Beam steering with the enhanced semiconductor-based hyperprism

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To the best of our knowledge topological change of the iso-frequency surface of hyperbolic metamaterials paves the way for the unique capabilities aiming to engineer propagation of the wave. Herein, an enhanced semiconductor-based hyperprism structure is presented aiming to seek for the optical switching and beam steering dependencies. Based on the outcomes of the numerical simulations one may conclude that by engineering the doping level of the semiconductor-based hyperprism, a maximum adjustable angle of 1.4 rad can be obtained. It has been concluded that changes in doping level allow for a variety of fascinating phenomenon.

Introduction

Hyperbolic metamaterials (HMs) [1-5] belong to the class of uniaxially anisotropic materials. These unique substances, being highly advantageous from different perspectives have attracted lots of attention during the last decades. For instance, the anisotropic media with lower losses may possess the characteristics of negative refraction and subwavelength imaging. The former allows for an easier fabrication process [1]. The optical topological transitions not long ago detected in electromagnetic metamaterials open the wide avenues for the unprecedented phenomenon. It should be noted, that aforementioned optical effects are not limited by the Fermi exclusion principle [2]. Topological conversion of dispersion in highly anisotropic metamaterials is typically understood as the sign change of one element either of permittivity (ε) or permeability (μ) from positive to negative. In this case isofrequency contour shifts from a closed ellipsoid to an open hyperboloid. A closed iso-frequency surface takes place in a case of dielectric. The surface shrinks to a simple sphere if the substance is not anisotropic. In contrast, an open iso-frequency surface is the main characteristic of the hyperbolic substance. In this case the wavenumbers of the propagating waves are not subject to the restrictions of the frequency. In this relation, the conventional diffraction limit is broken causing a broad bandwidth singularity of the photonic density of states [6] in the effective medium limit. It is worthwhile mentioning, that HMs pave the way for scientists. Thus, the horizons for metamaterials at mid-infrared frequencies are opened because of the metallic behavior of highly doped semiconductor materials. Doing so, hyperbolic behavior of the composite can be obtained by composing the structure of alternating layers of semiconductor materials possessing different level of concentration [4]. Additionally, HMs were considered as electromagnetic absorbers for scattered fields from the theoretical perspectives. The former was confirmed through the experiment by putting scatters on top of HM, resulting in the enhanced absorption but it was neither perfect nor narrow-band absorption [5]. Actually, the isofrequency wavevector dispersion in an uniaxially anisotropic substance can be elliptic for some polarization. Moreover, a hyperbolic relation causing many fascinating physical phenomenon can evolve [7, 8] under certain conditions. If a hyperbolic dispersion occurs, preferably, the waves can propagate and carry power over a wide spatial spectrum as opposed to a finite propagating spectrum in common (elliptic) media. The unprecedented interest to study of hyperbolic media can be explained by their comparatively plain geometry and a range of fascinating properties, including high density of states, all-angle negative refraction and hyperlens imaging beyond the diffraction limit [8, 9].

It should be mentioned, that no complete study has been performed on direct engineering techniques applicable for metamaterials manufactured from directly engineerable building blocks. The main property of the directly engineerable metamaterials is the variable electromagnetic characteristic of metamaterial component. Moreover, there are many similar materials. For example, doped semiconductors (e.g., GaAs, InSb, InAs, ZnO) and conducting oxide (e.g., ITO [10]) are conventional materials whose free electrons (free carriers) are effortless to engineer by electric fields, pumping lights or temperature fields, and which can also be used to manufacture metamaterials [11].

Herein, we investigate the unique dispersion equation in the semiconductor-based hyperprism system and analyze the propagation of the electromagnetic TM polarization wave at the boundary separating the semiconductor-based hyperprism and the isotropic substance. The semiconductor-based hyperprism system is constructed by transforming a nanostructured semiconductor-based metamaterial into a prism structure with the tilted optical axis. The structure is significantly enhanced as it allows for a comparatively simple engineering manifestations including the changes of the doping level of the semiconductor.

Theory

As it is shown in [9], a TM-polarization wave with an incident angle of θ is incident from the air to the semiconductor-based hyperprism (Fig. 1). Afterwards the wave is refracted from the semiconductor-based hyperprism to the substance A. One may consider substance A to be a non-absorptive isotropic medium. Herein, we will make a step forward by enhancing the structure under consideration. Doing so, we present the semiconductor-based hyperprism being a prism structure composed of semiconductor-based hyperbolic metamaterials. Hyperprism consists of the alternating dielectric sheet with a width of d_d and relative permittivity ε_d, and a semiconductor monolayer with a width of d_s and permittivity, ε_s.

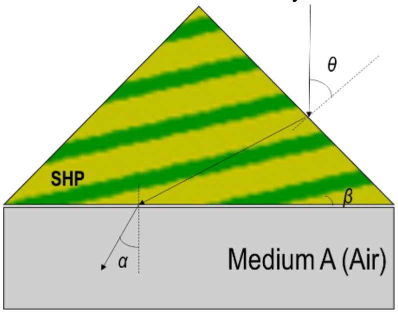


Fig. 1. Schematic diagram of the incident TM-polarization wave with the angle of incidence θ on the interface of air and the semiconductor-based hyperprism. A metamaterial is constructed by employing alternating semiconductor (denoted with green) and dielectric (denoted with yellow) layers. α – is the refraction angle.

Permittivity of a semiconductor may be written as

$$\varepsilon_s = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2} \tag{1}$$

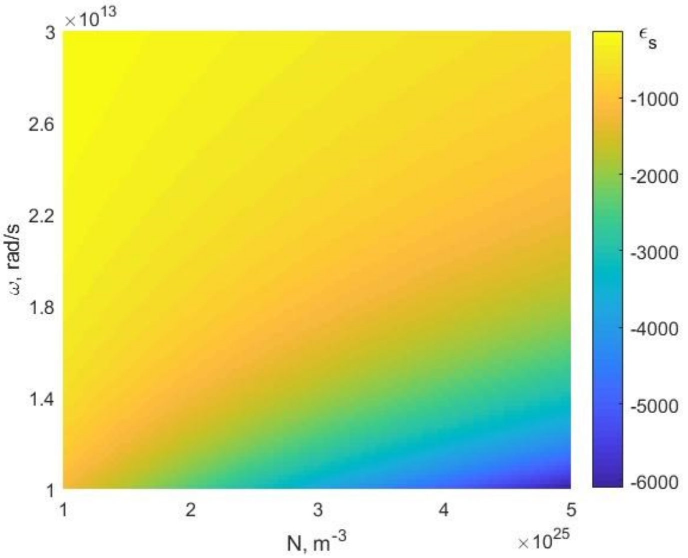
with neglecting damping. The vacuum contribution and the interband electronic transitions are represented by introducing the dielectric constant ε_∞, $\omega_p = e\sqrt{N/(\varepsilon_0 m)}$ is the bulk plasmon frequency, where N is the free carrier concentration, and m is the effective mass (ε_0 is the vacuum permittivity and e is the electron charge).

To describe the optical response of the semiconductor-based hyperprism, we apply the effective-medium approach which is justified if the wavelength of the radiation considered is much larger than the thickness of any layer. It is based on averaging the structure parameters. Hence, further in this paper we consider the effective homogeneous media for the semiconductor-based hyperprism. The effective permittivities are as follows:

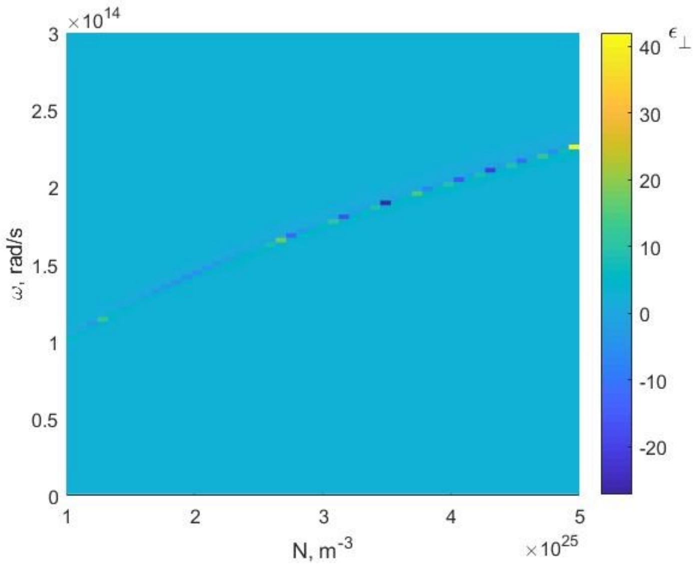
$$\varepsilon_\parallel = \frac{\varepsilon_s d_s + \varepsilon_d d_d}{d_s + d_d} \tag{2}$$

$$\varepsilon_\perp = \frac{\varepsilon_s \varepsilon_d (d_s + d_d)}{\varepsilon_s d_d + \varepsilon_d d_s}, \tag{3}$$

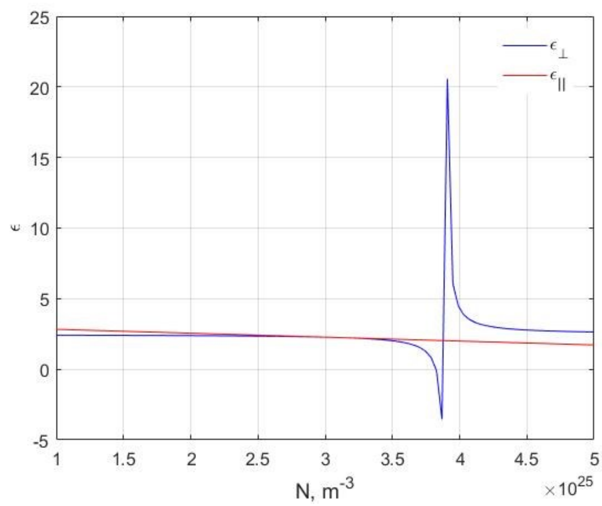
Aiming to demonstrate tunable properties of the hyperbolic semiconductor-based metamaterial structure, dependence of the $\mathrm{Re}(\varepsilon_\perp)$ [12] upon semiconductor doping level N and frequency ω is analyzed and presented in Fig. 2(b). In Fig. 2(b), $\mathrm{Re}(\varepsilon_\perp)$ of the semiconductor/dielectric structure, possessing the feature of changing the sign as the frequency varies is demonstrated. Consequently, in Fig. 2(c), it can be observed that as the N grows, the values $\mathrm{Re}(\varepsilon_\perp)$ and $\mathrm{Re}(\varepsilon_\parallel)$ also switch the sign from positive to negative. The values can be flexibly adjusted by changing N as it is shown in Fig. 2. When ω=2·10^{14} rad/s, N changes and the sign of $\varepsilon_\perp$ is changed at the crucial point of N=3.9·10^{25} m^{-3}.



(a)



(b)



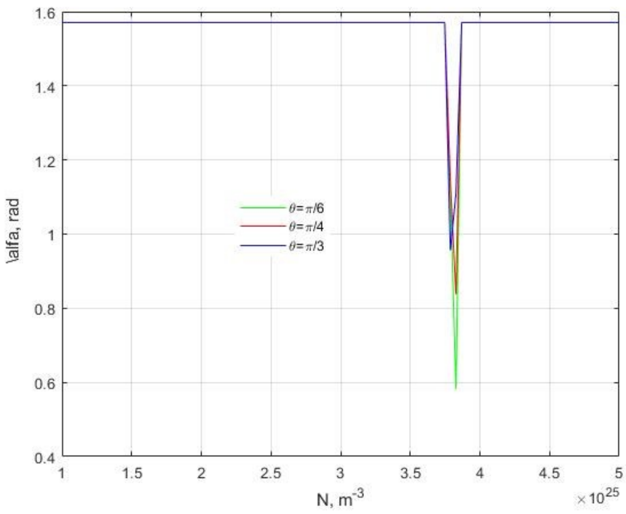
(c)

Fig. 2. The distribution of (a) $\mathrm{Re}(\varepsilon_s)$, (b) $\varepsilon_\perp$ in ωN plane. (c) In case of ω=2·10[14] rad/s, the effective parameters $\varepsilon_\parallel$, and $\varepsilon_\perp$ can be engineered modifying the doping level of the semiconductor N in the multilayer structure. In case of the increased value, the sign of $\varepsilon_\perp$ is changed, and $\varepsilon_\parallel$ remains positive.

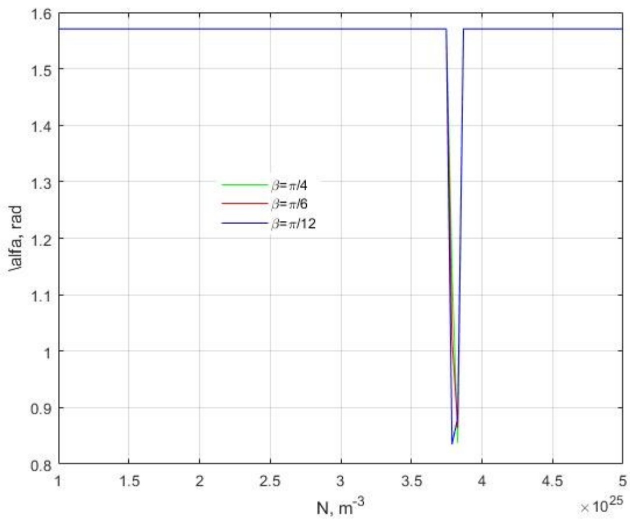
Beam steering enhancement

It should be noted that if the switch is on-state, the direction of the transmitted beam will be dramatically affected by engineering doping level of the semiconductor N. The angle between the transmitted beam varying with N and the z'-axis is defined as the angle of beam steering, denoted as α [9]. Consequently, we will have a deeper insight into the phenomenon of engineering the angle of beam steering.

$$\alpha = \arcsin\left(\left|\frac{\sqrt{\left(1-\frac{\sin^2\theta}{\varepsilon_\perp}\right)\cdot\varepsilon_\perp} - \sin\theta\cdot\tan(\pi-\beta)}{\sqrt{\tan^2(\pi-\beta)+1}}\right|\right) \tag{4}$$



(a)



(b)

Fig. 3. Dependence of an angle α (a) upon N with $\beta=\pi/4$, and (b) upon N with $\theta=\pi/4$.

Until now, we have assumed that β=45. As it is demonstrated in Fig. 3, we will further investigate dependence of the angle α upon doping level N at various θ and β. Form Figs. 3, it can be observed that the angle of refraction α is dramatically influenced by the doping level N of the semiconductor. If $\theta=\pi/4$ and $\beta=\pi/4$, the variable angle range is $\Delta\alpha$=0.7338 rad. In this case α_{max}=1.571 rad, α_{max}=0.8372 rad. To have a deeper insight into the possible applications, one can conclude with the proper regulation range by engineering the values of θ and β according to the construction needs. Furthermore, the anticipated adjustment range is selected, one only needs to modify the doping concentration of the semiconductor. These characteristics pave the way for industrial applications focused on the angle of the beam control.

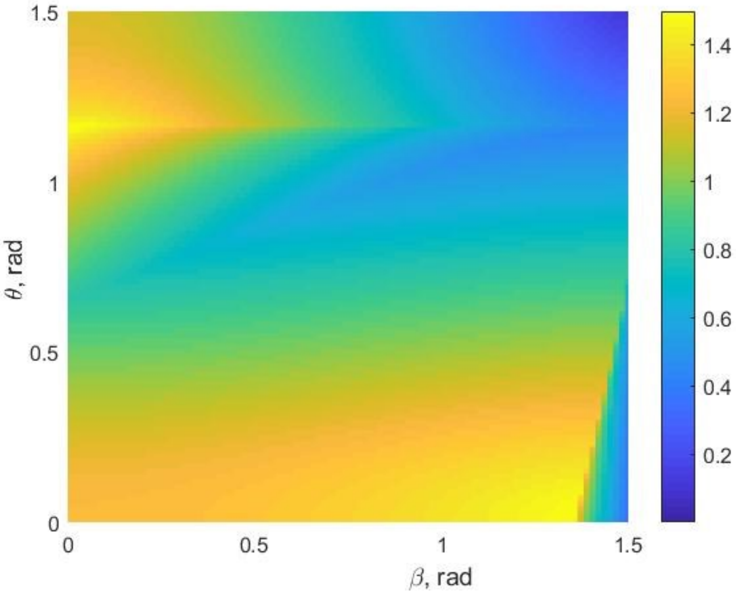


Fig. 4. The highest variable refraction angle $\Delta\alpha$ diagram related to various θ and β in semiconductor-based hyperprism.

One may obtain the maximum adjustable angle $\Delta\alpha$ by engineering various incident angles θ and optical axis rotation angles β. Fig. 4 is the $\Delta\alpha$ diagram related to various incident angle θ. By choosing various rotation angles β of the optical axis, one may conclude with two large variable angle zones that will be created. The highest variable angle $\Delta\alpha$ can reach 1.4 rad under hyperbolic restrictions.

Conclusion

Herein, we have investigated the engineerable beam management phenomenon in the mid-infrared spectrum by having a deep insight into the adjustable hyperbolic dispersion of the semiconductor-based nanostructured hyperbolic metamaterial prism system. It can be concluded that engineering the doping level of the semiconductor paves the way for a variety of the possible applications. Doing so, switching phenomenon that can be caused by actively modifying the doping level of the semiconductor without needs to change the system and angle of the incident wave stands for as the main benefit of this category of optical switch. The results clearly show that a beam steering effect can be achieved by the transmitted beam with the increase of the doping level. In this relation, the maximum variable angle can attain 1.4 rad. This system has a high operating potential in real applications. The obtained outcomes pave the way for the variety of applications in the spheres of optical data storage, modulator, and integrated photonic circuit.

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Disclosures. The authors declare no conflicts of interest.

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