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Article

On the Study of Advanced Nanostructured Semiconductor-Based Metamaterial

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Abstract: Tunable metamaterials belonging to the class of different reconfigurable optical devices have proved to be an excellent candidate for dynamic and efficient light control. However, due to the consistent optical response of metals, there are some limitations aiming to directly engineer electromagnetic resonances of widespread metal-based composites. The former is accomplished by altering the features or structures of substrates around the resonant unit cells only. In this regard, the adjusting of metallic composites has considerably weak performance. Herein, we make a step forward by providing deep insight into a direct tuning approach for semiconductor-based composites. The resonance behavior of their properties can be dramatically affected by manipulating the distribution of free carriers in unit cells under an applied voltage. The mentioned approach has been demonstrated in the case of semiconductor metamaterials by comparing the enhanced propagation of surface plasmon polaritons with a conventional semiconductor/air case. Theoretically, the presented approach provides a fertile ground to simplify the configuration of engineerable composites and provides a fertile ground for applications in ultrathin, linearly tunable, and on-chip integrated optical components. These include reconfigurable ultrathin lenses, nanoscale spatial light modulators, and optical cavities with switchable resonance modes.

Keywords: metamaterial; nanostructure; semiconductor

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1. Introduction

Metamaterials have inspired scientists to think about their fascinating properties, including allowing for the nonconventional propagation of electromagnetic waves. These include negative phase velocity or negative refraction. Nanostructured metamaterials, a class of hyperbolic composites, are making a substantial contribution to the field. A significant number of attractive applications, for example, ultracompact wave plates [1], broadband absorbers [2], and optical circuit boards [3], has been possible due to numerous unusual trends in anisotropic composites. These include invisible cloak [4], negative refraction [5], and abnormal refection [6]. It should be noted that electromagnetic features of composites can be engineered by lights [7], electrics [8], magnetics [9], temperatures [10], and engineering material structure or geometry of metamaterial unit cells.

It should be mentioned that most of the presented reconfigurable metamaterials, composed of noble metals, lack a direct tuning option. The former occurs due to the fact that free electrons in metal unit cells are unmanageable. The findings presented up to now have focused on changing features of substrates or structures aiming to tune the metamaterial properties. These include refractive index [11], depletion width of GaAs [12], optical constants of graphene [13], permittivity of ITO [14], shape of PDMS [15], and vanadium dioxide conductivity [16]. In addition to changing the response of the materials that are used to construct metamaterials, structurally engineering meta-atoms are considered another efficient approach to reconfigure the metamaterial properties [17]. In comparison with direct metamaterial tuning, these indirect engineering techniques do not allow to go beyond the current state of the art. Enabling the control of free electrons in metamaterial unit cells, the direct tuning technique can benefit from an adequately large free electron distribution and density variation in a material (e.g., heavily doped semiconductor or conducting oxide). The former may result in the variation in resonance frequency and resonance strength of composites. Unsurprisingly, this immediately reconfigurable metamaterial approach will benefit due to a combination of benefits of the individual modulation of metamaterial building blocks, leading to exceptionally lower power dissipation.

However, to date, no comprehensive research has been related to direct tuning techniques applied for metamaterials composed of directly reconfigurable inclusions. The main outstanding feature of immediately tunable metamaterials is the variability in the electromagnetic property of the metamaterial building blocks. For instance, doped semiconductors, such as GaAs, InSb, InAs, and ZnO, and conducting oxides, such as ITO [14], are classic examples of materials comprising free electrons (free carriers) that are easily tunable by means of electric fields, pumping lights, or temperature fields. These instances can additionally be employed to create metamaterials [18]. In this paper, semiconductors were applied with the aim of modeling nanostructured semiconductor metamaterials to show a directly reconfigurable metamaterial approach, providing a fertile ground for dynamic electric control. Herein, metamaterial unit cells are created by employing doped semiconductors. The former would allow to deal with metal with a minor metamaterial case.

2. Methods

Herein, we present an approach to homogenizing nanostructured metamaterial [19] consisting of oscillating semiconductor (InAs) and dielectric layers. An experimental demonstration of tunable graphene–polaritonic hyperbolic metamaterial has been studied in [20]. The main feature of InAs is related to the weak response in the presence of externally applied temperature. Thus, the magnetic field for this material should be taken into account. In the presence of a magnetic field, this material behaves as a gyroelectric anisotropic material, and its relative permittivity is drastically dependent on an externally applied magnetic field. Herein, aiming to obtain numerical outcomes, we have assumed a magnetic field along the x-axis that is governed following equations:

$$\varepsilon_{\perp} = \varepsilon_{\infty} - \frac{\omega_p^2(\omega^2 + i\omega\gamma)}{(\omega^2 + i\omega\gamma)^2 - \omega^2\omega_c^2} \tag{1}$$

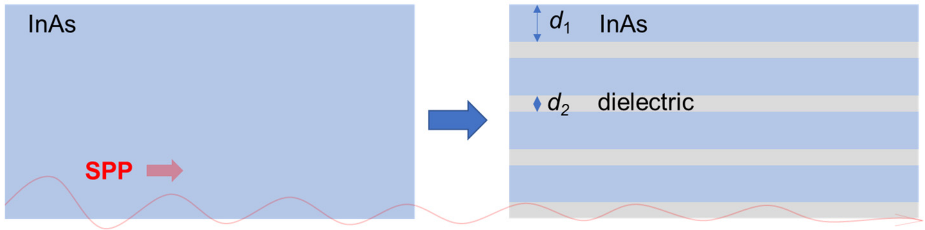
$$\varepsilon_{||} = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\omega\gamma} \tag{2}$$

$\varepsilon_{\infty} = 16.3$ is the high-frequency dielectric constant, ω_p is the plasma frequency $\omega_p = \sqrt{\frac{Nq^2}{m^*\varepsilon_0}}$, $N = 1.0 \times 10^{23}$ m^{-3} is the free charge carrier density, $m^* = 4 \times 10^{-3} m_e$ is the effective carrier mass, $\gamma = 15 \times \pi 10^{11}$ rad/s is the damping constant, and ω_c is the cyclotron frequency strongly dependent on the magnetic field $\omega_c = \frac{qB_0}{m^*}$.

It should be mentioned that all the simulations were performed in Matlab by simulating the dispersion relation [19,21–25] of the surface plasmon polaritons propagating at the boundary of the structure under consideration.

3. Results

In this paper, a phenomenon of the propagation of surface waves at the boundary of tunable hyperbolic metamaterial was studied. It is worthwhile mentioning that its resonance can be directly controlled by changing the concentration of the free carriers of the semiconductor. Specifically, we studied the propagation of surface plasmon polaritons at the boundary of the anisotropic media (Figure 1). It should be mentioned that we examined two different samples, i.e., anisotropic InAs semiconductor (Figure 1a) and hyperbolic metamaterial constructed by providing a combination of the alternating dielectric and InAs layers (Figure 1b). The nanostructured metamaterial under consideration can be fabricated by utilizing a synergy of plasma-enhanced vapor deposition techniques [20].



(**a**) (**b**)

Figure 1. A sketch of the problem under consideration, i.e., propagation of surface plasmon polaritons at the boundary of anisotropic semiconductor (**a**) and hyperbolic metamaterials (**b**) with definitions of the geometrical parameters.

Hyperbolic metamaterials have attracted a great deal of attention over the years [26]. Nanostructured metamaterials, belonging to a class of hyperbolic metamaterials composed of alternating dielectric layers with a permittivity $\varepsilon_2 > 0$ and conductive layers with a permittivity $\varepsilon_1 < 0$, can be grown with molecular beam epitaxy on lattice-matched substrates [27]. Moving free electrons in conductive layers can create an electric dipole. The former is crucial in aiming to induce electric resonances in nanostructured metamaterials. Based on the above stated, noble metals are taken into consideration as the conductive layers because of their larger number of free electrons leading to stronger resonances. However, such composites cannot be directly tuned. In this paper, a layered metamaterial is numerically demonstrated, tuning its properties by changing the parameters of the employed semiconductor. The increase in free carrier concentration will raise the free electron collision rate and provide a fertile ground for a reduction in the effective path length of free electrons. In other words, the resonance will move to shorter wavelengths.

It is worthwhile noting that doped semiconductors in short-wavelength bands (e.g., near-IR, visible, and UV bands) cannot demonstrate plasma behavior (i.e., $\varepsilon_1 > 0$). In this relationship, the suggested cavity will not be obtainable in these bands. However, one can choose a low effective mass and high-mobility semiconductor (e.g., indium tin oxide, zinc oxide doped with aluminum or gallium [28]) or add metallic layers in the nanostructured metamaterial to escape this challenge. The frequency-dependent permittivities [19–25] of both anisotropic semiconductor and semiconductor-based nanostructured metamaterials are presented in Figure 2. It should be noted that permittivities tend toward the negative values at the lower frequency ranges. As can be observed in Figure 2a, the frequency range of the negative values moves to the higher frequency range as the magnetic field strength increases. The same is valid for the semiconductor-based metamaterial case (Figure 2b). However, the shift is less observable in Figure 2b. It should be mentioned that $\varepsilon_\perp$ only is tunable in the case of varying magnetic field strength along with the permittivity of the dielectric layer in Figure 2a–c. The example depicted in Figure 2d is of particular interest, as it presents the impact of the engineering concentration of the free carriers in the semiconductor. The resonant frequency of $\varepsilon_\perp$ increases with an increase in the N value. The former is justified by Figure 3. An increase in the concentration allows for a significant enhancement in resonant behavior.

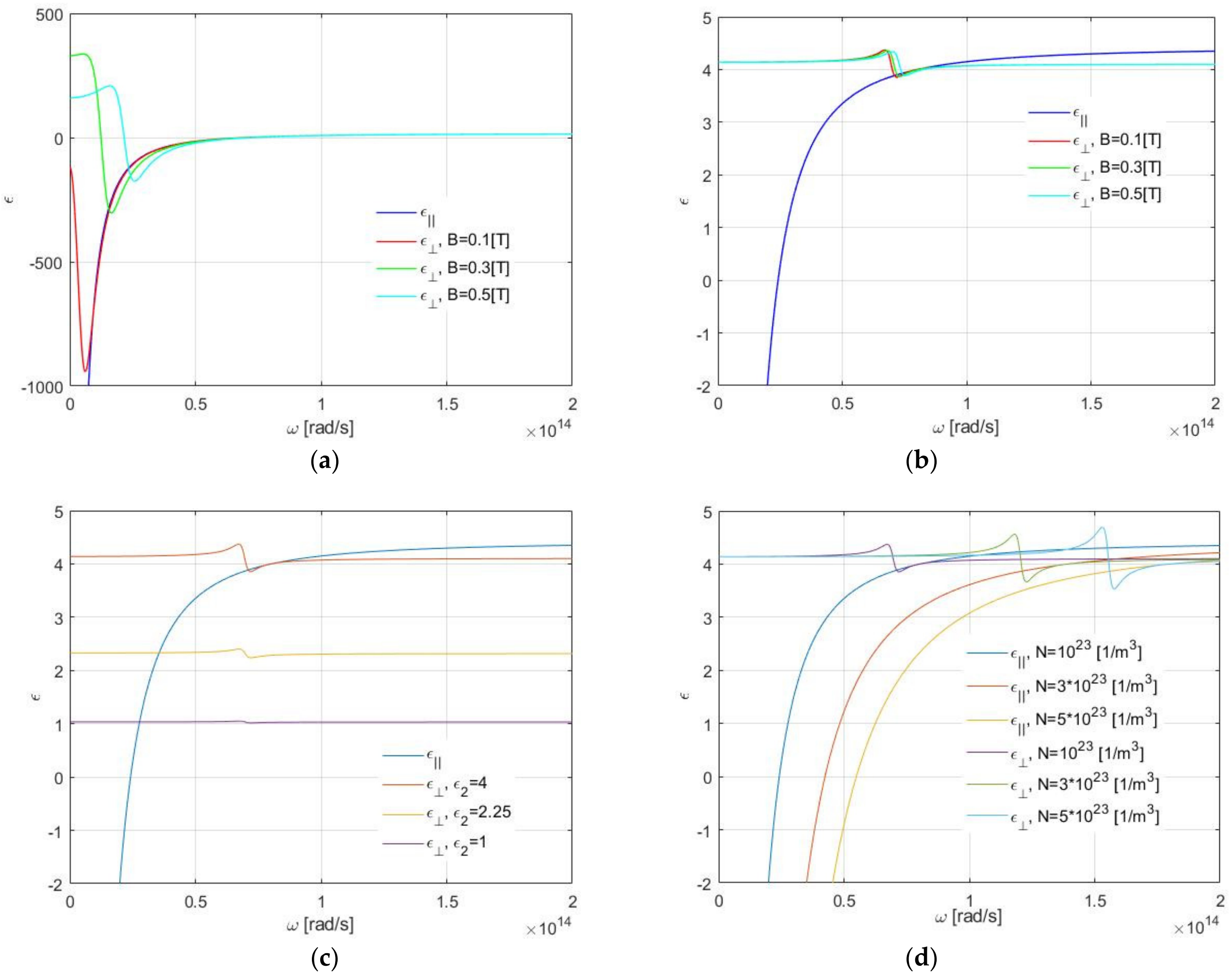


Figure 2. Dependencies of the optical properties of anisotropic semiconductor (**a**) and semiconductor-based nanostructured metamaterial (**b**–**d**) versus frequency.

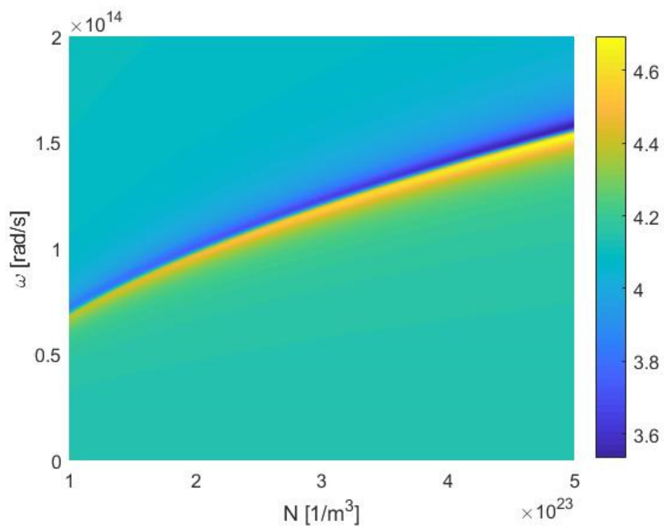


Figure 3. Dependence of the $\varepsilon_{\perp}$ upon frequency and concentration of the free carriers.

One may conclude by comparing Figures 4 and 5a that by employing air-filled layers into the metamaterial nanostructure, dispersion diagrams fully coincide with those obtained for the conventional case of propagation of surface plasmon polaritons at the semiconductor air interface. As can be observed in Figure 5a, by varying the permittivity of the metamaterial layer ε_2, one may tune the dispersion maps [19–25], intending to increase the frequency range of surface wave existence.

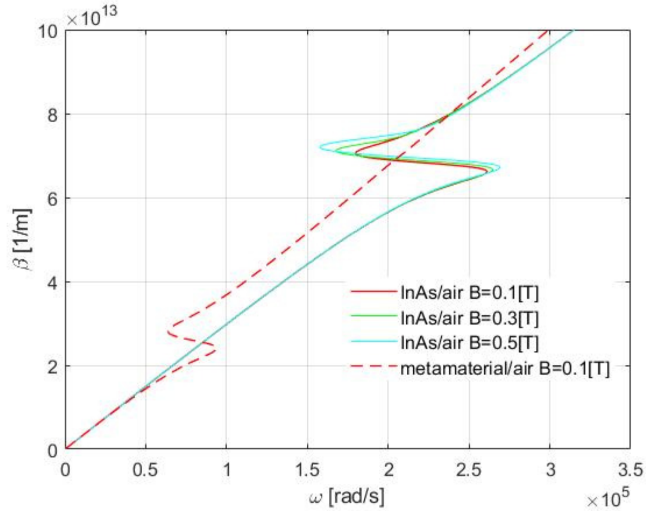


Figure 4. Dispersion maps of the surface plasmon polaritons propagating at the boundary of anisotropic semiconductor.

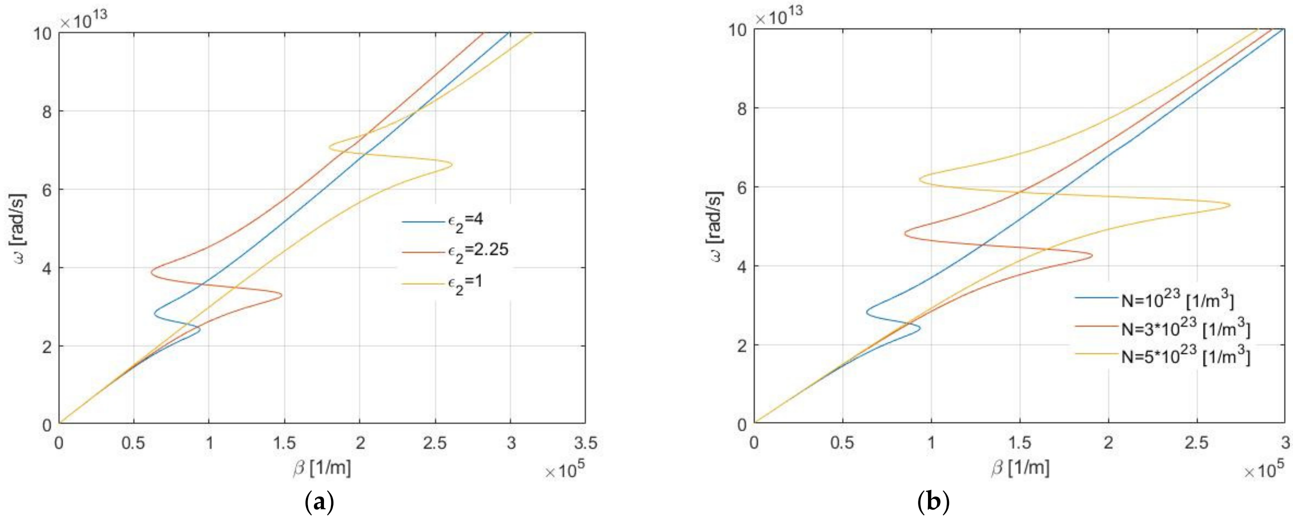


Figure 5. Dispersion maps of the surface plasmon polaritons propagating at the boundary of semiconductor-based metamaterial: (**a**) dielectric tunable dispersion; (**b**) concentration tunable dispersion.

It can be concluded from Figure 5 that the inclusion of the semiconductor layers into the nanostructured metamaterial structure allows for an unprecedented degree of freedom, aiming to monitor the dispersion properties of the structure under consideration. By increasing the concentration of the semiconductor careers, the frequency range of the existence of surface plasmons is drastically enlarged. The former opportunity is possible only in the case of semiconductor inclusions. Moreover, it can be observed in Figure 5b that the plasma frequency increases with an increase in the concentration of the free carriers. The former coincides with an increase in the resonant frequency of $\varepsilon_\perp$ in Figure 2d. It can be concluded that one may tune nanostructured metamaterial by modifying the properties of the inclusions with no need for geometrical alterations of the structure.

4. Conclusions

To conclude, a direct tuning approach for reconfigurable semiconductor metamaterial is suggested, and its modulation mechanisms are reported by studying the dispersion maps of surface plasmon polaritons. It should be stressed that the inclusion of semiconductor layers into the nanostructured metamaterial structure allows for an unprecedented degree of freedom, aiming to control the dispersion properties of the structure under consideration. By increasing the concentration of the semiconductor careers, the frequency range of the existence of surface plasmons is drastically enlarged. The results demonstrate that the resonance frequency and dispersion maps can be directly tuned by modifying the parameters of the semiconductor. The discussed tunable metamaterials have significant applications in the broad electromagnetic spectrum due to the tunable characteristics of the operating frequency band. For example, semiconductor-based metamaterials can be used to fabricate tunable phase shifters and filters [29,30] and to design filter antennas, nonlinear components [31,32], and absorbers [33].

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