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Dyakonov surface waves in lossy metamaterials

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ABSTRACT

We analyze the existence of localized waves in the vicinities of the interface between two dielectrics, provided one of them is uniaxial and lossy. We found two families of surface waves, one of them approaching the well-known Dyakonov surface waves (DSWs). In addition, a new family of wave fields exists which are tightly bound to the interface. Although its appearance is clearly associated with the dissipative character of the anisotropic material, the characteristic propagation length of such surface waves might surpass the working wavelength by nearly two orders of magnitude.

1. Introduction

Surface plasmons (SPs) appear in the disruption surface of isotropic media where the material permittivity changes of sign occurring with a metal in contact with a dielectric [1]. The relevance of these surface plasmons falls not only upon its inherent subwavelength localization, but also they enable an amplification of evanescent signals traveling near the surfaces [2]. These functionalities are being implemented within the last years for applications including optical sensing [3], signal filtering [4], subdiffraction focusing and subwavelength resolution imaging [5–9].

Alternatively, the existence of lossless surface waves at the interface of two different transparent dielectrics has been theoretically and experimentally demonstrated, provided one of them is anisotropic [10,11]. In opposition with SPs, this sort of surface waves has the peculiarity of possessing hybrid polarization [12]. The presence of hybrid surface waves with some parallel characteristics, additionally, may be found replacing the uniaxial medium by a biaxial crystal [13,14], an indefinite medium [15,16], and a structurally chiral material [17,18]. In the latter case, the authors adopted a methodology developed by Tamm [19] finding a new type of surface wave, called as Dyakonov–Tamm wave, as it combines the features of Dyakonov surface waves and Tamm states. The use of structured materials with extreme anisotropy offered an alternative to increase the range of directions of DSWs substantially, as it is compared with the rather narrow range observed with natural birefringent materials [20,21]. In particular, striking results are attained if the anisotropic structures include metallic nanoelements, as it occurs for example with a simple metal-dielectric (MD) multilayer, a case where the angular range may surpass half of a right angle [22,23]. Caused by the specific damping capacity of metals, however, the propagation length of these DSWs is strongly limited by the penetration depth inside the lossy metamaterial [24].

In this paper we perform a thorough analysis of DSWs taking place in lossy uniaxial metamaterials. Special emphasis is put when the effective-medium approach (EMA) induces satisfactory results. We examine lossy metamaterials that exhibit closed spatial-dispersion curves, in the same manner that occurs with natural birefringent crystals. Contrarily, the introduction of losses leads to a transformation of the isofrequency curves, which deviates from spheres and ellipsoids, as commonly considered by ordinary and extraordinary waves, respectively. As a consequence, two families of surface waves are found. One family of surface waves is directly related with the well-known solutions derived by Dyakonov [10]. Importantly, we reveal the existence of a new family of surface waves, which is closely connected to the presence of losses in the uniaxial effective crystal. The dominant diffusion dynamics of the latter surfaces waves is thoroughly examined.

2. Theory and configuration

We first analyze the dispersion properties of DSWs supported by a 1D array of semi-infinite layers made of a metal and a dielectric, displaced alternately as shown in Fig. 1(a), where w_m (w_d) is the width of the metallic (dielectric) layer within a given unit cell, and ϵ_m (ϵ_d) represents the dielectric constant of this material. In the semi-space $z > 0$ we have a lossless dielectric environment

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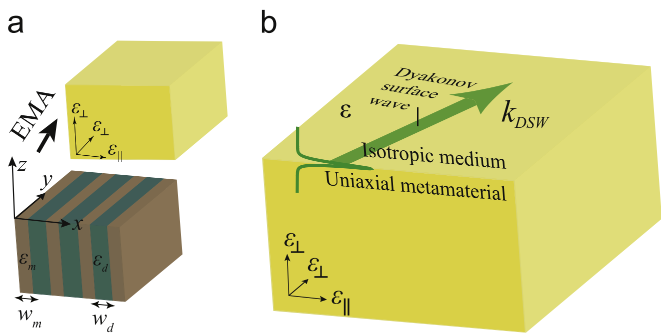

Fig. 1. (a) The effective anisotropy of a multilayered metal-dielectric metamaterial is represented by the on-axis permittivity, $\epsilon_\parallel$, and the permittivity over its perpendicular direction, $\epsilon_\perp$. (a) Schematic arrangement under study, consisting of the birefringent metamaterial ($z < 0$) and an isotropic lossless medium ($z > 0$) of dielectric constant ϵ. A Dyakonov surface wave propagates obliquely in the vicinities of the interface between the isotropic and the effective uniaxial medium with propagation constant k_{DSW}.

of relative permittivity ϵ. An effective medium approach based on the long-wavelength approximation is used to calculate the permittivity of the anisotropic metamaterial along its optical axis $\epsilon_\parallel$, that is the x-axis, and the permittivity in its normal direction, $\epsilon_\perp$. A schematic of the modeled uniaxial metamaterial is shown in Fig. 1 (b). Under these conditions, DSWs of propagation constant k_{DSW} can be observed provided that $\epsilon_\perp < \epsilon < \epsilon_\parallel$ [10].

Form birefringence in the anisotropic metamaterial is estimated in a simple way within the long-wavelength regime that enables a homogenization of the structured metamaterial [25,26]. The EMA demonstrates to be reliable for photonic structures including elements with sizes that are significantly smaller than the wavelength. At infrared and visible wavelengths, the skin depth of noble metals is clearly subwavelength and, in this case, material homogenization requires that the metallic units had sizes of a few nanometers [27–29]. In this case, the superlattice behaves as a uniaxial crystal whose optical axis is normal to the layers. The model estimates the relative permittivities along the optical axis:

$$\epsilon_\parallel = \frac{\epsilon_m \epsilon_d}{(1-f)\epsilon_m + f\epsilon_d}, \tag{1}$$

and transversally,

$$\epsilon_\perp = (1-f)\epsilon_d + f\epsilon_m, \tag{2}$$

where $f = w_m/(w_d + w_m)$ is the metal filling factor. If we neglect losses by setting $\mathrm{Im}(\epsilon_\parallel) = 0$ and $\mathrm{Im}(\epsilon_\perp) = 0$, the effective birefringence of the MD superlattice is $\Delta n = \sqrt{\epsilon_\parallel} - \sqrt{\epsilon_\perp}$. A small filling factor of the metallic composite may lead to an enormous birefringence, as inferred from Fig. 2.

The effective permittivities of a MD periodic multilayer made of silicon dioxide ($\epsilon_d = 2.25$) and silver ($\epsilon_m = -11.7 + i0.83$ taken from [30]) at a wavelength $\lambda_0 = 560$ nm are displayed in Fig. 2, showing how they vary for a different metal filling factor f. For the sake of clarity, we ignored the dissipative effects in the uniaxial metamaterial, and here we considered the real part of $\epsilon_\parallel$ and $\epsilon_\perp$ obtained from Eqs. (1) and (2), respectively. In this case, these are real and positive permittivities provided that $f < 0.161$, in addition leading to positive birefringence. Otherwise, the permittivity $\epsilon_\perp$ became negative for a higher metal filling factor. In addition, we considered cases where $f > 0.0896$, that is uniaxial metamaterials whose perpendicular permittivity satisfies $\epsilon_\perp < \epsilon$ enabling the existence of DSWs; in this numerical simulation we considered $\epsilon = 1$ corresponding to air.

In Fig. 3 we represent the solutions of the Dyakonov equation, namely

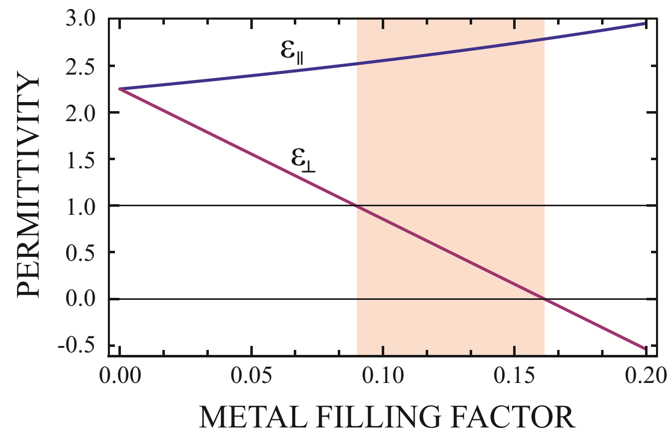

Fig. 2. Effective permittivities $\epsilon_\parallel$ and $\epsilon_\perp$ of a SiO_2–Ag multilayered metamaterial, at $\lambda_0 = 560$ nm, as a function of the metal filling factor f. In this simulation we disregard losses in the metamaterial, that is we used $\mathrm{Re}(\epsilon_\parallel)$ and $\mathrm{Re}(\epsilon_\perp)$. The shadowed region indicates the range of values of f providing a necessary condition $0 < \epsilon_\perp < \epsilon < \epsilon_\parallel$ for the existence of DSWs, where we considered $\epsilon = 1$ corresponding to air.

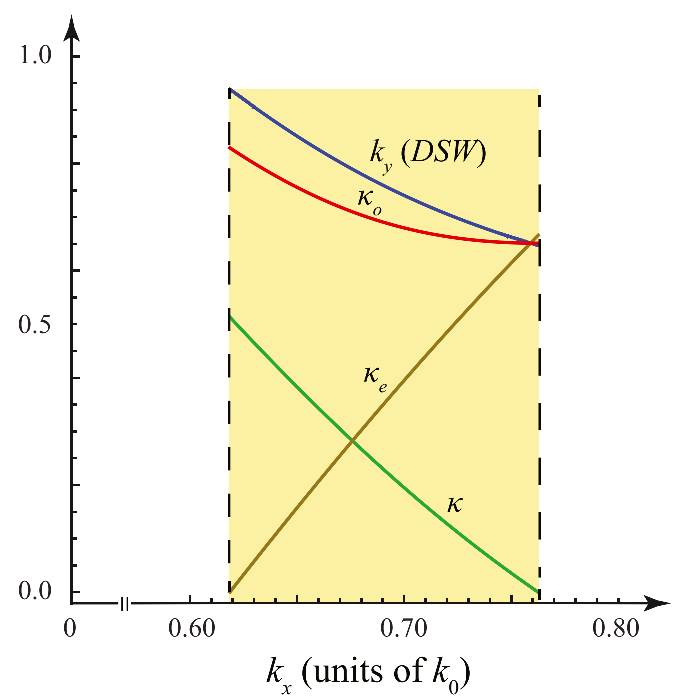

Fig. 3. Isofrequency curve in the plane k_x–k_y of the solutions of the Dyakonov equation (3) calculated for $\epsilon_\parallel = 2.625$, $\epsilon = 1$, and $\epsilon_\perp = 0.576$, at a wavelength $\lambda_0 = 650$ nm. We include the dependence of κ, κ_o, and κ_e on the spatial frequency k_x. The spatial spectrum that corresponds to DSWs is bounded by $k_x = 0.619k_0$ ($\kappa_e = 0$) and $k_x = 0.763k_0$ ($\kappa = 0$). (For interpretation of the references to color in this figure, the reader is referred to the web version of this paper.)

$$\left(\kappa + \kappa_e\right)\left(\kappa + \kappa_o\right)\left(\epsilon\kappa_o + \epsilon_\perp\kappa_e\right) = \left(\epsilon_\parallel - \epsilon\right)\left(\epsilon - \epsilon_\perp\right)k_0^2\kappa_o, \tag{3}$$

providing the in-plane wave vector (k_x, k_y) of the hybrid-polarized surface wave; note that the modulus of such a wave vector is the propagation constant k_{DSW} of the DSW. The electromagnetic fields are evanescent in the isotropic medium, proportional to $\exp(-\kappa|z|)$, where $k_0 = 2\pi/\lambda_0$. On the other side of the boundary, the ordinary and extraordinary waves in the effective uniaxial medium also decay exponentially with rates given by κ_o and κ_e, respectively. To illustrate the characteristic dispersion of DSWs, we solved Eq. (3) for the uniaxial SiO_2–Ag metamaterial described above, where the