

On the propagation of surface plasmon polaritons at the interface of low-dimensional acoustic metamaterials

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Abstract

As a novel type of artificial media created recently, metamaterials demonstrate novel performance and consequently pave the way for potential applications in the area of practical engineering in comparison with the conventional materials. Acoustic metamaterials and phononic crystals possess a wide variety of exceptional physical features. These include effective negative parameters, band gaps, negative refraction, etc. Doing so, the acoustic properties of existing materials are extended. Acoustic metamaterials are periodic structures with the effective properties that can be tuned seeking for the dramatic control on wave propagation. Homogenization of the infinite periodic system is needed aiming to calculate permittivity of metamaterial. Dispersion properties of surface waves propagating at the interface between a nanocomposite made of a semiconductor inclusions systematically distributed in a transparent matrix and low-dimensional acoustic metamaterial, constructed by an array of nanowires implanted in a host material are investigated. We observed propagation of surface plasmon polaritons. It is demonstrated that one may dramatically modify properties of the system by tuning the geometry of inclusions.

1. Introduction

During the past years interest in creating materials allowing to control the flow of electromagnetic waves (e.g. light) in exceptional ways has increased dramatically. Novel engineering tools have opened the wide avenues to construct artificial materials possessing properties that are not possible in case of the naturally existing materials. The new design is possible due to the wide variety of inclusions. Moreover, the novel response appears because of the specific interactions with electromagnetic fields. These designs can be scaled down and constructed thanks to the nanotechnology. Hyperbolic metamaterials stand for as a multi-functional platform providing a fertile ground for realization of waveguiding, imaging, sensing, quantum and thermal engineering beyond conventional devices. This metamaterial utilizes the concept of engineering the basic dispersion relation of surface plasmon polaritons aiming to

generate exceptional electromagnetic modes having a wide spectrum of applications. The hyperbolic metamaterial can be considered from the perspective of the polaritonic crystal. Doing so, the coupled states of light and matter provide a fertile ground for a larger bulk density of electromagnetic states.

Based on the frequency range, one may divide sound waves into the types as follows: low frequency, intermediate frequency and high frequency. Noise has strong penetrating power and dissipates slowly during propagation. Doing so, it is a challenging task to engineer the sound waves. Moreover, sound waves can also resonate with certain important organs of the human body. Consequently, health is dramatically affected. Hence, it is particular importance to focus on the investigation of the sound waves and vibration control. The study of surface waves and plasmonics stand for as another inherent part of nanophotonics. The former allows to reduce the length scales and dimensionality of various electromagnetic phenomena. Not surprisingly, nonreciprocity and unidirectional propagation of surface plasmon-polaritons (SPPs) have recently stimulated a tremendous interest. Magneto-optical nonreciprocity in the transverse Voigt geometry is mostly dealt with in these studies, including topological quantum-Hall-effect states. Herein we consider a novel approach allowing for propagation of SPPs at the acoustic metamaterial interface. It is worthwhile noting, that inclusions of the composites are fulfilled from the transparent conducting oxides (TCOs) making a stronger case towards implementation the properties of possible devices.

2. Geometry of the problem

Herein, we deal with the plane interface between a nanocomposite (NC) semi-infinite layer, which fills the half-space $x < 0$ and an adjacent to it hypercrystal filling the half-space $x > 0$ (Fig. 1). It is worthwhile mentioning, that the surface waves under consideration propagate along z axis. It is worthwhile noting, that the structure under the study can be constructed by means of molecular beam epitaxy [1], chemical vapor deposition, atomic layer deposition and sacrificial etching [2]. Nanocomposite is presented as a non-conductive transparent matrix with a

permittivity ϵ_n , in the volume of which regularly distributed semiconductor nanoparticles with permittivity ϵ_m . The dielectric function of the TCO based nanoparticles is of particular interest. An emerge of high-conducting metal being transparent has opened the wide avenues recently. The issue has attracted lots of interest within scientific community because of the metal being opaque for light. From the perspectives of the potential applications, transparent conducting metals described by high DC conductivity (σ_{DC}) are anticipated for optoelectronic devices, ranging from solar cells to electronic paper, touch screens and displays. Though, since $\sigma_{DC} = n_e e^2 \tau / m$ of a metal is associated with plasmon frequency $\omega_p^2 = n_e e^2 / \epsilon_0 m$ through the free-electron density n_e , a high-conducting metal (with a high n_e) is naturally opaque for light due to its permittivity ϵ being usually very negative caused by its high ω_p . Typical techniques to produce transparent conducting metals include the decrease of the n_e , by utilizing transparent conducting oxides (TCOs).

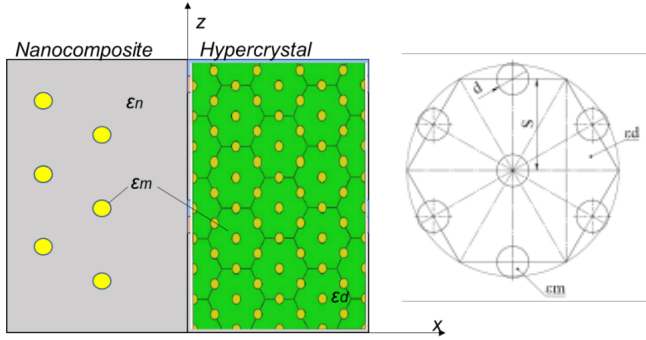


Fig. 1. Schematic geometry under study, consisting of a semi-infinite hypercrystal ($x > 0$) and a nanocomposite with semiconductor inclusions ($x < 0$), metamaterial (hypercrystal) unit cell (inset).

3. Discussion

Herein, the permittivity components of a hypercrystal and nanocomposite versus frequency are studied numerically aiming to identify the frequency ranges of Dyakonov surface waves (DSWs) and SPP waves existence (Fig. 2).

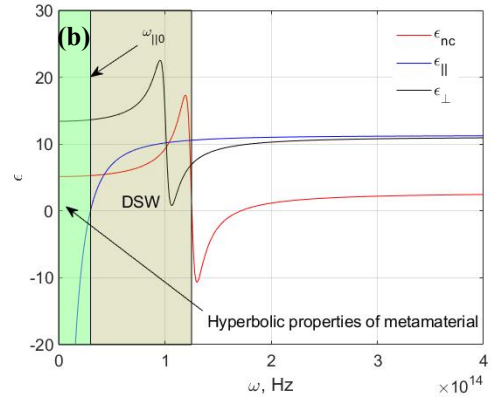
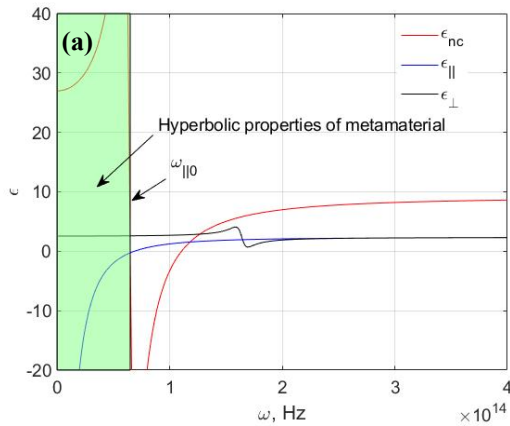


Fig. 2. Relative permittivity components of the nanocomposite and hypercrystal versus frequency. Herein, $f=0.3$. (a): $\epsilon_n = 11.8$, $\epsilon_d = 2.25$; (b) $\epsilon_n = 2.25$, $\epsilon_d = 11.8$. Herein AZO inclusions are employed in nanocomposite and hypercrystal.

In the frequency ranges below the frequency $\omega_{||0}$ the semiconductor-dielectric metamaterial possesses hyperbolic properties. It is worthwhile noting, that in this frequency range the presence of conventional surface plasmon polaritons waves with propagation parallel to the optical axis is feasible under specific conditions. One may conclude from Fig. 2, that propagation of DSW is possible in case of $\epsilon_n = 2.25$, $\epsilon_d = 11.8$. It is worthwhile noting, that regime of DSW propagation is possible in case of $\epsilon_{||}, \epsilon_{nc} > 0$.

4. Conclusions

Through theoretical derivation the excellent transmission characteristics of SPPs were analyzed and verified effectively in this paper. The dependence of the transmission characteristics on frequency for different filling ratios was obtained in this paper. Moreover, the possibilities to increase frequency ranges of DSW existence have been demonstrated. This work is of great significance to further research of optical devices based on SPPs.

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