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Impact of nonlocal response on propagation of surface plasmon polariton in anisotropic insulator/metal/insulator structures

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ABSTRACT

We discuss the effects of nonlocality on the characteristics of surface plasmon polariton (SPP) in anisotropic insulator/metal/insulator structures by using the hydrodynamic model. The differences of the dispersion relation and the propagation length of the SPP between nonlocal and local case, are derived and numerically solved. The dependence of propagation length on the angle of rotation of the crystal axes is investigated and an effective method for altering the propagation length is provided.

1. Introduction

Since the traditional optical devices can only reach micron level because of the diffraction limit, they can no longer satisfy the higher requirements for highly integrated photonic and optoelectronic circuits. Then surface plasmon polariton is proposed, which can break through the diffraction limit of light due to their tight field intensity confinement to the metal surface [1,2]. SPP has widespread applications in, e.g., the near field optical spectroscopy [3,4], optical data storage [5] and biosensing [6,7]. Thanks to the great progress in new analytical and nanofabrication technologies, SPP is entering the nanometer regime and shows great promises for applications in highly integrated photonic circuits, so that new optical peculiarities receive much attention. In metallic structures with features on the order of 10 nm or less, nonlocal response is likely to be crucial for optimizing field localization and enhancement [8–10]. Hence, more detailed descriptions on nonlocality of SPP are needed.

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Symmetric insulator/metal/insulator (IMI) slab waveguides are the most fundamental metallic waveguide structures, and can provide a solid foundation for the understanding of more complex plasmonic waveguides. Moreau et al. have utilized the IMI waveguides to analyze the essence of nonlocality by deriving the formulas in detail and have introduced the impact of nonlocality on optical patch antennas [11]. Ruppin has presented the effects of nonlocality on the dispersion relation of SPP and given the results of numerical calculations for silver slabs by using the IMI waveguide structure [12]. Raza et al. have compared the effects of nonlocal response on SPP in the metal–insulator (MI), metal-insulator-metal (MIM) and insulator-metal-insulator (IMI) slab waveguides [13]. The above results indicate that nonlocal response is important when the waveguide scale is at the nanometer or sub-nanometer regimes, so further theoretical work should be performed on IMI waveguides.

The characteristics of electromagnetic wave propagation through anisotropic slab waveguide has attracted enormous interest [14,15], and long-range SPPs have been also studied in the anisotropic systems [16]. Jacob et al. have introduced the dispersion relations of SPP modes in MIM and IMI structures by use of the anisotropy insulator layers [17]. Nagaraj and Krokhin have studied the long-range SPPs propagating in a thin metallic film between two anisotropic materials [18].

In this paper, we consider a symmetrical metal-dielectric system, i.e., an ultrathin metal film sandwiched between two identical anisotropic materials, where the nonlocal response in the thin metallic film will be taken into consideration. We discuss the effects of nonlocality on the dispersion relation of SPP in the structure. As known, the propagation length of SPP is of great significance; in this respect, although many studies have been carried out, they focus mainly on local waveguide structures [15,18,19]. Therefore, we explore the propagation length of SPP in the nonlocal model and compare it with that in local model concretely. Finally we discuss the dependence of the propagation length on the angle of rotation of the crystal axes.

2. Basic theory

2.1. Nonlocal response

Without considering the nonlocal response, SPP can be accounted for solely by the Drude-like model for the permittivity, which has the frequency-dependent form (assuming a time dependence of $e^{-i\omega t}$)

$$\varepsilon_m = 1 - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}, \tag{1}$$

where ω is the frequency of light, ω_p is the plasma frequency, γ is the Drude damping, respectively. However, with decreasing the thickness of metal film, nonlocal response becomes obvious and crucial. The nonlocal nature of the metal results in the appearance of a longitudinal bulk plasmon mode. Drude-like model cannot give the new longitudinal plasmon mode, so the hydrodynamic model has been introduced for the force-response relationship between the field and the current density [11,20].

By defining the free electric polarization vector through $\dot{\mathbf{P}}_f = \mathbf{J}$ ($\mathbf{J}$ is the current density) and based on the hydrodynamic model, a linearized relation of $\mathbf{P}_f$ to the electric field is given by [11,21]

$$-\beta^2\nabla(\nabla\cdot\mathbf{P}_f) + \ddot{\mathbf{P}}_f + \gamma\dot{\mathbf{P}}_f = \varepsilon_0\omega_p^2\mathbf{E}, \tag{2}$$

where β is the nonlocal parameter. For nonlocal response, Maxwell's equation can be written as [11]

$$\nabla\times\mathbf{E} = i\omega\mu_0\mathbf{H}, \tag{3}$$

$$\nabla\times\mathbf{H} = -i\omega\varepsilon_0\left[\left(1 + \chi_b + \frac{\omega_p^2}{\omega^2 + i\gamma\omega}\right)\mathbf{E} - \frac{(1+\chi_b)\beta^2}{\omega^2 + i\gamma\omega}\nabla(\nabla\cdot\mathbf{E})\right]. \tag{4}$$

Here χ_b being the susceptibility of the bound electrons. There are two different solutions to Maxwell's equations. The first solution satisfies $\nabla\cdot\mathbf{E} = 0$, then the solution of Maxwell's equations is the usual form. Obviously, in the case the wave is transverse. The second solution satisfies $\nabla\times\mathbf{E} = 0$, which