Large Near-Field Enhancement in Terahertz Antennas by Using Hyperbolic Metamaterials with Hole Arrays

Cong Cheng 1,2,†, Wei Chen 1,†, Yuanfu Lu 1,,*†, Fangming Ruan 2,3 and Guangyuan Li 1,*‡

1 Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, China; cong.cheng@siat.ac.cn (C.C.); chenwei@siat.ac.cn (W.C.)
2 College of Big Data and Information Engineering, Guizhou University, Guiyang 550025, China; ruan.fm9@gmail.com
3 College of Big Data and Computer Science, Guizhou Normal University, Guiyang 550001, China
* Correspondence: yf.lu@siat.ac.cn (Y.L.); gy.li@siat.ac.cn (G.L.)
† These authors contributed equally to this work.

Abstract: Terahertz antennas can greatly enhance the near fields and enable strong light–matter interactions, and thus have been widely used in applications such as terahertz sensing and detection. Here we propose a novel approach to further enhance the near fields in terahertz antennas. We show that by sandwiching hyperbolic metamaterials that are composed of InSb and SiO$_2$ multilayer and that are dressed with hole arrays, between a terahertz dipole antenna and the substrate, the near-field electric field intensities in the antenna can be further enhanced by more than three times. Simulations reveal that this enhancement originates from the doubly enhanced in-plane electric field component and the significantly enhanced out-of-plane electric field component. We expect this work will advance the design of terahertz antennas that are widely used in sensors and detectors.

Keywords: near-field enhancement; terahertz antenna; hyperbolic metamaterials

1. Introduction

Terahertz (THz) wave refers to electromagnetic radiation with a frequency of 0.1–10 × 10$^{12}$ Hz (corresponding to wavelength of 3 mm–30 µm). Because of its unique characteristics such as superior spatial resolution, perspective, and spectroscopic fingerprints, terahertz wave has been widely used in security or industrial inspection [1,2], material composition identification [3,4], and biosensing [5]. Since commercially available high-power terahertz sources are expensive, it is crucial to enhance the localized field intensity, thus enabling strong light–matter interactions in diverse exciting applications such as detection [6], sensing [7], absorption [8], spectral filtering [9], and emission [10], and significantly improving the performance of the corresponding devices. For example, by confining most electric energy to a small region filled with microfluid, the sensitivity of a terahertz sensor can be greatly improved [11].

By efficiently coupling and confining the free-space terahertz radiations to a small (usually subwavelength) region, a terahertz antenna can greatly enhance the localized near fields. Therefore, terahertz antennas have been widely used in a diverse range of applications including biosensing [11–16] and detection [17,18]. An important figure of merit for these terahertz antennas is the near-field enhancement, which is defined as the ratio of the near-field electric field intensity and the electric field intensity of the incidence [19]. In particular, for a dipolar type antenna, of which the
strongly enhanced fields are mainly confined to the gap region of the dipole unit, the field enhancement usually refers to the enhancement of the near field in the gap. Since the field enhancement strongly depends on the antenna geometry, various antenna structures have been designed, including dipole antennas [20–22], log-periodic antennas [23,24] and spiral antennas [17,25]. To achieve large near-field enhancement, major efforts have been put on careful design and optimization of terahertz antennas.

In this work, we propose a novel approach to further improve the near-field enhancement of the terahertz dipole antenna. We show that by adding a hyperbolic metamaterial with hole arrays beneath the antenna, the near-field electric field intensity within the gap of the antenna can be further enhanced by more than three times. We will also analyze the underlying physics for this improvement and discuss the effects of the gap width and of the hyperbolic dispersion relationship of the metamaterials. We expect this proposed approach can be extended to other types of terahertz antennas.

2. Design and Theory

Figure 1 depicts the proposed terahertz dipole antenna, which is composed of two gold (Au) strips on top of a polyimide (PI) substrate, sandwiched by multiple alternating thin films of Indium Antimonide (InSb) and silica (SiO$_2$) that are dressed with periodic hole arrays. The two gold strips are of thickness $t_{Au}$, width $w$ and length $L$, and are separated by an air gap of width $g$. The individual thicknesses of the InSb and SiO$_2$ layers are $t_m$ and $t_d$, respectively. The hole arrays in the InSb-SiO$_2$ multilayers, as illustrated in Figure 1a inset, have a radius of $r$ for the holes and a period of $p$ for the arrays. Compared with a conventional terahertz dipole antenna, which directly sits on the substrate, the sandwiched multilayers with hole arrays are novel.

![Figure 1](image-url)

**Figure 1.** (a) Schematic of the proposed approach to further enhance the near fields of a terahertz dipole antenna composed of two metal stripes. A hyperbolic metamaterial (HMM) dressed with periodic hole arrays (inset) is sandwiched between the substrate and the dipole antenna. The HMM is composed of alternating layers of InSb (in blue) and SiO$_2$ (in green) with thicknesses of $t_m$ and $t_d$, respectively. A terahertz plane wave polarized in $x$ direction with unitary amplitude normally impinges onto the structure. (b) Frequency-dependent complex relative permittivity of InSb at THz frequencies, which is calculated using the Drude model. (c) Real parts of the effective relative permittivity tensor components of the InSb-SiO$_2$ multilayer metamaterial according to the effective media theory. The purple region indicates that the metamaterial has hyperbolic dispersion characteristics.
Because the individual InSb and SiO$_2$ layer dimensions satisfy the criteria of effective medium theory (EMT) [26], the effective dielectric tensor components of the anisotropic metamaterial composed of the InSb-SiO$_2$ multilayers can be calculated using the EMT,

$$\mathbf{\varepsilon} = \begin{pmatrix} \varepsilon_\perp & 0 & 0 \\ 0 & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_\parallel \end{pmatrix},$$  (1)

where the subscripts $\parallel$ and $\perp$ indicate the components that are parallel and perpendicular to the $x$-$y$ plane, respectively, and these components are given by [27],

$$\varepsilon_\parallel = \frac{t_m\varepsilon_m + t_d\varepsilon_d}{t_m + t_d},$$  (2)

$$\varepsilon_\perp = \frac{\varepsilon_m t_m(t_m + t_d)}{t_m\varepsilon_d + t_d\varepsilon_m}. $$  (3)

The unique properties of such metamaterials stem from the isofrequency surface of extraordinary (transverse magnetic polarized) waves, which is given by [28]

$$\frac{k_x^2 + k_y^2}{\varepsilon_\parallel} + \frac{k_z^2}{\varepsilon_\perp} = \left(\frac{\omega}{c}\right)^2,$$  (4)

where $k_x, k_y$ and $k_z$ are wave vectors, $\omega$ is the wave frequency and $c$ is the speed of light. By tuning the parameters of $\varepsilon_m, \varepsilon_d, t_m,$ and $t_d$ such that $\varepsilon_\parallel \varepsilon_\perp < 0$, one can attain the hyperbolic regime [28].

The frequency-dependent complex permittivities of semiconductor InSb at terahertz frequencies can be described by the Drude model [29]

$$\varepsilon_m = \varepsilon(\infty) - \frac{\omega_p^2}{\omega^2 + i\omega\gamma},$$  (5)

where $\varepsilon(\infty)$ is the high-frequency permittivity, $\omega$ is the excitation frequency, $\omega_p^2 = n e^2/(m^*\varepsilon_0)$ is the plasma frequency with $n$ the free electron density, and $e$ and $m^*$ the electron’s charge and effective mass, respectively. $\gamma = 1/\tau$ is the carrier momentum relaxation rate and $\tau$ is the average collision time of the charge carriers. For undoped InSb at 300 K, $\varepsilon(\infty) = 15.68$, $\gamma/(2\pi) = 0.05$ THz, $\omega_p/(2\pi) \approx 2.8$ THz [29,30]. By using Equation (5), the real and imaginary parts of the permittivity of InSb are shown by Figure 1b, which are similar to those of metals in the visible and near-infrared.

We take the dielectric constant of SiO$_2$ to be $\varepsilon_d = 3.8$, and the thicknesses of InSb and SiO$_2$ layers to be $t_m = t_d = 0.1$ $\mu$m. With Equations (2) and (3), the numerically obtained dielectric tensor components from the above equations are shown in Figure 1c. Results show that the InSb-SiO$_2$ multilayers exhibit hyperbolic dispersion relationship for $f < 1.65$ THz, as indicated by the purple region.

All the simulations in this work were performed with finite-difference-time-domain (FDTD) method based on MEEP codes. The structure under study is illuminated by terahertz plane wave polarized along the $x$ direction, and the perfect matching layers were adopted as the boundary conditions for all the three directions. A uniform mesh size of 20 nm in the $z$ direction and 100 nm in the $x$ and $y$ directions was used for the multilayer region with hole arrays. We take the substrate to be polyimide (PI) with a refractive index of $n_{sub} = 1.8$, take the normally incident terahertz wave to be of Gaussian profile with unitary electric field amplitude ($|E_0| = 1$). The length and width of the gold dipole antenna are $L = 50$ $\mu$m and $w = 4$ $\mu$m, respectively, which has been optimized so as to be resonant at the frequency of 1.62 THz, at which the metamaterial composed of the InSb-SiO$_2$ multilayers has hyperbolic dispersion relationship. The thickness of the gold antenna is $t_{Au} = 0.2$ $\mu$m and the gap width is $g = 1$ $\mu$m. The radius and period of the hole arrays are $r = 0.3$ $\mu$m and $p = 0.9$ $\mu$m,
respectively. The number of InSb and SiO$_2$ layers is set to be $N = 11$. Please note that here $N$ is an odd number since we have InSb on the top and the bottom of the InSb-SiO$_2$ multilayers.

3. Results and Discussion

Figure 2 shows the simulated near-field distributions in the $y = 0$ or/and $z = 1.2\, \mu m$ cross sections. It is clear that the terahertz electric field intensity in the antenna gap has been greatly enhanced, no matter the InSb-SiO$_2$ multilayers with/without the hole array is sandwiched between the gold dipole antenna and the substrate or not. For the conventional terahertz antenna which directly sits on the PI substrate, the electric field intensity in the gap is enhanced to be $1.12 \times 10^4$ of the incidence intensity, as shown by Figure 2a,d,g. By sandwiched with the HMM composed of the InSb-SiO$_2$ multilayers, Figure 2b,e,h shows that the enhancement is slightly increased to $1.85 \times 10^4$, corresponding to 50% improvement compared with the conventional terahertz dipole antenna. By further drilling periodic hole arrays in the HMM, as illustrated in Figure 1, Figure 2c,f,i shows that the enhancement can be further increased to $3.65 \times 10^4$, more than three times of that for the conventional antenna. Therefore, simulations reveal that by introducing the HMM with periodic hole arrays between the terahertz dipole antenna and the substrate, the near-field intensity localized in the antenna gap can be further enhanced by more than three times. Please note that quantitatively similar enhancement can also be achieved by using square-shaped periodic hole arrays.

Figure 2. Comparison of three configurations on electric field intensity enhancement. (a,d,g) The gold dipolar antenna sits on the PI substrate directly. The antenna and the substrate is buffered by (b,e,h) the HMM composed of the multilayer structure, or (c,f,i) by the HMM with hole array structure. (a-c) side view at $y = 0$, (d-f) top view at $z = 1.2\, \mu m$, and (g-i) line view at $y = 0$ and $z = 1.2\, \mu m$. The red horizontal lines indicate the value of field enhancement in the gap.

To understand the origins of this near-field enhancement, we further plot the dominant in-plane and out-of-plane components of the electric field in Figures 3 and 4. Results show that $E_y$ is negligible, $|E_x|^2$ in the gap of the conventional antenna is greatly enhanced to $1 \times 10^4$, whereas $|E_z|^2$ is very weak (only 12). In other words, $E_x$ dominates the near field, consistent with the literature [11]. However, for the proposed antenna structure, both the electric field components are greatly enhanced: $|E_x|^2 = 2.4 \times 10^4$, $|E_z|^2 = 1.5 \times 10^4$. Compared with the conventional antenna, $|E_x|^2$ is doubled, whereas $|E_z|^2$ is enhanced by three orders of magnitude such that it is now comparable to $|E_z|^2$. Figure 3a,b shows that the $|E_x|^2$ energy transmitted through the gap of the conventional dipole antenna is efficiently reflected back by the HMM with periodic hole arrays, resulting in double enhancement.
of the near-field intensity in the gap. A similar reflection effect also occurs for the $E_z$ component, as shown by Figure 3c,d.

![Figure 3](image_url)

**Figure 3.** Local field enhancement contributed from electric field components $E_x$ and $E_z$ in side view at $y = 0$. The gold antenna (a,c) directly sits on the PI substrate, or (b,d) sits on the PI substrate buffered by the HMM with hole array.

![Figure 4](image_url)

**Figure 4.** Electric field components $E_x$, $E_y$, $E_z$ at $y = 0$ and $z = 1.2 \mu m$, highlighting the totally negligible $E_y$ component and the field enhancement in the gap.

Figure 5a shows that the gap width $g$ plays a key role on the near-field enhancement. In above discussions, we take $g = 1 \mu m$ and obtain three times further enhancement compared with the conventional antenna. As $g$ increases, the near-field enhancement factors for both the proposed and the conventional antennas decrease, consistent with the literature. Their ratios also decrease from 3.3 to 2.2, indicating smaller enhancement due to the introduction of the HMM with periodic hole arrays.

Figure 5b shows that the large near-field enhancement factor can be achieved only for $t_m/t_d = 1:1$, and that the enhancement factors are small for both $t_m/t_d = 1:2$ and $t_m/t_d = 2:1$. Please note that for fair comparison, the individual layer thicknesses are properly chosen such that the InSb-SiO$_2$ multilayers have exactly the same total thicknesses for these different values of $t_m/t_d$. To understand this interesting phenomenon, we turn to the effective relative permittivities expressed by Equations (2) and (3). As we have shown in Figure 1c, the InSb-SiO$_2$ multilayers with $t_m/t_d = 1:1$ have hyperbolic dispersion relationship since $\epsilon_{||}|\epsilon_{\perp}| < 0$ at $f = 1.6$ THz. For both $t_m/t_d = 1:2$ and $t_m/t_d = 2:1$; however, Figure 5c,d shows that the InSb-SiO$_2$ multilayers exhibit elliptical dispersion relationship because of the anisotropic uniaxial effective relative permittivities at $f = 1.6$ THz, i.e., $\epsilon_{||}|\epsilon_{\perp}| > 0$ and meanwhile
\( \varepsilon_\parallel \neq \varepsilon_\perp \). Therefore, these results reveal that the hyperbolic regime of the HMM composed of the InSb-SiO\(_2\) multilayers is vital for achieving large field enhancement.

**Figure 5.** (a) Field enhancement factor versus the gap width for the dipole antenna on top of the PI substrate directly or sandwiched by the HMM with periodic hole arrays. (b) Field enhancement factor versus the ratio of the InSb and SiO\(_2\) thicknesses, \( t_m/t_d \). (c,d) Effective relative permittivities of the InSb-SiO\(_2\) multilayers with (c) \( t_m/t_d = 1:2 \) or (d) \( t_m/t_d = 2:1 \).

Please note that in this work we choose the InSb-SiO\(_2\) multilayers to form the hyperbolic metamaterial because they are typical hyperbolic metamaterial structures that are easy to fabricate through thin-layer deposition. In principle, we expect similar results can also be obtained by using other types of hyperbolic metamaterials.

### 4. Concluding Remarks

In conclusion, we have proposed a novel approach to further enhance the near-field intensity in the terahertz dipole antenna. It is achieved by introducing HMM with periodic hole arrays between the terahertz antenna and the substrate, where the HMM is composed of InSb-SiO\(_2\) multilayers. Fully vectoral simulation results have shown that by using this approach, the near-field intensity of a conventional dipole antenna can be further enhanced by more than three times. The greatly enhanced near-field intensity can improve the sensitivity of terahertz detectors or sensors. Simulations have also revealed that this enhancement originates from doubled \( |E_x|^2 \) and significantly enhanced \( |E_z|^2 \).

We have showed that the smaller gap width, the larger the enhancement, and that the hyperbolic characteristic of the multilayers is vital for achieving large enhancement. Although we have focused on terahertz dipole antennas, we believe this approach should be applicable for other types of antennas. The proposed approach should also be applicable for other spectral regimes. For example, in the visible or near-infrared regime, one can shrink the size for such short waves according to the electromagnetic scaling law, which requires that the ratio of the geometric length to the wavelength is the same for different electromagnetic wave regimes. Furthermore, the semiconductor InSb used for the terahertz should also be replaced with noble metal gold for the visible. This is because InSb at THz frequencies and gold in the visible have similar permittivities \([29]\). A possible problem could be the structure size is so small that it may pose difficulties in fabrication. Therefore, we expect this work will advance the design of terahertz antennas, as well as antennas the visible and near-infrared regimes, which are widely used in biosensing and detecting applications.
Author Contributions: Conceptualization, C.C. and G.L.; methodology, C.C., W.C., Y.L., and G.L.; software, C.C., W.C., and G.L.; investigation and data analysis, all authors; writing—original-draft preparation, C.C. and G.L.; writing—review and editing, all authors; supervision, Y.L. and G.L.

Funding: This research was funded by the Shenzhen Research Foundation (Grant No. JCYJ20160531174039457, JCYJ20150925163313898, and JCYJ20160510154531467), the National Key Research and Development Program of China (No. 2017YFC0803506), and the Youth Innovation Promotion Association of the Chinese Academy of Sciences (No. 20160320).

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

References
1. Jepsen, P.U.; Cooke, D.G.; Koch, M. Terahertz spectroscopy and imaging—Modern techniques and applications. Laser Photonics Rev. 2011, 5, 124–166. [CrossRef]
2. Skvortsov, L.A. Standoff detection of hidden explosives and cold and fire arms by terahertz time-domain spectroscopy and active spectral imaging (review). J. Appl. Spectrosc. 2014, 81, 725–749. [CrossRef]
3. Zhong, H.; Redo-Sanchez, A.; Zhang, X.C. Identification and classification of chemicals using terahertz reflective spectroscopic focal-plane imaging system. Opt. Express 2006, 14, 9130–9141. [CrossRef] [PubMed]
4. Shen, Y.C. Terahertz pulsed spectroscopy and imaging for pharmaceutical applications: A review. Int. J. Pharm. 2011, 417, 48–60. [CrossRef] [PubMed]
5. Xu, W.; Xie, L.; Ying, Y. Mechanisms and applications of terahertz metamaterial sensing: A review. Nanoscale 2017, 9, 13864–13878. [CrossRef] [PubMed]
6. Vicarelli, L.; Vitiello, M.S.; Coquillat, D.; Lombardo, A.; Ferrari, A.C.; Knap, W. Graphene field-effect transistors as room-temperature terahertz detectors. Nat. Mater. 2012, 11, 865–871. [CrossRef]
7. Al-Naib, I. Biomedical sensing with conductively coupled terahertz metamaterial resonators. IEEE J. Sel. Top. Quantum Electron. 2017, 23, 4700405. [CrossRef]
8. Massiot, I.; Vandamme, N.; Bardou, N.; Dupuis, C.; Lemaître, A.; Gamelin, D.; Collin, S. Metal nanogrid for broadband multiresonant light-harvesting in ultraslim GaAs layers. ACS Photonics 2014, 1, 878–884. [CrossRef]
9. Sarma, R.; Campione, S.; Goldflam, M.; Shank, J.; Noh, J.; Smith, S.; Smith, S.; Ye, P.D.; Sinclair, M.; Klem, J.; et al. Low dissipation spectral filtering using a field-effect tunable III–V hybrid metasurface. Appl. Phys. Lett. 2018, 113, 06110. [CrossRef]
10. Vasa, P.; Lienau, C. Strong light–matter interaction in quantum emitter/metal hybrid nanostructures. ACS Photonics 2018, 5, 2–23. [CrossRef]
11. Zhang, R.; Chen, Q.; Liu, K.; Chen, Z.; Pikwell-MacPherson, E. Terahertz microfluidic metamaterial biosensor for sensitive detection of small volume liquid samples. IEEE Trans. Terahertz Sci. Technol. 2019, 9, 209–214. [CrossRef]
12. Kinkhabwala, A.; Yu, Z.; Fan, S.; Avlasevich, Y.; Mullen, K.; Moerner, W.E. Large single-molecule fluorescence enhancements produced by a bowtie nanoantenna. Nat. Photonics 2009, 3, 654–657. [CrossRef]
13. Ng, B.; Hanham, S.M.; Giannini, V.; Chen, Z.C.; Maier, S.A. Lattice resonances in antenna arrays for liquid sensing in the terahertz regime. Opt. Express 2011, 19, 14653–14661. [CrossRef] [PubMed]
14. Lee, D.; Kang, J.H.; Kwon, J.; Lee, J.S.; Lee, S.; Woo, D.H.; Kim, J.H.; Song, C.S.; Park, Q.H.; Seo, M. Nano metamaterials for ultrasensitive terahertz biosensing. Sci. Rep. 2017, 7, 8146. [CrossRef]
15. Serita, K.; Matsuda, E.; Okada, K.; Murakami, H.; Kawayama, I.; Tomouchi, M. Terahertz microfluidic chips sensitivity-enhanced with a few arrays of meta-atoms. APL Photonics 2018, 3, 051603. [CrossRef]
16. Yan, X.; Yang, M.; Zhang, Z.; Liang, L. The terahertz electromagnetically induced transparency-like metamaterials for sensitive biosensors in the detection of cancer cells. Biosens. Bioelectron. 2019, 126, 485–492. [CrossRef] [PubMed]
17. Guo, W.; Wang, L.; Chen, X.; Liu, C.; Tang, W.; Guo, C.; Wang, J.; Lu, W. Graphene-based broadband terahertz detector integrated with a square-spiral antenna. Opt. Lett. 2018, 43, 1647–1650. [CrossRef] [PubMed]
18. Castilla, S.; Terrés, B.; Autore, M.; Viti, L.; Li, J.; Nikitin, A.Y.; Vangelidis, I.; Watanabe, K.; Taniguchi, T.; Lidorikis, E.; et al. Fast and sensitive terahertz detection using an antenna-integrated graphene pn junction. Nano Lett. 2019, 19, 2765–2773. [CrossRef] [PubMed]
19. Natrella, M.; Mitrofanov, O.; Mueckstein, R.; Graham, C.; Renaud, C.C.; Seeds, A.J. Modelling of surface waves on a THz antenna detected by a near-field probe. Opt. Express 2012, 20, 16023–16032. [CrossRef]
20. Razzari, L.; Toma, A.; Shalaby, M.; Clerici, M.; Zaccaria, R.P.; Liberale, C.; Marras, S.; Al-Naib, I.A.I.; Das, G.; Angelis, F.D.; et al. Extremely large extinction efficiency and field enhancement in terahertz resonant dipole nanoantennas. Opt. Express 2011, 19, 26088–26094. [CrossRef]

21. Feuillet-Palma, C.; Todorov, Y.; Vasanelli, A.; Sirtori, C. Strong near field enhancement in THz nano-antenna arrays. Sci. Rep. 2013, 3, 1361. [CrossRef] [PubMed]

22. Savoini, M.; Grubel, S.; Bagiante, S.; Sigg, H.; Feurer, T.; Beaud, P.; Johnson, S.L. THz near-field enhancement by means of isolated dipolar antennas: the effect of finite sample size. Opt. Express 2016, 24, 4552–4562. [CrossRef] [PubMed]

23. Dykaar, D.R.; Greene, B.I.; Federici, J.F.; Levi, A.F.J.; Pfeiffer, L.N.; Kopf, R.F. Log-periodic antennas for pulsed terahertz radiation. Appl. Phys. Lett. 1991, 59, 262. [CrossRef]

24. Volkov, O.Y.; Divin, Y.Y.; Gubankov, V.N.; Gundareva, I.I.; Pavlovskiy, V.V. Josephson admittance spectroscopy of log-periodic antenna at the submillimeter wavelength range. J. Commun. Technol. Electron. 2009, 54, 1310–1314. [CrossRef]

25. Singh, R.; Rockstuhl, C.; Menzel, C.; Meyrath, T.P.; He, M.; Giessen, H.; Lederer, F.; Zhang, W. Spiral-type terahertz antennas and the manifestation of the mushiake principle. Opt. Express 2009, 17, 9971–9980. [CrossRef] [PubMed]

26. Cortes, C.L.; Newman, W.; Molesky, S.; Jacob, Z. Quantum nanophotonics using hyperbolic metamaterials. J. Opt. 2012, 14, 063001. [CrossRef]

27. Sreekanth, K.V.; Biaglow, T.; Strangi, G. Directional spontaneous emission enhancement in hyperbolic metamaterials. J. Appl. Phys. 2013, 114, 134306. [CrossRef]

28. Poddubny, A.; Iorsh, I.; Kivshar, P.B.Y. Hyperbolic metamaterials. Nat. Photonics 2013, 7, 948–957. [CrossRef]

29. Giannini, V.; Berrier, A.; Maier, S.A.; Sanchez-Gil, J.A.; Rivas, J.G. Scattering efficiency and near field enhancement of active semiconductor plasmonic antennas at terahertz frequencies. Opt. Express 2010, 18, 2797–2807. [CrossRef]

30. Howells, S.; Schlie, L.A. Transient terahertz reflection spectroscopy of undoped InSb from 0.1 to 1.1 THz. Appl. Phys. Lett. 1996, 69, 550. [CrossRef]