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Surface polaritons of a metal-insulator-metal curved slab

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ABSTRACT

The properties of s- and p-polarized surface polariton modes propagating circumferentially around a portion of a cylindrical metal-insulator-metal structure are studied, theoretically. By using the Maxwell equations in conjunction with the Drude model for the dielectric function of the metals and applying the appropriate boundary conditions, the dispersion relations of surface waves for two types of modes, are derived and numerically solved. The effects of the slab curvature and insulator thickness on the propagation of electromagnetic modes are investigated. The differences of the s- and p-polarized surface modes are also shown.

1. Introduction

In recent years there has been considerable interest in the metal-insulator-metal (MIM) waveguides, in which surface plasmon polriton (SPPs) field is confined in a 10 – 100 nm dielectric gap between two metal layers [1–7]. Such subwavelength confinement cannot be achieved by conventional dielectric optical waveguides [8,9]. More recently, the light-induced SPPs excitation within MIM waveguide has been proposed in Refs. [10–12]. However, we should note that this better field localization is obtained at the expense of a higher propagation loss (reduced propagation distance).

In particular, the nonlocal response of the SPP and surface plasmon waves of MIM waveguides has attracted a great deal of attention recently [13–16]. Sernelius [13] derived the general conditions for electromagnetic-normal modes at individual planar interfaces and for two half-spaces separated by a vacuum gap; the derivations were performed both with and without spatial dispersion taken into account. Moreau et al. [15] found that the fundamental mode of a MIM waveguide, sometimes called the gap plasmon, is very sensitive to nonlocality when the insulating, dielectric layers are thinner than 5 nm. In this way, Raza et al. [16], investigated the effects of nonlocal response on the SPP guiding properties of the metal-insulator (MI), MIM, and insulator-metal-insulator (IMI) waveguides. They showed that in the nonretarded limit, nonlocality breaks the complementarity of the MIM and IMI waveguides. As a new result, the nonlocal response distinguishes between the MIM and IMI waveguide modes, for both of the two surface modes [14,16].

From another side, several years ago, Berry [17] studied in detail the propagation of p-polarized surface electromagnetic wave circumferentially around a portion of a cylindrical metal channel and found that no attenuation of the wave occurs, and the wave is a true SPP wave bound to the interface. Also, more recently Polanco et al. [18,19] extended the Berry's results and derived the dispersion relations of the s-polarized and p-polarized SPP waves propagating circumferentially around a portion of a cylindrical metal micro-channel and showed that the dispersion relations for both s-polarized type and p-polarized type modes have multiplicity of solutions, where they have the nature of waveguide modes and owe their existence to the curvature of the interface. However, as far as we know, no explicit calculation can be found for the propagation of s- and p-polarized electromagnetic modes in a MIM curved slab.

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In the present work, motivated by the recent results given in Refs. [18,19], we investigate the properties of s- and p-polarized electromagnetic modes propagating circumferentially around a portion of a cylindrical MIM structure, theoretically. In this way, we use the Maxwell equations with appropriate boundary conditions and derive the dispersion relations of electromagnetic waves for two types of modes, on the basis of a Drude model for the dielectric function of the metals. Then, we study the effects of the slab curvature and insulator thickness on the propagation of polariton modes. In particular, we wish to distinguish the difference in the characters of two different propagating modes, i.e., s- and p-polarized electromagnetic modes.

The paper is organized as follows: In Section 2, we present main equations of our model. In Sections 3 and 4, we study the propagation of polariton waves with s- and p-polarized modes, respectively, circumferentially around a portion of a cylindrical MIM structure. Section 5 contains our conclusions.

2. Basic equations

Consider a slab of thickness $d = b - a$ that has been bent and occupies the region corresponding to the range $a < \rho < b$ in the usual cylindrical coordinate system (ρ,ϕ,z), as shown in Fig. 1. The medium bounding the curved slab is of metallic materials having dielectric function ε_1. The dielectric constant of the curved slab is ε_2. We wish to study the surface polariton modes propagating along the slab by treating again our problem in a two-dimensional setting (ignoring the z coordinate) and considering separately the s and p polarizations. Thus, all electromagnetic field components are assumed to have the variation $\exp(im\phi - i\omega t)$ where ω is the frequency of the wave and we assume the z direction to be coincident with the axis of the MIM curved slab. Let us note that the parameter m is not required to be an integer because we are not considering a complete MIM cylinder, but only a locally cylindrical surface [18,19]. Also, we use the Drude model for the optical properties of the medium bounding the curved slab, as:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}, \tag{1}$$

where ω_p is the plasma frequency of the metal.

For the s polarization, the electric field **E** is parallel to the z axis and, from Maxwell equations, it is easy to show that it satisfies

$$\frac{d^2E_z}{d\rho^2} + \frac{1}{\rho}\frac{dE_z}{d\rho} + \left(\varepsilon_1\frac{\omega^2}{c^2} - \frac{m^2}{\rho^2}\right)E_z = 0, \tag{2}$$

Outside the slab ($\rho < a$ and $\rho > b$), where $\varepsilon_1 = \varepsilon(\omega)$ and c is the light speed. Also, for inside the slab ($a < \rho < b$), we have

$$\frac{d^2E_z}{d\rho^2} + \frac{1}{\rho}\frac{dE_z}{d\rho} + \left(\varepsilon_2\frac{\omega^2}{c^2} - \frac{m^2}{\rho^2}\right)E_z = 0. \tag{3}$$

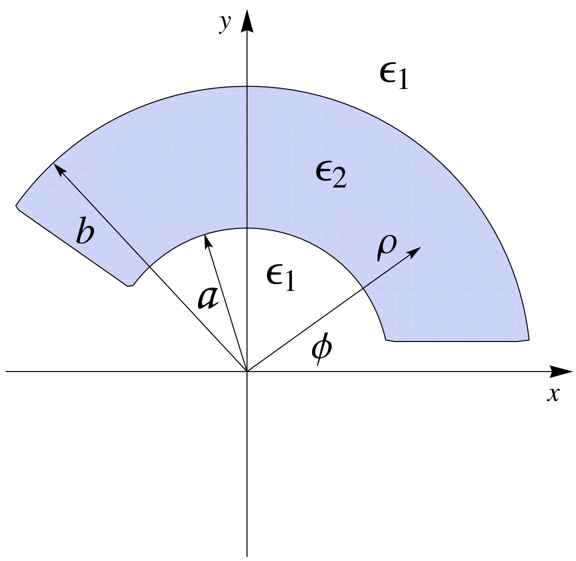

Fig. 1. Top view of a MIM curved slab. The inner and outer radii of the curved slab are denoted by a and b. The medium bounding the curved slab is of metallic materials having dielectric function $\varepsilon_1 = \varepsilon(\omega)$. The dielectric constant of the curved slab is ε_2.