left(k_z^{MG,non}\right)^2}{\varepsilon_t^{MG}} = k_0^2, \qquad (4)$$

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where q is the transverse wave number (in the xy–plane), and $k_z^{MC,non}$ is the longitudinal wavenumber with disregard for spatial dispersion and with nonlocal dispersion.

By substituting Eq. (1) into Eq. (4), there is one TM mode propagating inside the polaritonic metamaterials with the longitudinal component of the wave vector as

$$k_z^{MG} = \pm\sqrt{k_0^2 \varepsilon_t^{MG} - \frac{\varepsilon_t^{MG}}{\varepsilon_l^{MG}} q^2}. \tag{5}$$

Substituting Eq. (3) into Eq. (4) and using the transverse component of the effective permittivity derived from MG EMT, we have two different solutions for k_z^{non} in Eq. (6). In other words, two TM modes (mode 1 and mode 2) propagate inside the polaritonic metamaterials:

$$\left(k_{z1}^{non}\right)^2 = \frac{1}{2}\left(\varepsilon_t^{non}\left(k_0^2\varepsilon_d - q^2\right) + \left(k_0^2\varepsilon_d + k_c^2 - k_p^2\right) + Q\right), \tag{6a}$$

$$\left(k_{z2}^{non}\right)^2 = \frac{\left(\varepsilon_t^{non}\left(k_0^2\varepsilon_d - q^2\right) + P - Q\right)}{2}, \tag{6b}$$

where

$$k_c^2 = -\frac{k_p^2\varepsilon_d}{\left(\varepsilon_r(\lambda) - \varepsilon_d\right)N}, \tag{7}$$

$$\begin{aligned} P &= k_0^2\varepsilon_d + k_c^2 - k_p^2 \\ Q &= \sqrt{\left(\left(k_0^2\varepsilon_d - q^2\right) - P\right)^2 + 4\varepsilon_t^{non}k_p^2 q^2}. \end{aligned} \tag{8}$$

One can see from Fig. 3 and Fig. 4 that the nonlocal response strongly affects the optical response of the cylindrical polaritonic metamaterials near the ENZ regime. Near the wavelength of 10.3 μm for the $LiTaO_3$/Air sample and 10.8 μm for the $LiTaO_3/(C_3H_6)_n$ sample, $\mathrm{Re}[\varepsilon_{11}^{non}] < 0$ and $\mathrm{Re}[\varepsilon_{12}^{non}] > 0$. Hence, two TM modes can be excited from the nonlocal EMT. Thus, the polaritonic metamaterial slabs exhibit both positive and negative refractions, leading to the strong optical nonlocal phenomenon. The coexistence region of two modes is 10.15 μm < λ <10.35 μm for the $LiTaO_3$/Air sample and 10.75 μm < λ < 10.9 μm for the sample $LiTaO_3/(C_3H_6)_n$. In this circumstance and for the local MG EM, only one TM mode can be excited. When the wavelength is less than the wavelength of the ENZ point, only mode 2 ($\mathrm{Re}[\varepsilon_{12}^{non}] > 0$, $\mathrm{Re}[\varepsilon_{11}^{non}] \approx 0$) can be excited, and the metamaterial slabs exhibit positive refraction. This mode can be well described by the MG EMT. When $\lambda > \lambda_e$, only mode 1 can be excited ($\mathrm{Re}[\varepsilon_{11}^{non}] < 0$, $\mathrm{Re}[\varepsilon_{12}^{non}] \approx 0$), and the metamaterial slabs exhibit negative refraction. Besides, the optical nonlocal effects in cylindrical polaritonic metamaterials depend on the dielectric host matrix filling the cylindrical structure. If this structure is not in air (but in another dielectric medium, for example, polypropylene), the special dispersion leads to a deviation in the value of the structure's longitudinal permittivity compared with the Maxwell-Garnett effective medium theory.

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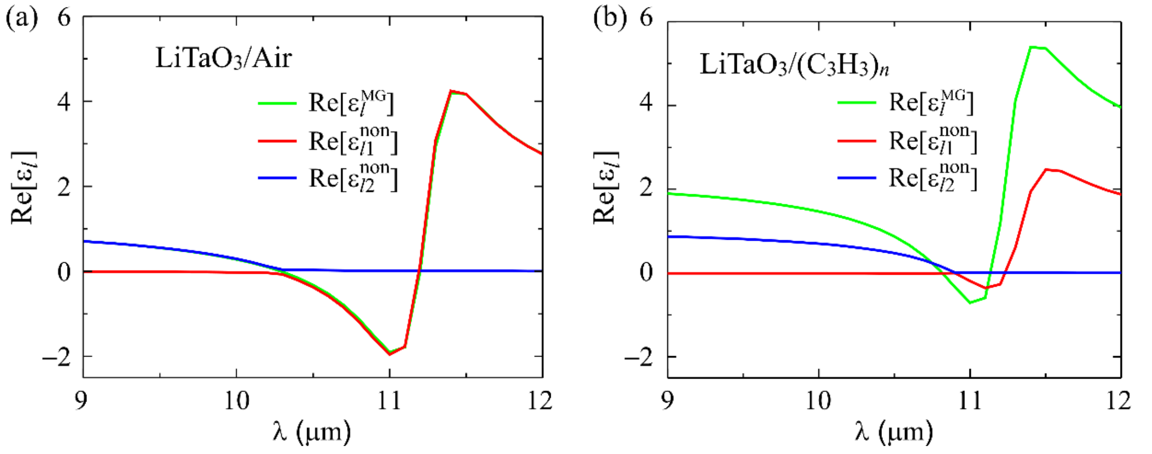

Fig. 3. Spectral dependence of the real part of longitudinal permittivity calculated from local MG EMT (green curve) and nonlocal EMT (red and blue curves) of the polaritonic metamaterials made of polaritonic cylindrical rods periodically with radius *R* of 0.1 μm embedded into air host matrix (a) and polypropylene host matrix (b)

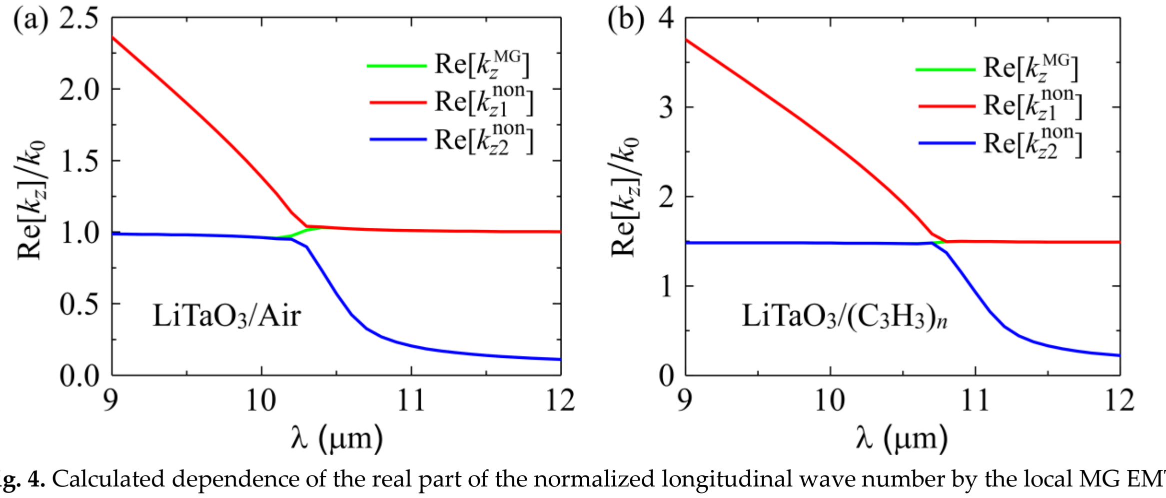

Fig. 4. Calculated dependence of the real part of the normalized longitudinal wave number by the local MG EMT $\mathrm{Re}[k_z^{\mathrm{MG}}]/k_0$ and nonlocal EMT $\mathrm{Re}[k_{z1,2}^{\mathrm{non}}]/k_0$ of the cylindrical polaritonic metamaterials $LiTaO_3$/Air (a) and $LiTaO_3/(C_3H_6)_n$ (b). The angle of incident light is 10°.

From Fig. 5, we can see that both mode 1 and mode 2 near the wavelength λ_e can be excited in the polaritonic metamaterials $LiTaO_3$/Air and $LiTaO_3/(C_3H_6)_n$. If the angle of the incident light increases, $\mathrm{Re}[k_{z1}^{\mathrm{non}}]$ also increases, but $\mathrm{Re}[k_{z2}^{\mathrm{non}}]$ decreases. When the angles of the incident light are between –20° and 20°, and for a small deviation λ_e in the direction of lower values, only mode 2 can be well described by using MG EMT, while only mode 1 can be described by using MG EMT in the direction of higher values. When the angle of the incident light is out of this region, the difference between the nonlocal EMT and local MG EMT results is more significant. In the angle region from –20 to 20°, a flat section in the curve $\mathrm{Re}[k_z]$ of mode 1 corresponds to the collinear group-velocity vectors. The energy of this mode is carried in one direction. The flat section of the angular dependence of $\mathrm{Re}[k_z]$ of mode 1 depends on the polaritonic metamaterials under consideration. Mode 1 has no phase shift when it propagates inside the ENZ polaritonic metamaterial.

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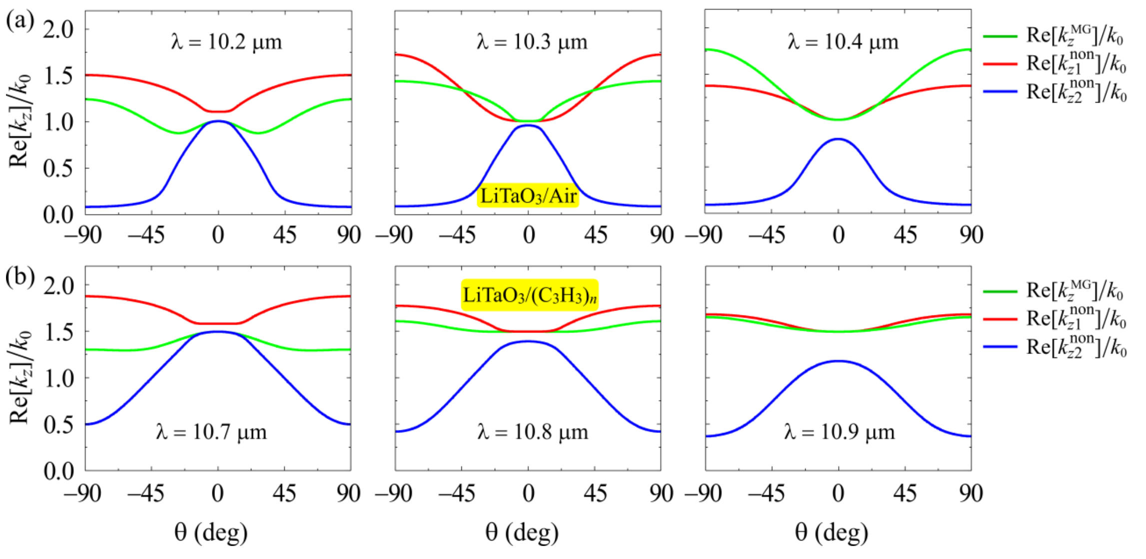

Fig. 5. Calculated angular dependence of the real part of the normalized longitudinal wavenumber by local MG EMT $\mathrm{Re}\left[k_z^{\mathrm{MG}}\right]/k_0$ and nonlocal EMT $\mathrm{Re}\left[k_{z1,2}^{\mathrm{non}}\right]/k_0$ of the extraordinary wave inside the cylindrical polaritonic metamaterials $LiTaO_3$/Air (a) and $LiTaO_3/(C_3H_6)_n$ (b) at different values of wavelength λ

3 Conclusion

This paper demonstrates and discusses the effect of the coexistence of two transverse-magnetic-polarized surface plasmon-polaritons in the epsilon-near-zero polaritonic metamaterials formed from the nanorod composite of thin polaritonic rods embedded in a dielectric host. Outside the epsilon-near-zero regime, only one plasmon-polariton can be excited and described by using the local Maxwell-Garnett effective medium theory. The features of the plasmon-polaritons in this metamaterial are considered. It is established that if the light falls from a dielectric with a typical value of the incident angle from –20 to 20°, the propagation of one of the excited surface plasmon-polaritons in epsilon-near-zero polaritonic metamaterials has no phase shift, and the energy of this mode is carried along one direction. Therefore, this mode may lead to new exciting applications of epsilon-near-zero polaritonic metamaterials.

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