applied sciences

MDPI

Article

Controlling Surface Plasmon Polaritons Propagating at the Boundary of Low-Dimensional Acoustic Metamaterials

Thanos Ioannidis [1], Tatjana Gric [1,2,3,*] and Edik Rafailov [2,4]

[1] Department of Electronic Systems, VILNIUS TECH, 10223 Vilnius, Lithuania; athanasios.ioannidis@vgtu.lt
[2] Aston Institute of Photonic Technologies, Aston University, Birmingham B4 7ET, UK; e.rafailov@aston.ac.uk
[3] Center for Physical Sciences and Technology, Semiconductor Physics Institute, 10222 Vilnius, Lithuania
[4] Peter the Great St. Petersburg Polytechnic University, 195251 St. Petersburg, Russia
* Correspondence: Tatjana.gric@vilniustech.lt

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 functional engineering in comparison to the conventional substances. Acoustic metamaterials and plasmonic structures possess a wide variety of exceptional physical features. These include effective negative properties, band gaps, negative refraction, etc. In doing so, the acoustic behaviour of conventional substances is extended. Acoustic metamaterials are considered as the periodic composites with effective parameters that might be engineered with the aim to dramatically control the propagation of supported waves. Homogenization of the system under consideration should be performed to seek the calculation of metamaterial permittivity. The dispersion behaviour of surface waves propagating from the boundary of a nanocomposite composed of semiconductor enclosures that are systematically distributed in a transparent matrix and low-dimensional acoustic metamaterial and constructed by an array of nanowires implanted in a host material are studied. We observed the propagation of surface plasmon polaritons. It is demonstrated that one may dramatically modify the properties of the system by tuning the geometry of inclusions.

Keywords: surface plasmon polaritons; low-dimensional; acoustic; metamaterial

check for updates

Citation: Ioannidis, T.; Gric, T.; Rafailov, E. Controlling Surface Plasmon Polaritons Propagating at the Boundary of Low-Dimensional Acoustic Metamaterials. *Appl. Sci.* **2021**, *11*, 6302. https://doi.org/10.3390/app11146302

Academic Editor: Luigi La Spada

Received: 25 May 2021
Accepted: 6 July 2021
Published: 8 July 2021

1. Introduction

Over the past few years, interest in creating materials allowing for the control the flow of electromagnetic waves (e.g., light) in exceptional ways has increased dramatically. Novel engineering tools have opened wide avenues to construct artificial materials possessing properties that are not possible in the case of the naturally existing materials. These new designs are possible due to the wide variety of inclusions. Moreover, the novel response appears to be because of their specific interactions with electromagnetic fields. These designs can be scaled down and constructed thanks to nanotechnology.

Hyperbolic metamaterials represent a multi-functional platform providing a fertile ground for the realization of waveguiding, imaging, sensing, quantum, and thermal engineering outside the scope of conventional devices. These novel composites utilize the notion of tuning the fundamental dispersion relation of surface plasmon polaritons aiming to generate exceptional electromagnetic modes with a wide spectrum of applications. The hyperbolic metamaterial can be considered from the perspective of polaritonic crystal.

The unique positioning of nanomaterials bridging atoms and bulk solids, along with their interesting features and potential applications [1] has provided a fertile ground for the growing scientific interest in them. The capability to create such nanoscale-sized materials advances many fields of modern science and technology.

Transparent conductive oxides (TCOs) are of particular interest within the scientific community. These might be utilized as the optional materials for plasmonic applications [2] in the near-infrared region. It should be mentioned that TCOs such as indium tin oxide

(ITO) show a wide spectrum of engineerable features [3]. The former is possible via doping and electric bias. The modelling and fulfillment of ultra-compact electro-absorption modulators [4–8], including the application of novel multimode modulator architectures, [9] has profited from the chance of actively switching between two different regimes.

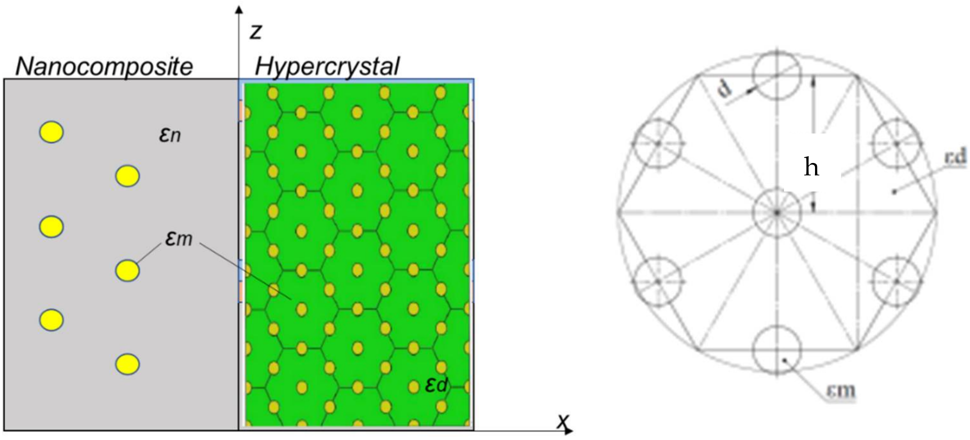
The unique properties of SP-based nanostructures and their applications in waveguides, sources, near-field optics, nonlinear optics, surface enhanced Raman spectroscopy (SERS), data storage, solar cells (or photovoltaic devices), chemical sensors, biosensors, etc. [10,11], have stimulated a tremendous interest in their properties.

Hyperbolic materials belong to a class of uniaxial materials. These are characterized by two different values for permittivity, i.e., parallel and perpendicular to the optical axis [12]. The exceptional wave is characterized by an electric field with components along the optical axis and perpendicular to it. Hyperbolic materials possess a remarkable property. They support propagating waves possessing arbitrary large wave vectors at a finite frequency [13–15]. Consequently, the corresponding local density of states is exceptionally large. In doing so, hyperbolic substances open wide avenues for many applications such as superresolution, enhanced spontaneous emission, and large energy density [16].

Based on the frequency range, one may divide sound waves into the types that follow: low frequency, intermediate frequency, and high frequency. Noise has a strong penetrating power and dissipates slowly during propagation. In doing so, it is a challenging task to engineer the sound waves. Hence, it is of particular importance to focus on the investigation of sound waves and vibration control. The investigations of surface waves and plasmonics represent an additional inherent part of nanophotonics. The former provide a fertile ground aiming to lower the length scales and dimensionality of a wide range of electromagnetic phenomena. Not remarkably, nonreciprocity and unidirectional propagation of surface plasmon-polaritons (SPPs) have stimulated a tremendous interest. Magneto-optical nonreciprocity in the transverse Voigt geometry is mostly dealt with in these studies, comprising topological quantum-Hall-effect states. Herein we consider a novel approach allowing for the propagation of SPPs at the acoustic metamaterial interface. It is worthwhile to note that inclusions of the composites are fulfilled by the TCOs, making a stronger case towards implementation the properties of possible devices. It should be mentioned, that in the present work we, deal with the spoof SPPs. Natural SPPs only exist at optical frequencies. To realize SPPs at lower frequencies, spoof SPPs are proposed. In doing so, we end up with the concept of “designer” surface modes.

2. Theoretical Approach

In the frame of the present study, we investigate the plane interface separating a nanocomposite (NC) semi-infinite layer and a hypercrystal that is adjacent to it (Figure 1). It is of particular importance to mention that the surface waves propagate along z axis. It is possible to construct the system under investigation by means of molecular beam epitaxy [17], chemical vapor deposition, atomic layer deposition and sacrificial etching [18]. Nanocomposite is understood as a non-conductive transparent matrix with a permittivity ε_n. Semiconductor nanoparticles with permittivity ε_m are regularly distributed in its host material. The dielectric function of the TCO based nanoparticles is of special importance to r the academic community. The topic has become one of significance due to the metal being opaque to light. The parameters of the Drude–Lorentz approach for AZO, GZO, and ITO are obtained from experimental data [2].



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

Figure 1. Schematic design under consideration, comprising a semi-infinite hypercrystal ($x > 0$) and a nanocomposite with semiconductor inclusions ($x < 0$) (**a**), metamaterial (hypercrystal) unit cell (**b**).

We have made an assumption that the size of the inclusions suspended in a dielectric matrix is much smaller than the wavelength and the electromagnetic field penetration depth in the material. It is worthwhile to mention that an effective Maxwell Garnett model can be employed, aiming to characterize the optical parameters of the nanocomposite under consideration. The former approach is possible if the interference impacts of the inclusions are neglected. In this relation, the homogenization of the system should be performed, and the effective dielectric permittivity of the nanocomposite can be expressed as follows:

$$\varepsilon_{nc} = \varepsilon_n \left[1 + \frac{f}{(1-f)/3 + \varepsilon_n/(\varepsilon_m - \varepsilon_n)} \right] \tag{1}$$

where f is the filling factor, i.e., the fraction of nanoparticles in the matrix.

Based on the effective medium approximation, the effective permittivities of the nanowire metamaterial (hypercrystal) can be obtained according to [19]:

$$\varepsilon_{\perp} = \varepsilon_d \left[\frac{\varepsilon_m(1+\rho) + \varepsilon_d(1-\rho)}{\varepsilon_m(1-\rho) + \varepsilon_d(1+\rho)} \right] \tag{2}$$

$$\varepsilon_{||} = \varepsilon_m \rho + \varepsilon_d(1-\rho) \tag{3}$$

Here, ρ is the metal filling fraction ratio which is defined as:

$$\rho = \frac{nanowire\ area}{unit\ cell\ area} \tag{4}$$

The calculation of the metal filling fraction (ρ) taking into account the data sheet of the pore diameter (d) and spacing (h) (Figure 1b). The following equation [20,21] is applied, taking into consideration a perfect hexagonal structure:

$$\rho = \frac{\pi d^2}{2\sqrt{3}h^2} \tag{5}$$

One may attain a surface mode with the propagation constant [22] by evaluating the tangential components of the electric and magnetic fields at the interface.

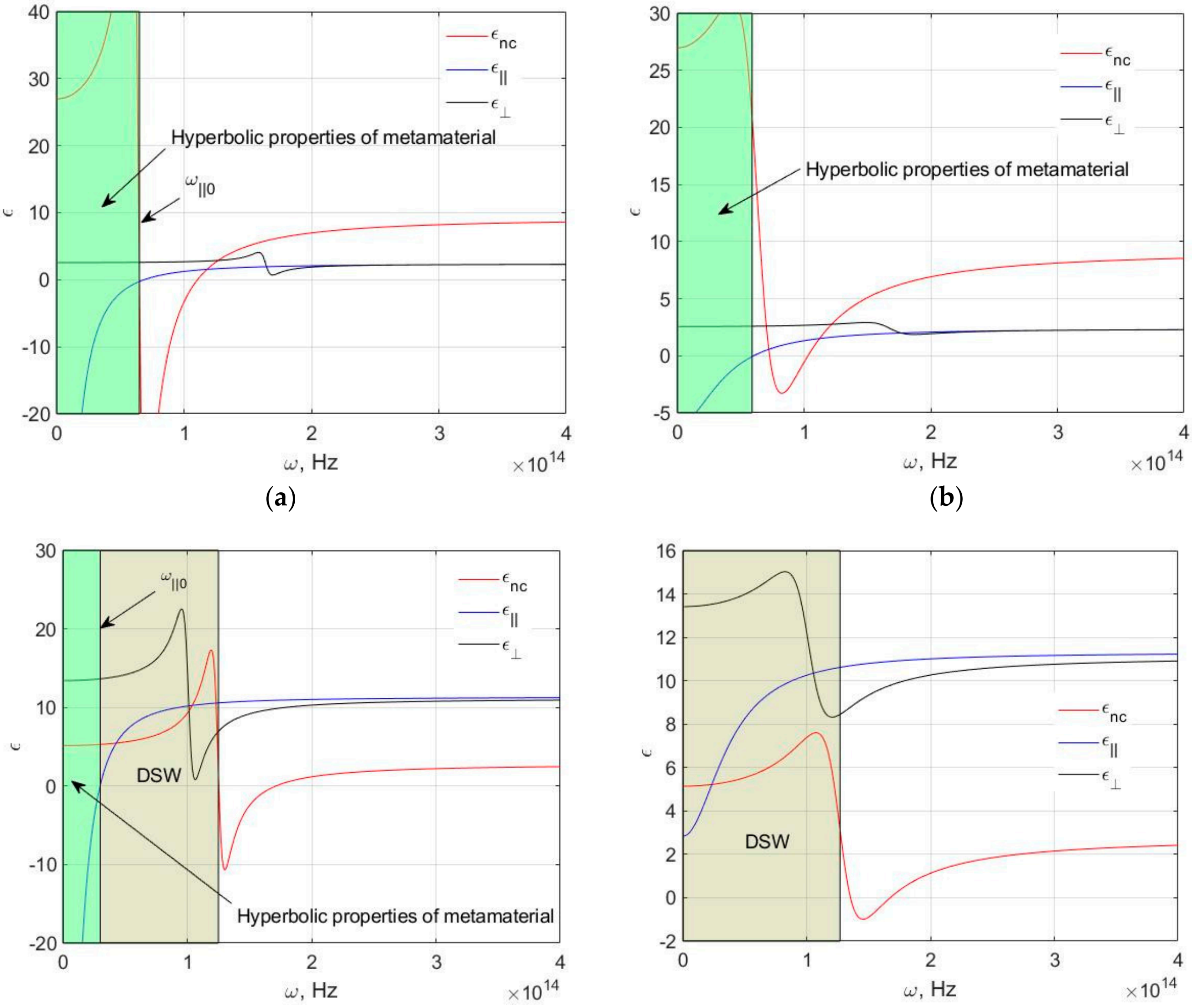
$$\beta = k \left(\frac{\left(\varepsilon_{||} - \varepsilon_{nc}\right)\varepsilon_{\perp}\varepsilon_{nc}}{\varepsilon_{\perp}\varepsilon_{||} - \varepsilon_{nc}^2} \right)^{1/2} \tag{6}$$

By substituting (1)–(3) in (6), the resulted dispersion relation is as follows:

$$\beta = k\left(-\frac{\varepsilon_n ba(\varepsilon_n a+\varepsilon_m\rho-\varepsilon_d(\rho-1))}{\left(\varepsilon_n^2 a^2+\frac{(\varepsilon_m\rho-\varepsilon_d(\rho-1))b}{\varepsilon_d(\rho+1)-\varepsilon_m(\rho-1)}\right)(\varepsilon_d(\rho+1)-\varepsilon_m(\rho-1))}\right)^{1/2}$$
$$a = \frac{f}{\frac{f}{3}+\frac{\varepsilon_n}{\varepsilon_n-\varepsilon_m}-\frac{1}{3}} - 1, b = (\rho-1)\varepsilon_d^2 - \varepsilon_m\varepsilon_d(\rho+1). \quad (7)$$

3. Results and Discussions

Herein, the dependencies of the permittivity components of a hypercrystal and nanocomposite upon frequency are modelled aiming to detect the frequency ranges of Dyakonov surface waves (DSWs) and the existence of SPP waves (Figure 2).



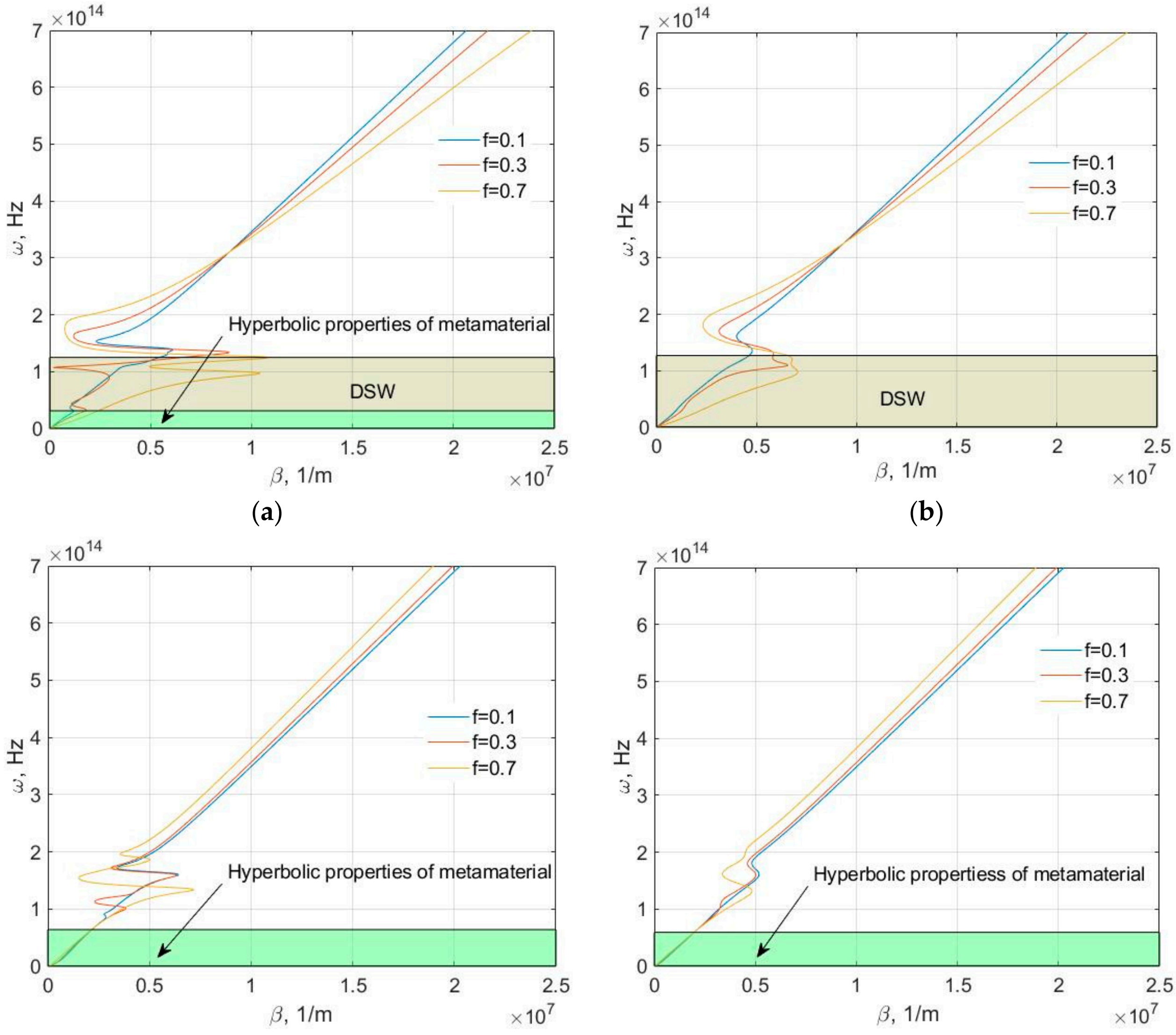
(**a**) (**b**)

(**c**) (**d**)

Figure 2. Relative permittivity components of the nanocomposite and hypercrystal versus frequency. Herein, f = 0.3. (**a**,**b**) $\varepsilon_n = 11.8$, $\varepsilon_d = 2.25$; (**c**,**d**) $\varepsilon_n = 2.25$, $\varepsilon_d = 11.8$. Herein AZO (**a**,**c**) and ITO (**b**,**d**) inclusions are employed in nanocomposite and hypercrystal.

In the range the frequency $\omega_{||0}$ the semiconductor-dielectric metamaterial possesses hyperbolic properties. It can be seen from Figure 2, that the propagation of DSW is possible in the case of $\varepsilon_n = 2.25$, $\varepsilon_d = 11.8$. It is worthwhile to note that the regime of DSW propagation is possible in the case of $\varepsilon_{||}$, $\varepsilon_{nc} > 0$. Moreover, it is possible to increase the frequency range of DSW existence by changing the nature of inclusions, i.e., by replacing AZO with ITO.

It is of particular interest to analyze two cases, i.e., when $\varepsilon_n > \varepsilon_d$ and $\varepsilon_d > \varepsilon_n$. The case when $\varepsilon_n = 2.25$, $\varepsilon_d = 11.8$ is depicted in Figure 3a. It can be observed that dispersion curves in these cases exhibit an exotic behavior in contrary to the conventional surface plasmons propagating at the metal/dielectric interface [23]. The case when $\varepsilon_n = 11.8$, $\varepsilon_d = 2.25$ is depicted in Figure 3b. By having a glance into the properties of DSW obtained by changing the filling factor of the nanocrystal as displayed in Figure 3a, one may observe that in contrast to the case depicted in Figure 3a, DSW does not propagate if $\varepsilon_n = 11.8$, $\varepsilon_d = 2.25$ (Figure 3c).

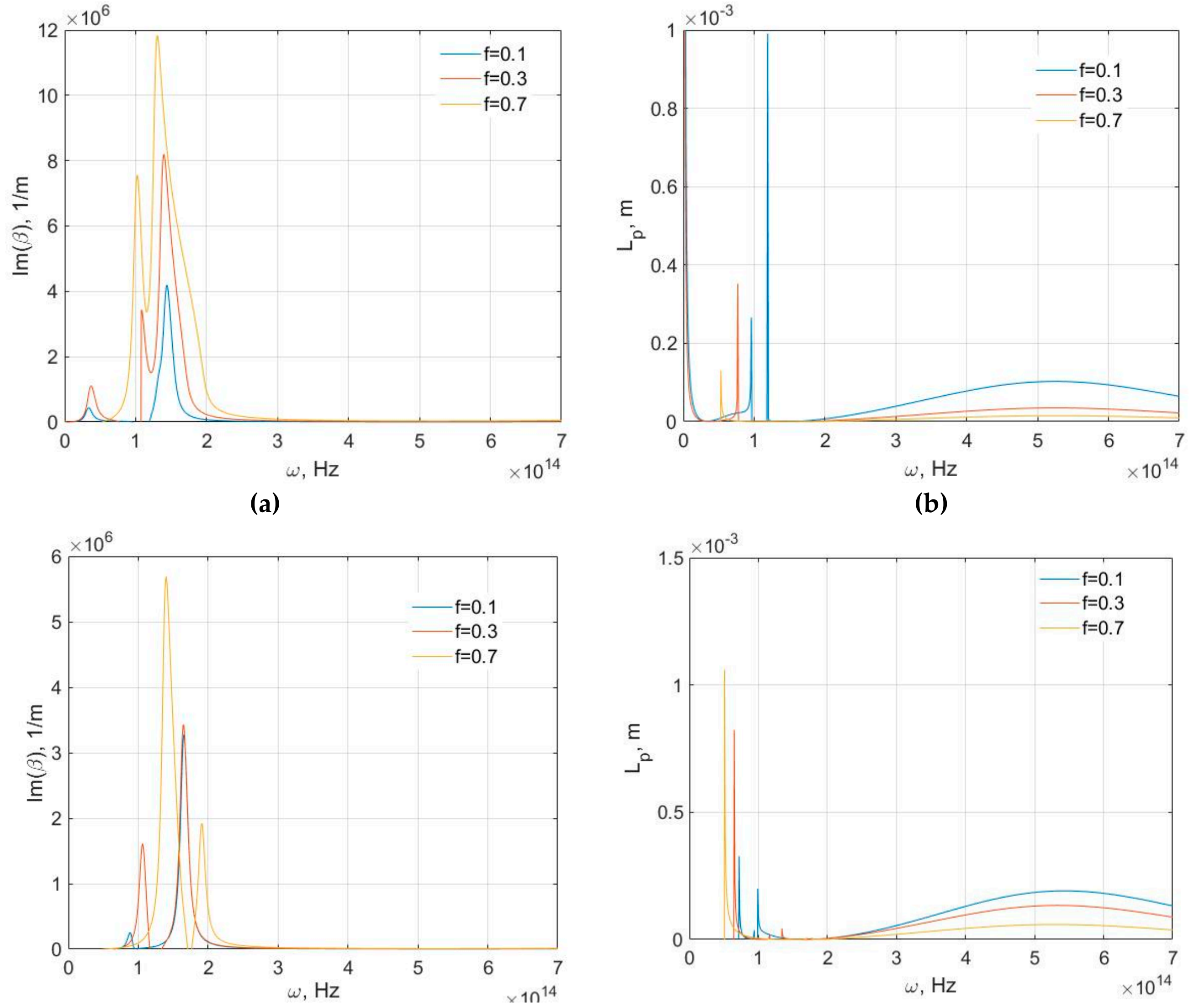


(**a**) (**b**)

(**c**) (**d**)

Figure 3. Solution of the wave equation for different filling ratio f: (**a**,**b**)—$\varepsilon_n = 2.25$, $\varepsilon_d = 11.8$; (**c**,**d**)—$\varepsilon_n = 11.8$, $\varepsilon_d = 2.25$. Herein AZO (**a**,**c**) and ITO (**b**,**d**) inclusions are employed in nanocomposite and hypercrystal.

Figure 4 demonstrates the transmission characteristics on frequency for various filling ratios. It can be seen in Figure 4a,c that with the increase of frequency, the imaginary part of β decreases at certain intervals, and the transmission distance increases. The former reveals the reduction of transmission loss with increasing frequency. Figure 4 shows that the filling ratio has a dramatic impact on the transmission characteristics of the SPPs. In this relationship, the realization of dimension-tunable SPPs is enabled. It is worth noting that the results presented in Figure 4a,c are very important for practical application. The increase of the absorption enhancement (imaginary part of the propagation constant) makes a dramatic impact while creating photoconductive antennas with this enhanced performance [24].



(a) **(b)**

(c) **(d)**

Figure 4. Dependence of transmission characteristics versus frequency for different filling factors: (**a**,**c**) the imaginary part of β; (**b**,**d**) the propagation length L_p. The case $\varepsilon_n = 2.25$, $\varepsilon_d = 11.8$.is presented in (**a**,**b**); $\varepsilon_n = 11.8$, $\varepsilon_d = 2.25$—(**c**,**d**). All of the presented results were obtained for the AZO inclusions.

4. Conclusions

Thorough 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 the frequency ranges where DSW can exist have been demonstrated. It has been concluded that with the increase of frequency, the imaginary part of β decreases at certain intervals, and the transmission distance increases. The former reveals the reduction of transmission loss with increasing frequency. The filling ratio has a dramatic impact on the transmission characteristics of SPPs. From this relationship, the realization of dimension tunable SPPs is enabled. This work is of great significance to the further research of optical devices based on SPPs.

Author Contributions: Conceptualization, T.I. and T.G.; methodology, T.I.; software, T.G.; validation, T.G. and E.R.; formal analysis, E.R.; investigation, T.I.; resources, E.R.; data curation, T.G.; writing—original draft preparation, T.I.; writing—review and editing, T.G. and E.R.; visualization, T.I.; supervision, T.G.; project administration, E.R.; funding acquisition, T.G. and E.R. All authors have read and agreed to the published version of the manuscript.

Funding: This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska Curie grant agreement No 713694 and from Engineering and Physical Sciences Research Council (EPSRC) (Grant No. EP/R024898/1). The work of E.U. Rafailov was partially funded by the Ministry of Science and Higher Education of the Russian Federation as part of World-class Research Center program: Advanced Digital Technologies (contract No. 075-15-2020-934 dated 17.11.2020).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Halperin, W.P. Quantum size effects in metal particles. *Rev. Mod. Phys.* **1986**, *58*, 533–606. [CrossRef]
2. Naik, G.V.; Shalaev, V.M.; Boltasseva, A. Alternative plasmonic materials: Beyond gold and silver. *Adv. Mater.* **2013**, *25*, 3264–3294. [CrossRef] [PubMed]
3. Feigenbaum, E.; Diest, K.; Atwater, H.A. Unity-Order Index Change in Transparent Conducting Oxides at Visible Frequencies. *Nano Lett.* **2010**, *10*, 2111–2116. [CrossRef]
4. Sorger, V.J.; Lanzillotti-Kimura, N.D.; Ma, R.-M.; Zhang, X. Ultracompacy silicon nanophotonic modulator with broadband response. *Nanophotonics* **2012**, *1*, 17. [CrossRef]
5. Cai, W.; White, J.S.; Brongersma, M.L. Compact, High-Speed and Power-Efficient Electrooptic Plasmonic Modulators. *Nano Lett.* **2009**, *9*, 4403–4411. [CrossRef] [PubMed]
6. Das, S.; Salandrino, A.; Wu, J.Z.; Hui, R. Near-infrared electro-optic modulator based on plasmonic graphene. *Opt. Lett.* **2015**, *40*, 1516–1519. [CrossRef]
7. Ye, C.; Khan, S.; Li, Z.R.; Simsek, E.; Sorger, V.J. λ-size ITO and graphene-based electro-optic modulators on SOI. *IEEE J. Sel. Top. Quantum Electron.* **2014**, *20*, 40.
8. Vasudev, A.P.; Kang, J.-H.; Park, J.; Liu, X.; Brongersma, M.L. Electro-optical modulation of a silicon waveguide with an "epsilon-near-zero" material. *Opt. Express* **2013**, *21*, 26387. [CrossRef]
9. Das, S.; Fardad, S.; Kim, I.; Rho, J.; Hui, R.; Salandrino, A. Nanophotonic modal dichroism: Mode-multiplexed modulators. *Opt. Lett.* **2016**, *41*, 4394–4397. [CrossRef]
10. Barnes, W.L.; Dereux, A.; Ebbesen, T.W. Surface plasmon subwavelength optics. *Nature* **2003**, *424*, 824–830. [CrossRef] [PubMed]
11. Zhang, J.; Zhang, L.; Xu, W. Surface plasmon polaritons: Physics and applications. *J. Phys. D Appl. Phys.* **2012**, *45*, 113001. [CrossRef]
12. Peragut, F.; Cerruti, L.; Baranov, A.; Hugonin, J.P.; Taliercio, T.; De Wilde, Y.; Greffet, J.J. Hyperbolic metamaterials and surface plasmon polaritons. *Optica* **2017**, *4*, 1409–1415. [CrossRef]
13. Zhukovsky, S.V.; Andryieuski, A.; Sipe, J.E.; Lavrinenko, A.V. From surface to volume plasmons in hyperbolic metamaterials: General existence conditions for bulk high-k waves in metal-dielectric and graphene-dielectric multilayers. *Phys. Rev. B* **2014**, *90*, 155429. [CrossRef]
14. Mahmoodi, M.; Tavassoli, S.H.; Takayama, O.; Sukham, J.; Malureanu, R.; Lavrinenko, A.V. Existence Conditions of High-k Modes in Finite Hyperbolic Metamaterials. *Laser Photon Rev.* **2019**, *13*, 1800253. [CrossRef]
15. Takayama, O.; Lavrinenko, A. Optics with hyperbolic materials. *J. Opt. Soc. Am. B* **2019**, *36*, F38–F48. [CrossRef]
16. Ferrari, L.; Lu, D.; Lepage, D.; Liu, Z. Enhanced spontaneous emission inside hyperbolic metamaterials. *Opt. Express* **2014**, *22*, 4301–4306. [CrossRef]
17. Hoffman, A.; Alekseyev, L.; Howard, S.; Franz, K.; Wasserman, D.; Podolskiy, V.; Narimanov, E.; Sivco, D.; Gmachl, C. Negative refraction in semiconductor metamaterials. *Nat. Mater.* **2007**, *6*, 946–950. [CrossRef]
18. Feng, J.; Chen, Y.; Blair, J.; Kurt, H.; Hao, R.; Citrin, D.S.; Summers, C.J.; Zhou, Z. Fabrication of annular photonic crystals by atomic layer deposition and sacrificial etching. *J. Vac. Sci. Technol. B Microelectron. Nanometer Struct.* **2009**, *27*, 568. [CrossRef]

19. Shekhar, P.; Atkinson, J.; Jacob, Z. Hyperbolic metamaterials: Fundamentals and applications. *Nano Converg.* **2014**, *1*, 1–17. [CrossRef] [PubMed]
20. Starko-Bowes, R.; Atkinson, J.; Newman, W.; Hu, H.; Kallos, T.; Palikaras, G.; Fedosejevs, R.; Pramanik, S.; Jacob, Z. Optical characterization of epsilon-near-zero, epsilon-near-pole, and hyperbolic response in nanowire metamaterials. *J. Opt. Soc. Am. B* **2015**, *32*, 2074–2080. [CrossRef]
21. Gric, T.; Hess, O. Surface plasmon polaritons at the interface of two nanowire metamaterials. *J. Opt.* **2017**, *19*, 085101. [CrossRef]
22. Iorsh, I.; Orlov, A.; Belov, P.; Kivshar, Y. Interface modes in nanostructured metal-dielectric metamaterials. *Appl. Phys. Lett.* **2011**, *99*, 151914. [CrossRef]
23. Maier, S. Surface Plasmon Polaritons at Metal/Insulator Interfaces. In *Plasmonics: Fundamentals and Applications*; Springer: New York, NY, USA, 2007.
24. Gric, T.; Gorodetsky, A.; Trofimov, A.; Rafailov, E.U. Tunable Plasmonic Properties and Absorption Enhancement in Terahertz Photoconductive Antenna Based on Optimized Plasmonic Nanostructures. *J. Infrared Millim. Terahertz Waves* **2018**, *39*, 1028–1038. [CrossRef]