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Multiple modes of surface plasmonic polaritons in transversely-truncated metal/dielectric superlattices

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ABSTRACT

The surface plasmonic polariton (SPP) of a transversely-truncated metal/dielectric superlattice (SL) structure has been solved with an approximate method. The effect of inter-layer interfaces in the SL is taken into consideration efficiently in comparison with the effective-medium method. The silver/air and silver/SiO_2 SLs with a shorter period are regarded as two specific examples in numerical calculation. A series of separated SPP modes are found and highly localized at the surface, and the highest-frequency mode is the only one also predicated by the effective-medium method. These results obviously show the effect of inter-layer interfaces in the case of short period, whilst the reliability and limitation of the effective-medium method is presented as well. Because the skin depths of the modes are extremely small, the SLs can be used as ideal surface-wave waveguides.

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1. Introduction

In the last 30 years, the surface excitations and surface polaritons (SPs) in periodical structures and metamaterials have attracted a great attention of scientists [1–4]. Among these structures, the superlattices (SLs) (one-dimensional photonic crystals) composed of alternating layers of different materials are the simplest examples. For the bulk-slab model, the SPs are often solved by two classical methods, the effective-medium method [5–8] and the transfer-matrix method [5,9–11]. The effective-medium method is available in the situation of long-wavelength limit. The transfer-matrix method is an accurate theory used to solve the SPs in the SLs with a parallel-surface. But the transfer-matrix method can not be directly used in the case of a semi-infinite SL with a transverse surface [6,8,12]. Although the effective-medium method can be applied in the long wavelength limit [5–8,13], it is a homogenization theory based on field averaging so that the effect of inter-layer interfaces and periodicity of the SLs on the SP is neglected.

The periodical metamaterials with one or two transverse surfaces, such as metal films with periodical arrays of air-holes [14–15] in them, are very important and possess a lot of distinctive optical properties [14–20]. These optical properties originate from the coupling between the surface plasmons and incident light waves, so the surface plasmon polaritons (SPPs) play a most important role [3,4]. The rigorous solutions of the SPPs in these structures are difficult to be found, so the effective-medium method is often used to discuss the dispersion spectra of the SPPs. Recently an improved method was presented to discuss the SPPs in the transverse-surface metal/dielectric SLs [8]. However, both the effective-medium method and this improved method neglected the optical effect of inter-layer interfaces in the SLs.

In this paper, we present a theoretical method to solve the SPPs in the transverse-surface metal/dielectric SLs. This method combines the concept of effective-medium method with the transfer-matrix method in order to include the effect of inter-layer interfaces and the SL periodicity. The semi-infinite SLs can also be considered as quite thick SL films so that the coupling between SPPs localized at their upper and lower surfaces can be ignored. The numerical calculations are based on the semi-infinite silver/air and silver/SiO_2 SLs.

2. Model and method

The transversely-truncated SL structure and the coordinate system are shown in Fig.1, where d_m and d_d are the thicknesses of metal and dielectric layers, respectively, and the SL period is $L = d_m + d_d$. ε_m and ε_d indicate the dielectric function of metal layers and the dielectric constant of dielectric layers, respectively. The upper half space is occupied by the medium with dielectric

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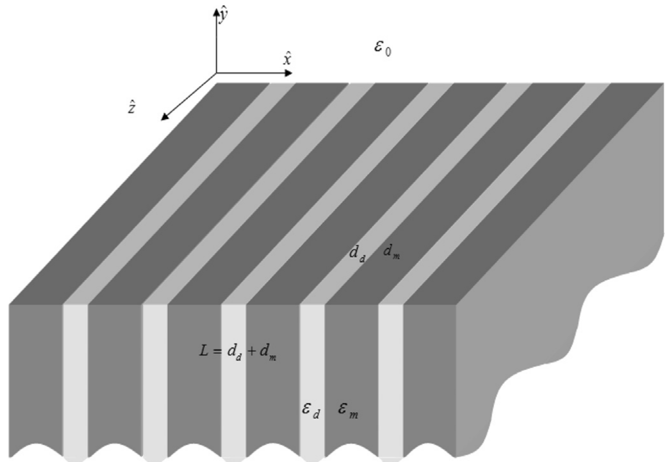

Fig. 1. Coordinate system and SL structure composed of alternating metal and dielectric layers. The SL occupies the half-space of $y < 0$ and the constituent-layer thicknesses are indicated by d_m and d_d, respectively. The transverse magnetic wave propagates along the x axis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

constant ε_c and the SL is situated in the lower half space. The constituent layers used here are nonmagnetic, so their magnetic permeability is the same as that in vacuum. Consequently, the SPP is a transverse-magnetic wave. It is assumed that the SPP magnetic field is parallel to the z-axis and the SPP propagates along the x-axis and attenuates exponentially along the y axis.

The SL can be considered as an uniaxial-anisotropy effective medium, its effective permittivity is written as the following form:

$$\overleftrightarrow{\varepsilon}_{eff} = \begin{pmatrix} \varepsilon_\perp & 0 & 0 \\ 0 & \varepsilon_\parallel & 0 \\ 0 & 0 & \varepsilon_\parallel \end{pmatrix} \tag{1}$$

and the SPP magnetic field is shown as follows:

$$H_y = A_v e^{\Gamma_0 y + i(qx - \omega t)} \quad (y > 0) \tag{2a}$$

$$H_y = A_b e^{-\Gamma y + i(qx - \omega t)} \quad (y < 0) \tag{2b}$$

where Γ and Γ_0 are the attenuation coefficients of the SPP in the effective medium and in the upper half space, respectively. The x-component of the SPP electric field can be obtained through the equation $E_j = \partial H_j / i\omega\varepsilon_j \partial x$ in different spaces. The electromagnetic boundary conditions lead to:

$$\Gamma + \varepsilon_\perp \Gamma_0 = 0 \tag{3}$$

The Maxwell equations directly offer [13,20] the additional equations to us:

$$\varepsilon_\perp q^2 - \varepsilon_\parallel \Gamma^2 = \varepsilon_\perp \varepsilon_\parallel \omega^2 \tag{4}$$

and

$$q^2 - \Gamma_0^2 = \varepsilon_c \omega^2 \tag{5}$$

These results all come from the concept of effective-medium method. However, the key point of effective-medium method is the nonzero elements of the effective permittivity, and they are expressed as follows:

$$\varepsilon_\perp = \varepsilon_d \varepsilon_m / (f_d \varepsilon_m + f_m \varepsilon_d) \tag{6a}$$

$$\varepsilon_\parallel = f_m \varepsilon_m + f_d \varepsilon_d \tag{6b}$$

where $f_m = d_m/L$ is the metal filling ratio and $f_d = d_d/L$ is the dielectric filling ratio[5,12,13]. The effective-medium method is an homogenization method based on field-averaging which ignores the optical effect of inter-layer interfaces and the SL periodicity. Therefore, it is significant to establish an approximate method including the effect to investigate the SPP in such a transverse-surface SL, and it may bring new SPP modes.

In the transfer-matrix method, one well-known polariton-dispersion equation in the infinite metal/dielectric SL is [5,8]

$$\cos(qL) = \cos(k_m d_m)\cos(k_d d_d) - \frac{(\varepsilon_d k_m)^2 + (\varepsilon_m k_d)^2}{2\varepsilon_d \varepsilon_m k_m k_d} \sin(k_m d_m)\sin(k_d d_d) \tag{7}$$

where q is the Bloch wave-vector along the x-axis. The propagation coefficients in Eq. (7) satisfy

$$k_m^2 = \varepsilon_m \omega^2 - k_y^2 \tag{8a}$$

$$k_d^2 = \varepsilon_d \omega^2 - k_y^2 \tag{8b}$$

in metal and dielectric layers. k_y is the wave vector along the y-axis. The attenuation coefficient $\Gamma = ik_y$ of the SPP in the transversely-truncated superlattice is positive, so k_d is always a real number. However, if $\varepsilon_m < 0$, k_m is real for a larger Γ, otherwise it is imaginary.

In our numerical calculations, frequency ω is always treated as an argument and the calculation steps are presented as follows: (a) We first propose an virtual wave attenuating along the y-axis with $\Gamma = ik_y$ and $q = 0$. After figuring out Γ by Eq. (7), we obtain $\varepsilon_\perp$ from Eq. (4). Hence the effect of inter-layer interfaces is at least partly contained in $\varepsilon_\perp$. (b) For the actual SPP with $q \neq 0$, we use $\varepsilon_\perp$ given on the a-step to calculate Γ of this SPP by Eq. (3). (c) Finally Γ is substituted into Eq. (7) and we obtain $q(\omega)$ including the contribution of both inter-layer interfaces and the SL periodicity to the SPP modes .

Eq. (3) implies $\varepsilon_\perp \leq 0$ and Eq. (5) shows that the dispersion curves of the SPP are all situated below the vacuum-light line. Because k_d and k_m are both real for larger values of Γ, the SPP possibly possesses multiple solutions. In mathematics, the sine and cosine functions in Eq. (7) are the periodical functions, but the whole equation is not periodical. In physics, the different forward and backward waves in any constituent layer can couple into a series of various modes, furthermore the couplings of such modes in adjacent layers can result in the multiple modes. The method is still an approximate method because Eq. (3) is used, but it is a more reasonable approximation for smaller SL periods. It is greatly important that this method includes the transmission and reflection effect of inter-layer interfaces on the SPP.

3. Numerical calculations of SPP

The dielectric function and other relevant physical parameters should be offered first in order to solve numerically dispersion-equations of the SPP. The semi-infinite silver/air and silver/SiO_2 SLs are taken as examples. In fact the silver/air SL is just a semi-infinite silver layer array. The dielectric function of silver layers is defined as

$$\varepsilon_m = \varepsilon_\infty - \frac{(\varepsilon_0 - \varepsilon_\infty)\omega_p^2}{\omega^2} \tag{9}$$

which appears appropriate for actual metals [21,23]. Our emphasis is only on dispersion properties of the SPP, hence, the damping has been neglected for simplicity, and this function is

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