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Surface modes at negative index material film

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ABSTRACT

We have investigated the existence of surface modes at negative index material (NIM) film for the S-polarized. Our attention is mainly focused in the excitation of surface modes through numerical simulation technique of attenuated total reflection (ATR) and the manner in which the electric field is coupled into the film interfaces at NIM. In the case of the ATR show well defined minima originated by the coupling of the incident light with the symmetric and asymmetric modes. Frequencies at the minima are used to obtain the optical dispersion relations (ODR) as function of the filling factor in the unit cell (vacuum – LHM or LHM –vacuum – LHM). The ODR indicates the behavior of surface modes as the film thickness of the NIM is varied.

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1. Introduction

Optical properties of materials have been investigated for many years provided that the knowledge of these properties defines the material applications in the optoelectronic industry. Plasmons, which are quanta of plasma oscillations, have been studied in metals since the pioneer work of Ritchie [1], and Stern and Ferrell [2]. Plasmons may propagate either in bulk or at the surface consequently they are termed as bulk or surface plasmons. Studies of surface plasmon polariton (SPP) propagation in metals have been done in simple surfaces and thin films using the Kretschmann [3–5] configuration for applications in sensors [6–13], these studies have used P-polarized light however it is also important to consider the surface modes (SM) with S-polarization which in the case of NIM or metamaterials allows the excitation and detection of surface modes. In metamaterials both dielectric permittivity and magnetic permeability have negative values which yield negative refraction index. The existence of these materials was predicted for the first time by Veselago [14] at the end of 1960 decade. Metamaterials are not available in nature however they may be fabricated. Because of this for a long time the scientific community paid no attention to their optical properties, however during the first decade of 2000 these materials took a great importance as they were fabricated for the first time [15,16]. Considering the existence of SM in S-polarized light en metamaterials to those who have not been devoted to investigating, in this work we take into account this fact to explore the existence of symmetric and asymmetric modes for S-polarized. We are aware that recent works have investigated plasmon propagation at surfaces of negative refraction index thin films [17–19] all these publications are far from the visible region of the electromagnetic spectrum, but with new advancements in technology manufacturing metamaterials in the visible spectrum region for interesting applications are expected [20–22]. Therefore we believe that it is important to study the excitation and detection of SM at metamaterial surfaces and thin films. There are works reported in the literature that deal with optical properties of SM and their coupling with P-polarized light, surprisingly less attention has been dedicated to the coupling to S-polarized light. The paper is organized as follows: In Section 2 we present the theory, in Section 3 we describe results and in Section 4 we make conclusions.

2. Theory

Consider the system seen in Fig. 1, where we study two types of symmetry, (a) prism-vacuum-LHM-vacuum and (b) prism-LHM-vacuum-LHM-vacuum, prism allows excite surface modes and is characterized by $\varepsilon_0 = 2.25$ and $\mu_0 = 1$, for the vacuum $\varepsilon_1 = 1$ and $\mu_1 = 1$. The metamaterial is characterized by the permittivity ε_2 and permeability μ_2 in a *xyz*-coordinate system. The permittivity is [23].

$$\varepsilon_2(\omega) = \varepsilon_{02} - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \tag{1a}$$

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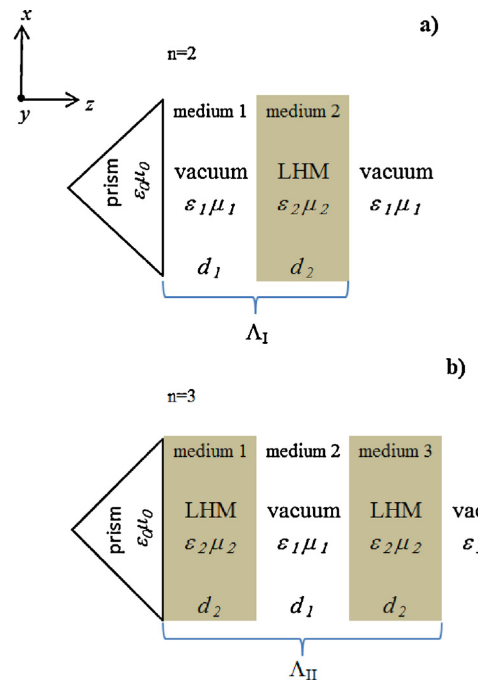

Fig. 1. The ATR geometry for the excitation of surface modes in LHM film. (a) Medium with symmetry type I and (b) medium with symmetry type II.

with $\varepsilon_{02} = 1.21$ and the permeability is

$$\mu_2(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)}, \tag{1b}$$

where, $\omega_p = F_{I,II}c/\Lambda_{I,II}$, the subscripts indicate the type of symmetry according to Fig. 1. and γ is the damping factor. To calculate the reflection of the system of Fig. 1 we use the formalism of the transfer matrix, for this we have the following fields:

$$E = -E_y \hat{j} e^{i(\beta x + qz - \omega t)} \tag{2a}$$

$$B = \left(B_x \hat{i} - B_z \hat{k}\right) e^{i(\beta x + qz - \omega t)} \tag{2b}$$

Making the corresponding algebra we obtain the reflectivity as:

$$|R|^2 = \left| \frac{(M_{12}Y_0 - M_{11})\,Y_{n+1} e^{iq_{n+1}\Lambda} + (M_{22}Y_0 - M_{21})\,e^{iq_{n+1}\Lambda}}{(M_{11} + M_{12}Y_0)\,Y_{n+1} e^{iq_{n+1}\Lambda} + (M_{21} + M_{22}Y_0)\,e^{iq_{n+1}\Lambda}} \right|^2 \tag{3}$$

with Λ the unit cell, $Y_0 = (\varepsilon_0/\mu_0)^{1/2}$ for the prism. $Y_{n+1} = (c/\omega)\,q_{n+1}$ and $q_{n+1} = (\omega/c)\left[1 - \varepsilon_0 \sin^2\theta\right]$ for the medium output (vacuum). The M_{11}, M_{12}, M_{21} and M_{22} are the components of the matrix M is given by:

$$\mathbb{M} = \prod_{j=1}^{n} \mathbb{m}_j = \mathbb{m}_1 \mathbb{m}_2 \cdots \mathbb{m}_n$$

and $\mathbb{m}_j$ is the matrix of the jth medium and is given by:

$$\mathbb{m}_j = \begin{pmatrix} \cos(q_j d_j) & -i\dfrac{sen(q_j d_j)}{Y_j} \\ -iY_j sen(q_j d_j) & \cos(q_j d_j) \end{pmatrix}$$

where, $Y_j = (c/\omega\mu_j)\,q_j$ and $q_j = (\omega/c)\left[\varepsilon_j\mu_j - \varepsilon_0\mu_0 \sin^2\theta\right]^{1/2}$ is the impedance and the wave vector in the direction of propagation of the jth medium, respectively. θ is the incident angle.

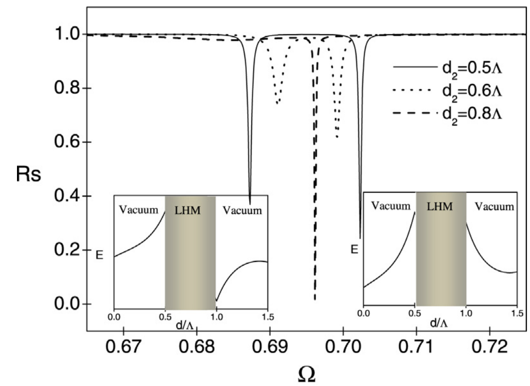

Fig. 2. Reflection spectrum for the prism-vacuum-LHM-vacuum system for different film thicknesses of LHM at an angle of incidence $\theta = 60^\circ$. The boxes shown the electric field within the structure for minimum reflection film thickness LHM $d_2 = 0.5\Lambda_I$ where the asymmetric mode (inset bottom left) and the symmetric mode (lower right inset) is observed.

3. Film surface modes

In what follows we describe the attenuated total reflection (ATR) calculations with S-polarization for symmetry type I [See Fig. 1(a)]. We consider the metamaterial refraction index modeled according to Eqs. (1a) and (1b) with $\gamma = 10^{-4}\omega_p$ with $\Lambda_I = d_1 + d_2$ (vacuum + LHM, respectively) and $F_I = 10$. The critical angle at the prism/vacuum interface is $\theta_c = \sin^{-1}(n_1/n_p) = 41.81^\circ$ therefore the incidence angle θ should be greater than θ_c to allow the incident light to couple to the film surface modes. The thickness of the metamaterial is considered in the calculations as function of the unit cell. Fig. 2 displays the calculated reflectivity R_s spectra as a function of the frequency $\Omega = \omega/\omega_p$ for an incident angle $\theta = 60^\circ$. For the thinner LHM the R_s curve clearly displays two deep minima which are originated by the coupling of the incident light with the asymmetric (lower frequency minimum) and symmetric (higher frequency minimum) surface modes of the film [as shown in the boxes of Fig. 2]. As the film thickness increases the surface modes exhibit weaker interactions, the two minima approach to each other, to finally degenerate into a minimum.

In Fig. 3 the optical dispersion relation (ODR) of the symmetric and asymmetric modes as function of the filling factor of the unit cell Λ_I (vacuum-LHM) is plotted and it is clear that for the film thickness of LHM $d_2 < 0.5\Lambda_I$ modes are widely dispersed in exchange for $d_2 > 0.5\Lambda_I$ modes are coming together to degenerate

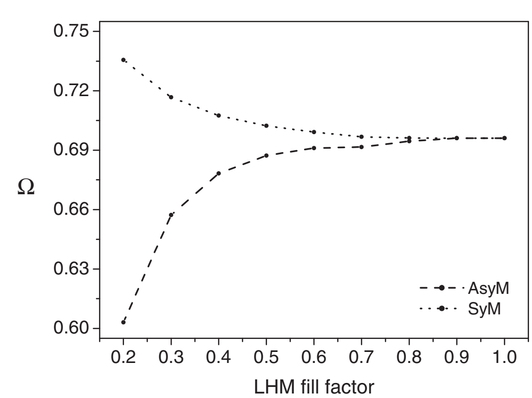

Fig. 3. Optical dispersion relation (ODR) as a function of film thickness of LHM. The behavior of the asymmetric modes (AsyM) and symmetric modes (SyM) as observed. For an angle of incidence $\theta = 60^\circ$.

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