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Oblique surface waves at an interface between a metal–dielectric superlattice and an isotropic dielectric

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Abstract

We investigate the existence and dispersion characteristics of surface waves that propagate at an interface between a metal–dielectric superlattice and an isotropic dielectric. Within the long-wavelength limit, when the effective-medium (EM) approximation is valid, the superlattice behaves like a uniaxial plasmonic crystal with the main optical axes perpendicular to the metal–dielectric interfaces. We demonstrate that if such a semi-infinite plasmonic crystal is cut normally to the layer interfaces and brought into contact with a semi-infinite dielectric, a new type of surface mode can appear. Such modes can propagate obliquely to the optical axes if favorable conditions regarding the thickness of the layers and the dielectric permittivities of the constituent materials are met. We show that losses within the metallic layers can be substantially reduced by making the layers sufficiently thin. At the same time, a dramatic enlargement of the range of angles for oblique propagation of the new surface modes is observed. This can lead, however, to field non-locality and consequently to failure of the EM approximation.

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(Some figures may appear in colour only in the online journal)

1. Introduction

In contrast to the well-known surface plasmon polaritons (SPP) that can propagate along the metal–dielectric boundary, there are surface waves that exist at an interface between two transparent and homogeneous media, provided that one of them is anisotropic. Such a unique type of surface wave has been termed the D'yakonov surface wave (DSW) [1]. These modes are not polaritons, like SPPs, as all three components of the electric, as well as the magnetic field are involved. Thus, they are hybrid surface modes. Although DSWs seem very attractive as they can propagate without losses, such modes exist under exceptionally stringent conditions. They can propagate obliquely, within a very narrow range of angles to the optical axes of an anisotropic medium with positive birefringence, along the boundary with an isotropic dielectric. Such conditions are very difficult to realize with natural materials. That is the main reason why it took over two decades to experimentally verify [2] theoretical predictions of D'yakonov.

As shown by Rytov back in 1955 [3], periodic media in the long-wavelength limit can be considered as uniaxial crystals with optical axes perpendicular to the layer interfaces. One-dimensional photonic crystals represent such a uniaxial medium. Unfortunately, periodic structures of that kind always exhibit a negative birefringence and thus cannot be used to demonstrate the existence of DSWs. In contrast to dielectric–dielectric superlattices, metal–dielectric ones (plasmonic crystals) show positive birefringence. Therefore, they are suitable to support DSWs, but at the expense of introducing dispersion and losses. It is the aim of this paper to demonstrate that a significant enlargement of the angular range for oblique propagation of D'yakonov-like modes can be achieved with reasonably low losses.

2. Infinite metal–dielectric superlattices

We consider a nanostructured metamaterial formed as a periodic layered structure with binary metal–dielectric unit cells. We denote the dielectric permittivity of metallic layers by ε_1 and their thickness by d_1, while the corresponding quantities in dielectric layers are ε_2 and d_2. The size of the unit cell is $d = d_1 + d_2$. When such a metamaterial is infinite and when the wavelength of radiation is much longer than the size of the unit cell, it is usually assumed that the Rytov [3] or effective-medium (EM) approximation is valid, and the plasmonic crystal can be represented by a diagonal permittivity tensor with elements $\{\varepsilon_\perp, \varepsilon_\perp, \varepsilon_\parallel\}$, where

$$\varepsilon_\perp = \frac{\varepsilon_1 d_1 + \varepsilon_2 d_2}{d}; \qquad \varepsilon_\parallel = \frac{\varepsilon_1 \varepsilon_2 d}{\varepsilon_1 d_2 + \varepsilon_2 d_1}. \tag{1}$$

The indices $\perp$, $\parallel$ indicate directions normal (x- and y-directions) or parallel to the optical axes (z-direction), respectively. Then, the general dispersion relation decays into two equations for the TE-polarized and TM-polarized modes, with respect to metal–dielectric interfaces

$$\text{TE:} \quad k_x^2 + k_y^2 + k_z^2 = k_0^2 \varepsilon_\perp, \tag{2}$$

$$\text{TM:} \quad \frac{k_z^2}{\varepsilon_\perp} + \frac{k_y^2 + k_x^2}{\varepsilon_\parallel} = k_0^2. \tag{3}$$

Here, $k_0 = \omega/c = 2\pi/\lambda$ represents the wavenumber in free space, while k_x, k_y and k_z are the wavevector components in the media. Since in the optical range of frequencies $\varepsilon_1 < 0$, and $\varepsilon_2 > 0$, it is clear that both $\varepsilon_\perp$ and $\varepsilon_\parallel$ can change sign depending on layer thicknesses d_1 and d_2. In the k-space, equation (2) represents a sphere, while equation (3) represents an ellipsoid provided both $\varepsilon_\perp$ and $\varepsilon_\parallel$ are positive. For the purpose of the present paper we will confine ourselves to that case only. We would like to emphasize here that the implementation of metallic layers is necessary to obtain positive birefringence. It is not difficult to see that in dielectric–dielectric superlattices, birefringence is always negative, i.e. $\varepsilon_\perp > \varepsilon_\parallel$ [4].

In fact, the exact dispersion relations are obtained via the transfer-matrix method [5]

$$\cos(k_z d) = \cos(k_1 d_1)\cos(k_2 d_2) - \frac{1}{2}\left(\alpha_{s,p} + \frac{1}{\alpha_{s,p}}\right)\sin(k_1 d_1)\,\sin(k_2 d_2). \tag{4}$$

Here, $k_{1,2} = \sqrt{k_0^2 \varepsilon_{1,2} - k_y^2 - k_x^2}$; $\alpha_s = k_1/k_2$ for the TE polarization and $\alpha_p = k_1 \varepsilon_2 / k_2 \varepsilon_1$ for TM polarization. Equations (2) and (3) are obtained from equation (4) by simple Taylor expansion by assuming $k_1 d_1 \ll 1$, $k_2 d_2 \ll 1$, and $k_z d \ll 1$. As can be easily seen, equations (4) are periodic in z, while EM equations (2) and (3) are not. To avoid this, k_z in (2) and (3) should be replaced by $(2/d)\sin(k_z d/2)$ to obtain the quasi-effective medium (QEM) approximation [6].

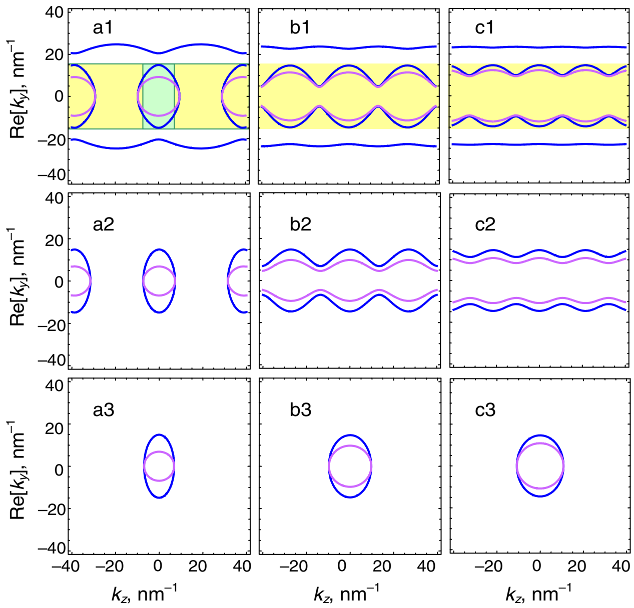

Figure 1. Equifrequency dispersion curves for an Ag-GaAs multilayer: $\lambda = 1.55\,\mu$m, $\varepsilon_1 = -116$, $\varepsilon_2 = 12.4$. In all cases $d_1 = 12$ nm. (1) Exact solutions; blue, TM; magenta, TE polarization; (2) QEM approach; (3) conventional EM theory: (a) $d_2 = 150$ nm, (b) $d_2 = 180$ nm and (c) $d_2 = 230$ nm. The yellow band represents the validity range of QEM and the light green band the validity range of conventional EM theory.

In order to gain insight into the validity of both EM and QEM theory, we have solved numerically equations (4) and compared the results with corresponding approximations. Supposing $k_x = 0$, without loss of generality, we present some results in figure 1. For simplicity, losses have been neglected in calculations of figure 1. Being aware that the dispersion of waves in strongly absorbing systems is qualitatively different from the lossless system with the same real parameters, we would like to point out that we consider the case of weak absorption. Really, if the thickness of the metallic layer in the unit cell is much smaller than the corresponding dielectric layer, and of the order of or less than the skin depth of the metal, the absorption can be assumed weak. Our calculations (not shown here) reveal that this is really the case.

As can be seen, EM theory can be used in a limited range of parameters, and for a very limited range of k_z and k_y. QEM is much better, but it does not reproduce the upper band in k_y for TM polarization. The main result of this investigation is that besides the well-known birefringence (circles for the TE and ellipses for TM polarization) there exists the second TM band. Thus, in a metal–dielectric superlattice, for sufficiently thin metallic layers, as well as for thin enough unit cells, we have two extraordinary TM-polarized modes and one ordinary TE-polarized mode. This novel effect can be termed tri-refringence. When the metallic layer thickness is fixed but the dielectric layer thickness is increased, the ellipses become thicker and thicker, until they start overlapping (see figures 1(a1), (b1), (a2) and (b2)). The effect appears when $\varepsilon_\perp > \pi/k_0 d$. In that case the EM theory fails completely,

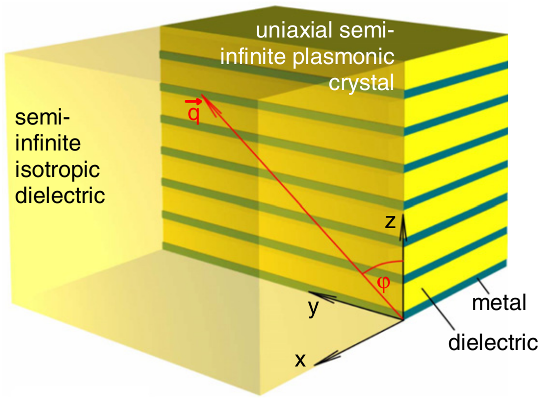

Figure 2. Geometry of the problem.

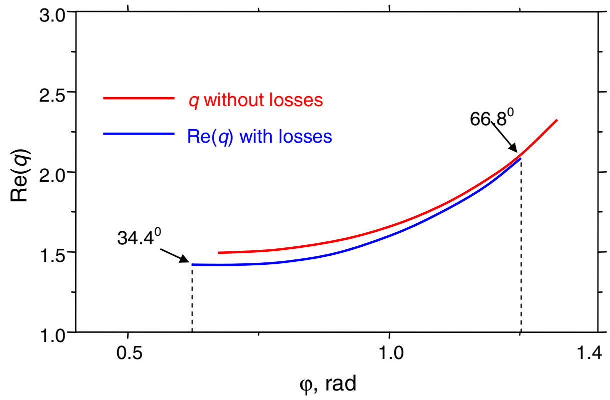

Figure 3. D'yakonov-like surface modes at the interface of a semi-infinite plasmonic crystal (Ag-GaAs) and a semi-infinite isotropic dielectric (SiO_2). $\varepsilon = 2.25$; $\lambda = 1.55\,\mu$m; $\varepsilon_1 = -116 + i11.1$, $d_1 = 12$ nm, $\varepsilon_2 = 12.4$, $d_2 = 150$ nm.

while the QEM approximation follows the trend of the exact solutions, but without the second TM band.

3. Surface waves at an interface of a semi-infinite metal–dielectric superlattice

Now, we investigate surface waves that propagate along the boundary between a semi-infinite metal–dielectric superlattice and a semi-infinite isotropic dielectric, as shown in figure 2. In contrast to conventional surface waves, when the superlattice is cut parallel to the layers (see, e.g., [5]), we consider a metal–dielectric superlattice cut normally to the layers in contact with an isotropic dielectric with dielectric permittivity $\varepsilon > 0$.

Such a configuration was investigated for the case of surface wave propagation along the z-axis [6], and it was shown that surface waves can exist if $\varepsilon_\perp < 0$, provided the use of EM theory can be justified. Here, we study the case when both $\varepsilon_\perp$ and $\varepsilon_\parallel$ are positive. In order to derive a dispersion relation of the surface waves, standard boundary conditions have to be applied. Then, the use of the EM theory leads to the following dispersion relation:

$$(k_d + k_{\mathrm{ex}})\,(k_d + k_{\mathrm{or}})\,(\varepsilon k_{\mathrm{or}} + \varepsilon_\perp k_{\mathrm{ex}}) = (\varepsilon_\parallel - \varepsilon)\,(\varepsilon - \varepsilon_\perp)\,. \quad (5)$$

Here, $k_d = \sqrt{q^2 - \varepsilon}$; ($k_z = k_0 q \cos\varphi$; $k_y = k_0 q \sin\varphi$);

$$k_{\mathrm{or}} = \sqrt{q^2 - \varepsilon_\perp}; \quad k_{\mathrm{ex}} = \sqrt{q^2\left(\frac{\varepsilon_\perp}{\varepsilon_\parallel}\cos^2\varphi + \sin^2\varphi\right) - \varepsilon_\perp}$$

are the imaginary wavevector components normal to the boundary (x-direction), which all have to be positive to obtain solutions of the surface wave type. We see from equation (5) that the necessary condition for the existence of surface waves is $\varepsilon_\parallel > \varepsilon > \varepsilon_\perp$. These D'yakonov-like surface modes can propagate obliquely with respect to the optical z-axis, i.e. in a certain range of the angle φ, $\varphi \neq 0$; $\pi/2$. It is worth noting that such modes are not polaritons. They are hybrid TE–TM modes [1].

In the present paper, we confine ourselves to studying an Ag-GaAs superlattice with SiO_2 cladding at $\lambda = 1.55\,\mu$m. In this case, $\varepsilon_1 = -116 + i11.1$, $\varepsilon_2 = 12.4$, $\varepsilon = 2.25$. The results are presented in figure 3. As can be seen, surface modes of this kind exist in a wide range of angles $34.4° < \varphi < 66.8°$. This is a dramatic enlargement in comparison to natural anisotropic materials, and at reasonably low losses. Our analysis shows that the figure of merit $\mathrm{Re}(q)/\mathrm{Im}(q)$ is higher than 20 in the entire range of angles where the modes exist.

4. Conclusion

We have demonstrated the existence and studied the dispersion properties of D'yakonov-like surface modes at an interface between a metal–dielectric superlattice, cut normally to the layers, and an isotropic cladding. It is shown within the framework of the EM approximation that such surface waves can propagate obliquely to the optical axes, and they are hybrid TE–TM waves that exhibit dispersion and losses. However, the range of propagation angles is substantially greater than for the natural anisotropic materials with reasonably small losses.

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