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PHOTONICS AND NANOSTRUCTURES
Fundamentals and Applications

Photonics and Nanostructures – Fundamentals and Applications 18 (2016) 16–22

www.elsevier.com/locate/photonics

Nonlocal dispersion anomalies of Dyakonov-like surface waves at hyperbolic media interfaces☆

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Received 9 July 2015; received in revised form 26 October 2015; accepted 3 December 2015
Available online 15 December 2015

Abstract

Dyakonov-like surface waves (DSWs) propagating obliquely on an anisotropic nanostructure have been theoretically proved in a few cases including 2D photonic crystals and metal-insulator (MI) layered metamaterials. Up to now, the long-wavelength approximation has been employed in order to obtain effective parameters to be introduced in the Dyakonov equation, which is largely restricted to material inhomogeneities of a few nanometers when including metallic elements. Here, we explore DSWs propagating obliquely at the interface between an insulator and a hyperbolic metamaterial, the latter consisting of a 1D MI bandgap grating using realistic slab sizes. We found unexpected favorable conditions for the existence of such surface waves. The finite element method is used to investigate the peculiarities of this new family of DSWs.

Keywords: Surface waves; Hyperbolic metamaterials; Electromagnetic optics

1. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic (EM) excitations coupled to surface collective oscillations of free electrons in a metal, which form two-dimensional EM modes propagating along MI interfaces and exponentially decay into neighboring media [1,2]. The profile of the metal surface determines the characteristics of SPP modes existing at flat and curved surfaces, including SPP modes of complex particle arrays and metal nanostructures [3]. SPP modes, whose propagation length is limited by ineluctable EM absorption in metals, induce unique plasmonic phenomena like EM field enhancement often resulting together in extreme light concentration [4,5]. Plasmonic nanostructures have also been considered in guiding electromagnetic waves by introducing solid-state materials [6,7]. Up to now, several architectures have been developed for efficiently guiding of electromagnetic surface waves, such as the channel plasmon polaritons including V-grooves [8], wedges [9], and strips [10], and the chain of closely spaced metal nanoparticles [11] to mention an few. The presence of a periodic distribution of holes and any other kind of carved subwavelength features in a metal surface may play a relevant role in fascinating phenomena like

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☆ The article belongs to the special section Metamaterials.
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http://dx.doi.org/10.1016/j.photonics.2015.12.001
1569-4410/

hyperlensing [12] and extraordinary optical transmission [13,14].

The description of SPP modes assisted by a 1D periodic arrangement of surface irregularities is well established when the flux of light is directed along the two perpendicular axes of symmetry [15,16]. However, oblique propagation is far less known. For instance, it has been predicted the existence of bound waves propagating at arbitrary angles on the boundary of a MI structure [17–20]. In the later case, Dyakonov-like surface waves [21] are prescribed on the anisotropic metamaterial implementing a simple homogenization theory based on the long-wavelength approximation (LWA). This was also applied in 2D photonic crystals [22]. Finally, hyperbolic metamaterials (HMMs) exhibiting principal permittivities with opposite sign may play a relevant role in the excitation of DSWs with unprecedented spatial-spectrum range and EM confinement [23–25].

Recently we demonstrated that the presence of metallic nanoelements leads to nonlocal effects and dissipation effects which reshape the propagation dynamics of the surface signal [26]. In this work, we examine extraordinary favorable conditions which may appear in bandgap MI layered media for the existence of DSWs. Engineering secondary bands by tuning the plasmonic-crystal geometry induces a controlled optical anisotropy, which is clearly dissimilar to the prescribed hyperbolic regime that is developed by the LWA, however, assisting the presence of DSWs on the interface between such HMM and an insulator. Moreover, the hyperbolic band remains passive for moderate and high band stops. Numerical simulations validate the efficient guiding of surface waves in a broad spatial-frequency band. Contrarily to ordinary hyperbolic DSWs, our numerical experiments show tight EM confinement around the metallic nanoplates and modal beating when the fields penetrate and attenuate into the HMM.

2. Dyakonov-like surface waves in hyperbolic metamaterials

We first consider a surface wave propagating on a silver grating of period Δ where the metal filling factor is given by the parameter $f = w_m/\Delta$. As shown in Fig. 1, w_m represents the width of a metal layer, which is oriented parallel to the xy-plane. We also assume that the interlayer space is loaded with a transparent material of relative permittivity ϵ_d. The environment medium, which is set above the metallic grating, will be characterized by a dielectric constant ϵ. In our numerical simulations we will consider germanium and silicon dioxide with permittivities $\epsilon_d = 18.3$ and $\epsilon = 2.08$ at a wavelength $\lambda_0 = 1550$ nm respectively [27,28]; silver permittivity is set as $\epsilon_m = -100.8 + i8.2$ [29].

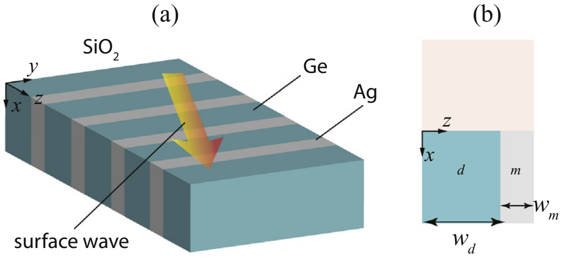

Fig. 1. (a) Geometry of the Ag-Ge hyperbolic metamaterial that is covered by SiO$_2$. (b) Front view of a single cell of the semi-infinite MI lattice placed under the isotropic medium.

In order to observe DSWs, further considerations are typically taken into account. Within the LWA, where the metal width remains far below the wavelength ($w_m \ll \lambda_0$), the EM wave can pass through the metallic walls of the grating with neglecting field attenuation (the penetration depth of silver in the visible and near-infrared is 24 nm approximately) leading to the homogenization of the field [30]. Under these conditions, the grating naturally behaves like a uniaxial medium whose optic axis is oriented normally to the MI layers, that is the z-axis. The relative permittivity along such a direction, $\epsilon_{||}$, and in the transverse direction, $\epsilon_{\perp}$, may be given in terms of ϵ_m, ϵ_d and f [31], as illustrated in Fig. 2. As a result, the surface wave will travel on the interface between a uniaxial homogenized medium of permittivity

$$\bar{\bar{\epsilon}} = \epsilon_{\perp}\,(\mathbf{xx} + \mathbf{yy}) + \epsilon_{||}\mathbf{zz}, \qquad (1)$$

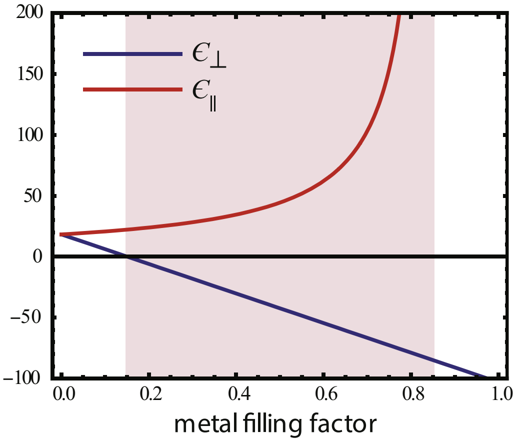

Fig. 2. Dielectric functions of the uniaxial effective medium composed of Ag and Ge at a wavelength $\lambda_0 = 1550$ nm, when we disregard losses in the metal (we set $\epsilon_m = -100.8$). The permittivities $\epsilon_{\perp}$ and $\epsilon_{||}$ were obtained by altering the metal filling factor, f. Within the range $0.154 < f < 0.846$ (shaded area), the metamaterial shows hyperbolic dispersion with $\epsilon_{\perp} < 0$ and $\epsilon_{||} > 0$.