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Original research article

Electromagnetic surface waves guided by a plane interface between a porous nanocomposite and a hypercrystal

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A R T I C L E I N F O

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A B S T R A C T

Dispersion properties of surface electromagnetic waves localized at the plane interface between a nanocomposite made of a semiconductor inclusions evenly distributed in a transparent matrix and a hypercrystal, formed by an alternating dielectric and hyperbolic layers are studied. Electrodynamic Maxwell Garnett model is applied to simulate the effective resonance permittivity of the nanocomposite. In the subwavelength approximation the hypercrystal is represented as the uniaxial media with two different principal permittivity tensor components. The particular attention is devoted to the study of dispersion properties of hybrid Dyakonov surface waves. It is shown that by properly choosing physical and geometrical parameters of the corresponding composites, like volume fractions of nano-inclusions, thicknesses of hyperbolic and dielectric layers, and materials used, the effective control over the properties of supported surface modes is possible.

1. Introduction

Recently, the interest in the study of electrodynamical properties of artificial anisotropic structures has significantly increased. In particular, the special interest is devoted to the study of various types of nanocomposite media, metamaterials, photonic crystals and hyperbolic media, which have a number of unusual properties that allow to create new materials with predetermined structural, electromagnetic and optical characteristics [1–13].

Electronic, optical and structural properties of such artificial materials are substantially determined by the physical and geometric characteristics of the materials from which they are composed. In particular, by appropriately selecting the constituent materials, namely their concentration, geometrical dimensions and physical properties, it is possible to achieve the bands of negative real parts of the complex dielectric and / or magnetic permeabilities in a certain frequency range, which leads to a number of unusual physical phenomena, such as negative refraction, super-lenses and super-prism, to name but a few [14–17].

Among the various types of artificial materials it is worth mention about the porous semiconductors and dielectrics, which formed by removing a part of the material from the volume [1,2]. The resulting pores and the remaining nanocrystals have sizes from one to hundreds of nanometers. The physical properties of such materials differ significantly from the properties of the host material due to the quantum-size and surface effects. Moreover, the simplicity of the manufacturing and processing, as well as the ability to control the physical properties of porous materials by changing the mode of formation make them promising in the creation of photonic media, in devices for plasmonics and optoelectronics. There are several methods usually used to create porous materials. The most common method is to use residual porosity from incomplete sintering. Another approach is to use a sacrificial pore former [18]. The

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porous semiconductor materials can be fabricated by electrochemical etching or gravimetric methods [19,20]. Microinclusions of materials characterized by a range of direct (InSb, PbS, InAs, InP, Te) and indirect bandgaps (Si, Ge), and, elemental and compound semiconductors, as well as metals are commonly used [21,22]. For example, in [21] authors explored the optical properties of nanoscopic gold particles prepared by electrochemically depositing Au within the pores of nanoporous alumina membranes. Maxwell Garnet effective medium theory has been used as a guide for modeling the optical properties of these Au nanoparticle/alumina membrane composites. Au nanoparticles with diameters from 52 nm down to 16 nm were prepared, and the optical properties of composites containing these nanoparticles were studied. For porous silicon in [19] the samples with the thicknesses 1.0 and 0.6 μm were fabricated and tested using Maxwell Garnett theory. Authors in [23] a as dielectric/metal nanoparticles material analyzed oxide/metal nano-shells, namely Mg/MgO and Al/Al_2O_3. For the case of metal/metal core-shells Mg/Ga and Al/Ga nanoparticles were studied (with nanoparticles radius 15–20 nm).

In the case when the characteristic dimensions of the pores and nanocrystals are much smaller than the wavelength of propagating electromagnetic waves, the nanostructured semiconductors can be regarded as a homogeneous optical medium possessing some effective refractive index, which is different from the refractive indices of the constituent materials. It is promising to use such nanocomposites with metallic inclusions, due to their strong linear and nonlinear dispersion of optical properties in the region of plasmon resonance. Absorptive and dispersion properties of such media are determined by the frequencies of the plasmon resonances, which depend on the shape of impurity metallic nanoparticles. Therefore, in composite media representing metal nanoparticles suspended in a dielectric matrix extraordinary optical properties are observed at the frequencies near the plasmon resonance of the inclusions [24].

Another type of materials, which recently attract the growing interest of researchers includes hyperbolic media, in particular, as a constituent part of a more complex systems, like hyper-crystals [6,7,11,13,25–27]. Hyperbolic metamaterials are a special kind of anisotropic metamaterials, which dielectric tensor elements have mixed signs. Their exotic features enable many intriguing applications, such as sub-wavelength imaging, hyper-lenses and enhanced spontaneous and thermal emissions that are infeasible with natural materials. Photonic hypercrystal is a periodical optical nanostructure that is formed by periodic variation of either natural or artificial hyperbolic medium and a second medium (a metal, or a dielectric, or another hyperbolic medium) [13]. Photonic hypercrystals are a class of artificial materials, which combines the most interesting features of photonic crystals (forbidden gaps near the boundaries of photonic Brillouin zones) and hyperbolic metamaterials (broadband divergence in their photonic density of states due to the lack of usual diffraction limit on the photon wave vector) [14]. Planar photonic hypercrystals can be designed using molecular-beam epitaxy [28], chemical vapor deposition, atomic layer deposition and sacrificial etching [29–31].

As an example of a dielectric hypercrystal a composite formed by layers of silicon as the isotropic dielectric, and sapphire as the natural hyperbolic medium with the thicknesses around 1 μm could be considered [13]. As an example of a "metallic" hypercrystal a composite formed by semiconductor hyperbolic metamaterial and a doped semiconductor can be considered. The semiconductor aluminum–indium–gallium–arsenide "platform" offers the capability of growing multilayer composites with atomic-level precision, leading to high-quality hypercrystals [28]. For example, the unit cell of the hypercrystal described in [13] consists of a 1.9 μm-wide layer of hyperbolic semiconductor metamaterial, followed by 100 nm of an n^+-doped $In_{0.53}Ga_{0.47}As$ semiconductor with a plasma frequency of 5 μm. The semiconductor hyperbolic metamaterial corresponds to system of interleaving layers of the dielectric $Al_{0.48}In_{0.52}As$ and n^+-doped $In_{0.53}Ga_{0.47}As$ semiconductor [13,28]. To demonstrate negative refraction at infrared wavelengths authors in [28] designed and fabricated four samples composed of interleaved 80 nm layers of $In_{0.53}Ga_{0.47}As$ and $Al_{0.48}In_{0.52}As$. The layers, approximately 8.1 μm thick, were grown by molecular beam epitaxy on lattice-matched InP substrates. The InGaAs layers were uniformly doped, at different densities for each sample, to provide a plasma resonance of free carriers.

The hypercrystals allow a number of unique properties, like an unprecedented degree of control of light, possibility to substantially reduce the highly detrimental effect of the material loss in plasmonic devices and systems, subdiffraction-limit localization of light, etc. Photonic hypercrystals hold great promise as platforms for sensing with mid-IR light [5,13,15].

As is generally known, depending on the type of interface between two contacting materials and system geometry, different types of electromagnetic surface waves can be supported. It is known that in the frequency range where one of the material parameters of the contacting media, dielectric permittivity or magnetic permeability, become negative, the propagation of surface plasmon polaritons (SPP) waves along the plane interface is possible. SPP waves are probably the most known case of surface waves, which incorporate resonant optical excitations at conductor–isolator interfaces [10,32–36]. The electromagnetic wave field of the SPP waves is localized in the near-surface region, the thickness of which on each side of the interface is of the order of wavelength. However, metal losses greatly restrain the energy transport of surface plasmons for long distances. Nevertheless, because of the unique properties of strong field confinement and intensity enhancement, SPP waves have been extensively explored in applications like super-resolution imaging, biosensing wave guiding and photolithography [37,38].

Other kind of polariton surface waves may exists, for instance, fields propagating along the optical axis when the anisotropic plasmonic crystal is cut normally to the orientation of the layers. In anisotropic media the properties of surface waves essentially depend on the direction of their propagation with respect to the anisotropy axes. It was shown that in such structures the so called Dyakonov surface waves (DSW) may be guided by the interface [39–43]. Like plasmon polaritons, they exist at the interface of two different materials, and should feature similar excitation and detection properties. However, in opposition with SPP waves, DSW have the peculiarity of possessing hybrid polarization, that is DSW is a superposition of the TE-polarized and TM-polarized surface modes [44]. There are a number of works devoted to the study of DSW properties at the interface of different media, like photonic crystals, metamaterials, dispersive media and hyperbolic systems [45–49]. DSW have been reported both experimentally and theoretically for a wide range of wavelength, from near infrared up to visible wave-lengths [50,51]. Dyakonov surface waves are also supported by the layered hyperbolic metamaterials and photonic crystals with enhanced angle range under the long-wavelength limit. Thus, it was