Guided and Leaky Surface Plasmon Polariton Modes on a Planar Structure with Uniaxially Anisotropic Material on Top of a Metal Thin Film

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Abstract

The surface plasmon polariton modes existing on a two-interface structure composed of a metal thin film having infinite cover region made of uniaxially anisotropic dielectric material and infinite substrate region made of isotropic dielectric material are analyzed based on a finite-element eigenmode solver. The dispersion characteristics with the optic axis of the unaxial material rotated in the plane parallel to the interfaces are investigated. In addition to the pure guided modes, possible leaky modes resulting from the material anisotropy are carefully determined by designing suitable perfectly matched layers in the solver to correctly calculate the complex-valued modal propagation constants.

1. Introduction

As a basic phenomenon in plasmonics, the surface plasmon polariton (SPP) existing at an interface between metal and dielectric material has been a well-known wave mode [1]. In most cases, the dielectric would be an isotropic one. The consideration of the more complicated structure with the dielectric being a uniaxially anisotropic material, e.g., the inclusion of liquid crystal, has useful applications such as designing tunable devices since the optic axis can be rotated and thus the corresponding effective refractive index changed by some suitable applied field. We have recently studied SPPs at an interface between metal and a uniaxially anisotropic dielectric material and found possible leaky-mode solutions in addition to the pure guided modes [2]. Earlier, Li *et al.* [3] reported the calculation of SPPs between a uniaxial crystal and an isotropic material with negative real relative permittivity, which is like a lossless metal, but only pure guided modes were solved. In [2], we have not only analyzed the leakage losses of the leaky modes but also taken the material loss of the real metal into consideration. The aforementioned structures are one-interface ones involving two material regions. In this paper, we extend our investigation to two-interface structures, i.e., a metal thin film with cover and substrate materials, which are quite popular structures except here we consider the cover region to be made of uniaxially anisotropic dielectric material. Similar problem was recently analytically solved by Luo *et al.* [4] but again possible leaky-mode phenomenon was not particularly treated. Here we will present numerical examples with the 5CB liquid crystal [5] being the cover material.

2. The Analysis Method

In [2], we obtained complex modal effective indices for the situation that the optic axis of the uniaxially anisotropic material was rotated in the plane of the interface based on suitable characteristic equations derived as well as a finite-element (FE) eigenmode solver we developed, and the respective results were shown to excellently agree with each other. This FE solver was formulated using either three electric-field components or three magnetic-field components with suitable perfectly matched layers (PMLs) incorporated, and can solve planar-waveguide structures involving anisotropic materials with arbitrary permittivity tensor. In this paper, this FE solver is employed to conduct the modal analysis.

3. Numerical Results

Fig. 1 shows the two-planar-interface structure and coordinate systems to be discussed in the following. The $x = d$ and $x = -d$ planes are the upper and lower interfaces, respectively, of the silver thin film with thickness $2d$. The $x > d$ region is made of 5CB liquid crystal material and the $x < d$ region is made of silicon. We consider the SPP modes

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propagating along the z-direction. The operating wavelength is taken to be λ = 0.644 μm, at which the relative permittivity of silver is $\varepsilon_m = (0.13763 - j4.0790)^2$ [6], the ordinary and extraordinary relative permittivities for the 5CB liquid crystal are $\varepsilon_o = (1.5292)^2$ and $\varepsilon_e = (1.7072)^2$, respectively [5], and the relative permittivity for silicon is $\varepsilon_s = (3.86122)^2$. We consider the film thickness is $2d$ = 80 nm and the situation that the optic axis of the liquid crystal falls in planes parallel to the y-z plane, i.e., $\phi = 90^\circ$, and can be rotated from $\theta = 0^\circ$ to 90°. The elements of the relative permittivity tensor for the liquid crystal become $\varepsilon_{xx} = \varepsilon_o$, $\varepsilon_{xy} = 0$, $\varepsilon_{xz} = 0$, $\varepsilon_{yx} = 0$, $\varepsilon_{yy} = \varepsilon_o + (\varepsilon_e - \varepsilon_o)\sin^2\theta$, $\varepsilon_{yz} = (\varepsilon_e - \varepsilon_o)\sin\theta\cos\theta$, $\varepsilon_{zx} = 0$, $\varepsilon_{zy} = (\varepsilon_e - \varepsilon_o)\sin\theta\cos\theta$, and $\varepsilon_{zz} = \varepsilon_o + (\varepsilon_e - \varepsilon_o)\cos^2\theta$.

Using the FE eigenmode solver, we obtain the Re[n_{eff}] and the modal loss in dB/μm versus θ curves, as shown in Figs. 2(a) and 3 for two different modes, respectively, where the effective index, or the modal index, n_{eff}, is defined as the modal propagation constant divided by the free-space wavenumber. The red dashed curve in Fig. 3 is the θ-dependent cutoff line defined by $n_{cutoff} = (\varepsilon_e\varepsilon_o)^{1/2}/(\varepsilon_o\sin^2\theta + \varepsilon_e\cos^2\theta)^{1/2}$ referring to the 5CB liquid crystal, as discussed in [2]. When the Re[n_{eff}] value is below the cutoff line, it would become a leaky mode with power leakage on the liquid crystal side. The Re[n_{eff}] versus θ curve in Fig. 2(a) is above the cutoff line and with Re[n_{eff}] > n_s = 3.86122 at all θ angles. It corresponds to a pure guided mode without leakage. However, its modal loss due to the lossy silver is seen to be quite huge. We show the profile of the real part of the y-component of the magnetic field (H_y) versus the x-position for this guided mode at $\theta = 45^\circ$ in Fig. 2(b). It can be seen that this mode is basically the SPP mode at x = – 0.04 μm interface between silicon and silver with the H_y peak located at the interface. The Re[n_{eff}] versus θ curve in Fig. 3 is above the cutoff line when $\theta < \sim 62^\circ$ but with Re[n_{eff}] < n_s = 3.86122. The corresponding mode therefore would possess

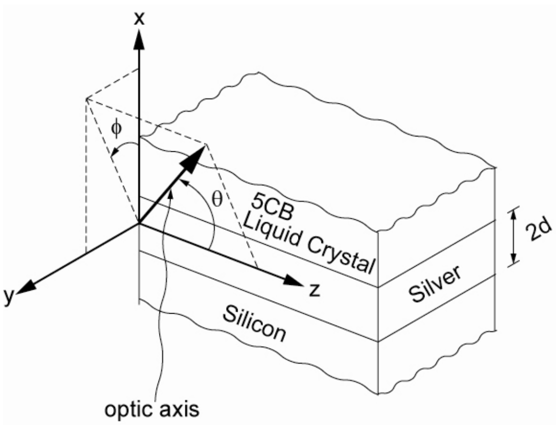
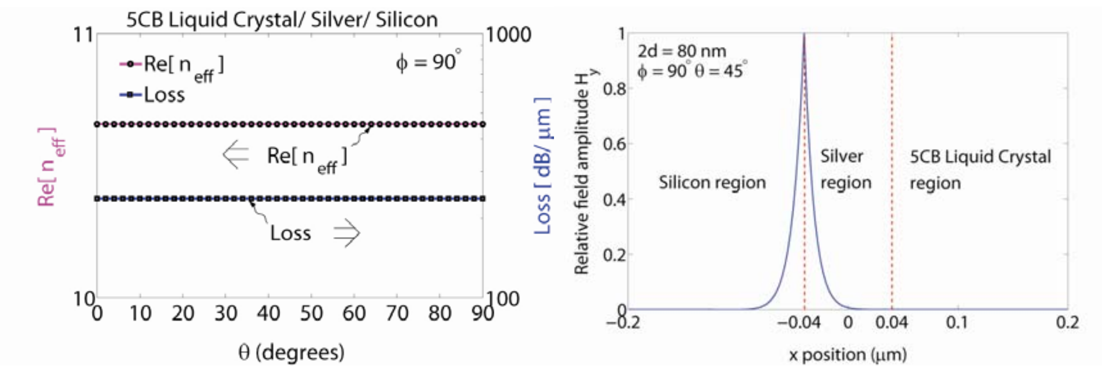


Fig. 1. A planar two-interface structure composed of 5CB liquid crystal cover region, the silver thin film of thickness $2d$, and silicon substrate region. The z-direction is the SPP propagation direction. The optic-axis orientation of the liquid crystal is described by the spherical angles ϕ and θ.



(a) (b)

Fig. 2. (a) The Re[n_{eff}] and modal loss in dB/μm versus θ results for the pure guided SPP mode from the FE analysis for the structure of Fig. 1 at λ = 0.644 μm for $\phi = 90^\circ$. (b) The Re[H_y] versus x profile of the mode in (a) when $\theta = 45^\circ$.

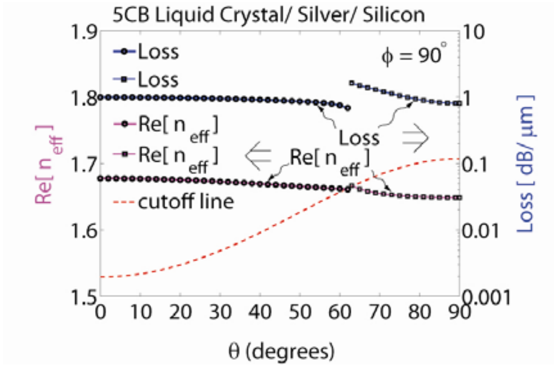
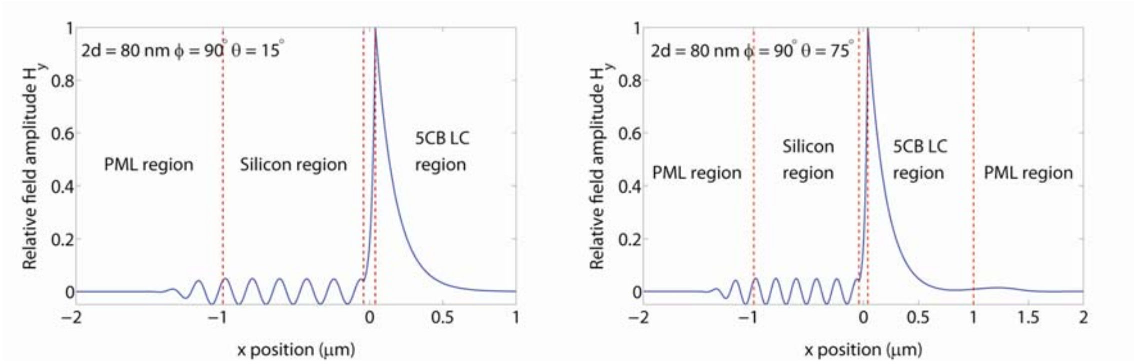


Fig. 3. The Re[n_{eff}] and modal loss in dB/μm versus θ results for the SPP mode with power leakage from the FE analysis for the structure of Fig. 1 at λ = 0.644 μm for ϕ = 90°.



(a) (b)

Fig. 4. The Re[H_y] versus x profile of the mode in Fig. 3 when (a) θ = 15° and (b) θ = 75°.

leakage behavior on the silicon side although it is with purely decaying field on the liquid crystal side in the transverse plane, as seen in Fig. 4(a) which shows the Re[H_y] versus x profile when θ = 15°. In contrast to Fig. 2(b), this mode now has the characteristic of the SPP at x = 0.04 μm interface between silver and liquid crystal. Due to the field leakage, in the FE analysis, we design the – 2 μm < x < – 1 μm region as the PML region to absorb the – x traveling wave, as indicated in Fig. 4(a). Finally, we observe the Re[n_{eff}] versus θ curve in Fig. 3 is below the cutoff line when θ > ~ 62° and again with Re[n_{eff}] < n_s = 3.86122. In addition to the aforementioned leakage on the silicon side, power leakage on the liquid crystal side would also occur, as seen in Fig. 4(b) which shows the Re[H_y] versus x profile when θ = 75°. For properly treating this additional leakage, the 1 μm < x < 2 μm region is also set as the PML region, as indicated in Fig. 4(b). In Fig. 3, we can observe the modal loss, including that due to the lossy metal and that due to the field leakage, is around 1 dB/μm over the whole θ range, which is much smaller than the loss shown in Fig. 2(a).

4. Conclusion

We have successfully analyzed and determined the SPP modes existing on a two-interface structure composed of a metal thin film having infinite cover region made of uniaxially anisotropic dielectric material and infinite substrate region made of isotropic dielectric material using a finite-element eigenmode solver. As a numerical example, we consider a silver thin film with silicon substrate and with the 5CB liquid crystal as the cover material for which the optic axis is rotated in the plane parallel to the interfaces. In addition to the pure guided modes, possible leaky modes including that with power leakage into the silicon region and that having additional leakage into the liquid crystal region resulting from the material anisotropy are carefully determined by designing suitable perfectly matched layers in the solver. A θ-dependent cutoff line is used to identify possible leakage modes due to the material anisotropy as in the analysis of the one-interface structure [2].

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