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Compound surface-plasmon-polariton waves guided by a thin metal layer sandwiched between a homogeneous isotropic dielectric material and a structurally chiral material

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ABSTRACT

Multiple compound surface plasmon-polariton (SPP) waves can be guided by a structure consisting of a sufficiently thick layer of metal sandwiched between a homogeneous isotropic dielectric (HID) material and a dielectric structurally chiral material (SCM). The compound SPP waves are strongly bound to both metal/dielectric interfaces when the thickness of the metal layer is comparable to the skin depth but just to one of the two interfaces when the thickness is much larger. The compound SPP waves differ in phase speed, attenuation rate, and field profile, even though all are excitable at the same frequency. Some compound SPP waves are not greatly affected by the choice of the direction of propagation in the transverse plane but others are, depending on metal thickness. For fixed metal thickness, the number of compound SPP waves depends on the relative permittivity of the HID material, which can be useful for sensing applications.

1. Introduction

The propagation of a surface-plasmon-polariton (SPP) wave is guided by a planar metal/dielectric interface, the field strengths decaying exponentially away from the interface in both materials [1]. If the dielectric material is homogeneous and isotropic, only one SPP wave can propagate parallel to the interface at a specific frequency. If the dielectric material is periodically nonhomogeneous in the direction normal to the interface, multiple SPP waves that differ in polarization state, phase speed, attenuation rate, and field profile can be guided simultaneously by the interface at a specific frequency [2].

This multiplicity is attractive for optical sensing applications, as the sensitivity and reliability of sensing can be enhanced thereby [3]. Furthermore, the number of the simultaneously detected analytes can then also be greater than one, the usual number [4]. The same multiplicity will enhance SPP-wave-based microscopy [5] and communications [6] as well.

For about three decades, one way to further increase the number of SPP waves is to interpose a thin metal layer between two suitably chosen homogeneous dielectric materials [7,8]. The two SPP waves, each guided separately by a metal/dielectric interface when the metal layer is thick, hybridize into compound SPP waves. Motivated by that possibility, recently we analyzed the propagation of multiple compound SPP waves guided by an isotropic metal layer sandwiched between a homogeneous isotropic dielectric (HID) material and a periodically multilayered isotropic dielectric (PMLID) material. We demonstrated that compounding occurs even when one of the two metal/dielectric interfaces is capable of guiding multiple SPP waves by itself [9].

In this paper, we extend the scope of the multiple-compound-SPP-wave phenomenon to encompass anisotropic dielectric materials by replacing the PMLID material by a dielectric structurally chiral material (SCM). Exemplified by Reusch piles [10,11], cholesteric liquid crystals [12,13], and chiral sculptured thin films [14], a dielectric SCM is anisotropic and helically nonhomogeneous along a fixed axis. Whereas a planar metal/HID interface by itself can guide a single SPP wave, the planar interface of a metal and a dielectric SCM by itself can guide multiple SPP waves [15].

This paper is organized as follows. A description of the boundary-value problem is provided in Section 2, but we have elected not to describe the procedure to obtain the dispersion equation for compound SPP waves, as the methodology is available

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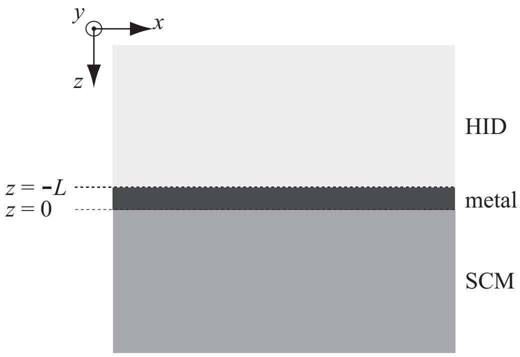

Fig. 1. Schematic of the boundary-value problem. A metal layer of thickness L separates a half space occupied by a HID material and another half space occupied by a dielectric SCM.

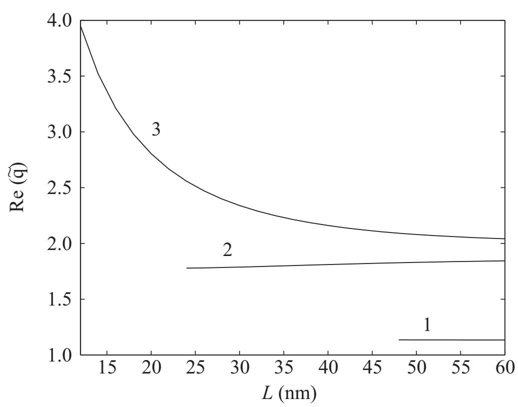

Fig. 2. Variation of $\mathrm{Re}(\tilde{q})$ with the thickness L of the metal layer when $\varepsilon_d = 3.1634$ and $\psi = 0°$.

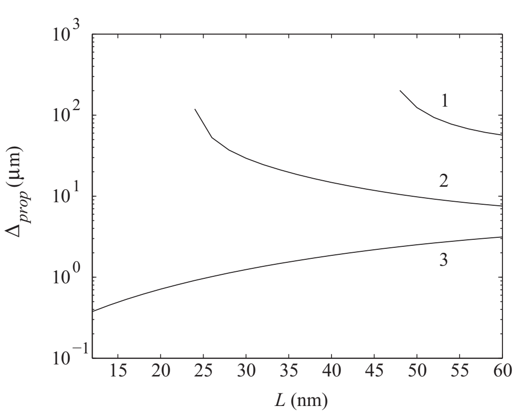

Fig. 3. Variation of the propagation distance Δ_{prop} with the thickness L of the metal layer when $\varepsilon_d = 3.1634$ and $\psi = 0°$.

in detail elsewhere [2, Chapter 3]. In Section 3 numerical results showing the compounding of the SPP waves guided by the metal/HID and metal/SCM interfaces are presented in relation to both the thickness of the metal layer, the relative permittivity of the HID, and the direction of propagation in the transverse plane. Concluding remarks are given in Section 4.

An $\exp(-i\omega t)$ dependence on time t is implicit, with ω denoting the angular frequency and $i = \sqrt{-1}$. Furthermore, $k_0 = \omega\sqrt{\varepsilon_0\mu_0}$ and $\lambda_0 = 2\pi/k_0$, respectively, represent the wavenumber and the wavelength in free space, with μ_0 being the permeability and ε_0 the permittivity of free space. The speed of light in free space is denoted by $c_0 = 1/\sqrt{\varepsilon_0\mu_0}$. Vectors are in boldface; dyadics are double

Table 1
Values of $\tilde{q}$ computed for compound SPP waves belonging to the three solution branches when $\psi = 0°$ and the metal layer has either a thickness $L = 60$ nm or $L \simeq L_{th}$, where L_{th} is the minimum thickness for which a solution on a specific branch was found. Solutions obtained for SPP waves guided by either the metal/SCM interface alone or the metal/HID interface alone are also provided.

Branch →	1	2	3
$L \simeq L_{th}$	1.1356 + i0.0005	1.7785 + i0.0008	3.9514 + i0.2679
$L = 60$ nm	1.1344 + i0.0018	1.8436 + i0.0133	2.0417 + i0.0321
$\tilde{q}_{met/SCM}$	1.1340 + i0.0025	1.8584 + i0.0181	–
$\tilde{q}_{met/HID}$	–	–	2.0100 + i0.0230

underlined; Cartesian unit vectors are denoted by $\mathbf{u}_x$, $\mathbf{u}_y$, and $\mathbf{u}_z$; and the asterisk denotes the complex conjugate.

2. Theoretical framework

The geometry of the boundary-value problem for the propagation of compound SPP waves is schematically illustrated in Fig. 1. The half space $z < -L$ is occupied by a HID material with real-valued relative permittivity $\varepsilon_d > 0$. An isotropic metal layer of thickness L and complex-valued relative permittivity ε_m separates the HID material from a dielectric SCM which occupies the half space $z > 0$. The chosen SCM is periodically nonhomogeneous along the z-axis with period 2Ω and can be characterized by the relative-permittivity dyadic [2]

$$\underline{\underline{\varepsilon}}_{SCM}(z) = \underline{\underline{S}}_z(h\pi z/\Omega)\cdot\underline{\underline{S}}_y(\chi)\cdot\underline{\underline{\varepsilon}}^{o}_{ref}\cdot\underline{\underline{S}}_y^{-1}(\chi)\cdot\underline{\underline{S}}_z^{-1}(h\pi z/\Omega), \tag{1}$$

where $h = 1$ for a right-handed SCM or $h = -1$ for a left-handed SCM; the dyadic

$$\underline{\underline{\varepsilon}}^{o}_{ref} = \varepsilon_a\mathbf{u}_z\mathbf{u}_z + \varepsilon_b\mathbf{u}_x\mathbf{u}_x + \varepsilon_c\mathbf{u}_y\mathbf{u}_y \tag{2}$$

contains the principal relative permittivity scalars ε_a, ε_b, and ε_c; and the rotation dyadics

$$\underline{\underline{S}}_z(\zeta) = \mathbf{u}_z\mathbf{u}_z + (\mathbf{u}_x\mathbf{u}_x + \mathbf{u}_y\mathbf{u}_y)\cos\zeta + (\mathbf{u}_y\mathbf{u}_x - \mathbf{u}_x\mathbf{u}_y)\sin\zeta \tag{3}$$

and

$$\underline{\underline{S}}_y(\chi) = \mathbf{u}_y\mathbf{u}_y + (\mathbf{u}_x\mathbf{u}_x + \mathbf{u}_z\mathbf{u}_z)\cos\chi + (\mathbf{u}_z\mathbf{u}_x - \mathbf{u}_x\mathbf{u}_z)\sin\chi \tag{4}$$

capture the helical nonhomogeneity. Whereas $\varepsilon_a = \varepsilon_c \neq \varepsilon_b$ and $\chi = 0$ for cholesteric liquid crystals, $\varepsilon_a \neq \varepsilon_b \neq \varepsilon_c$ and $\chi \in (0, \pi/2]$ for chiral smectic liquid crystals [16] and chiral sculptured thin films [17]. All three materials are assumed to be nonmagnetic.

Without loss of generality, we consider a compound SPP wave propagating parallel to the unit vector $\mathbf{u}_{prop} = \mathbf{u}_x\cos\psi + \mathbf{u}_y\sin\psi$, $\psi \in [0°, 360°)$, in the transverse (i.e., xy) plane and decaying far away from the metal layer. The electric and magnetic field phasors can be written everywhere as

$$\left.\begin{aligned} &\mathbf{E}(x, y, z)\\ &\quad = [e_x(z)\mathbf{u}_x + e_y(z)\mathbf{u}_y + e_z(z)\mathbf{u}_z]\cdot\\ &\qquad \exp[iq(x\cos\psi + y\sin\psi)]\\ &\mathbf{H}(x, y, z)\\ &\quad = [h_x(z)\mathbf{u}_x + h_y(z)\mathbf{u}_y + h_z(z)\mathbf{u}_z]\cdot\\ &\qquad \exp[iq(x\cos\psi + y\sin\psi)] \end{aligned}\right\}, \quad z \in (-\infty, \infty), \tag{5}$$

where q is the complex-valued wavenumber. The procedure to obtain a dispersion equation for the wavenumber q is provided in detail elsewhere [2, Section 3.6]. Once q has been numerically determined from that dispersion equation, the piecewise