All-Dielectric Terahertz Plasmonic Metamaterial Absorbers and High-Sensitivity Sensing

Yue Wang,*†‡ Dongying Zhu,‡∥ Zijian Cui,‡∥ Lei Hou,† Lei Lin,§ Fangfang Qu,§ Xiaoxi Liu,§ and Pengcheng Nie§

†Key Laboratory of Ultrafast Photoelectric Technology and Terahertz Science in Shaanxi, Xi’an University of Technology, Xi’an 710048, China
‡Key Laboratory of Engineering Dielectric and Its Application, Ministry of Education, Harbin University of Science and Technology, Harbin 15008, China
§College of Biosystems Engineering and Food Science, Zhejiang University, Hangzhou 310058, China

ABSTRACT: Two types of plasmonic metamaterial absorbers (PMAs) formed from patterned all-dielectric resonators are designed and demonstrated experimentally in the terahertz (THz) range. Both PMAs use a simple grating design on highly N-doped silicon. The first shows broadband absorption with near-perfect peak absorbance at 1.45 THz and a bandwidth of 1.05 THz for 90% absorbance, while the second is a dual-band absorber. Experiments show that the second absorber has two distinct absorption peaks at 0.96 and 1.92 THz with absorption rates of 99.7 and 99.9%, respectively. A fundamental cavity mode coupled to coaxial surface plasmon polaritons is responsible for the characteristics of both PMAs. Additionally, the optically tunable responses of these all-dielectric absorbers demonstrate that the absorption behavior can be modified. The quality factor (Q) values of the dual-band resonances are 4.6 and 7.8 times larger than those of the broadband PMAs, respectively, which leads to a better sensing performance. As an example, the two proposed PMAs act as high-sensitivity sensors and demonstrate considerable potential for chlorpyrifos detection. These results show that these PMAs can be used as sensors that can detect the presence of trace pesticides in adsorption analyses, among other practical applications.

1. INTRODUCTION

Metamaterials composed of artificially constructed electromagnetic materials have recently attracted considerable research interest because of their ability to produce unusual engineered electromagnetic responses that are not available in nature; the electromagnetic properties of these metamaterials can be described using effective parameters such as the effective permittivity and effective permeability.1 In electromagnetics, metamaterials are artificially engineered materials that gain their effective properties from the metamaterial structures rather than inheriting them directly from their constituent materials.2 New composite materials with subwavelength sizes and exotic electromagnetic properties that are generally unattainable in nature are being designed and produced for a variety of applications, including perfect lenses,3 cloaking devices,4 resonators,2 and agile antennas.6 Another important application of these metamaterials is in the development of spectrally selective perfect absorbers that can be used to develop high-sensitivity detectors for a variety of security-related applications, along with biosensing7,8 and tunable filter applications.9

In general, traditional perfect absorbers have taken the form of metallic resonators on a ground plane and are designed to eliminate reflections and enhance absorption.10 While major progress has been made in the development of metallic metamaterials over the past few years that can achieve multiband absorption,11 there have also been some drawbacks, such as their complex design and challenging fabrication requirements to achieve broadband operation,12 high material Ohmic losses, and anisotropic properties.13,14 Recently, all-
dielectric metamaterials have been gaining considerable attention because of their low intrinsic loss and tunable characteristics. This article presents all-dielectric perfect absorbers in which the thermal conductivity is approximately 3 orders smaller than that of metals for operation at terahertz (THz) frequencies, at which silicon with its relatively limited conductivity can support either bound surface waves or surface plasmon polaritons (SPPs). The past few years have seen substantial progress in all-dielectric plasmonic metamaterial-based photonic devices, and numerous applications, such as plasmonic sensors, have been reported. For plasmonic sensors, the quality factor (Q) serves as a measure of sensor performance, which is dependent on the shape, size, and other parameters of the resonator. Reported results have indicated that a narrow linewidth may potentially be helpful in improving the performance of these sensors.

Here, we introduce novel Si-based plasmonic metamaterial absorbers (PMAs) that are composed of a simple single-layer structure to develop a broadband absorber and a double-band absorber for use in the terahertz region. The fabricated broadband absorber shows nearly 99.9% absorbance at 1.45 THz and a bandwidth of ~1.05 THz, while the double-band absorber shows two distinctive absorption peaks at 0.96 and 1.92 THz, with absorbance rates of 99.7 and 99.9%, respectively. We show that these absorbers are dynamically controllable under optical excitation and that they have significant potential for use in biological monitoring and sensing applications. The proposed absorbers also have potential for use in improving the sensitivity of semiconductor devices.

2. RESULTS AND DISCUSSION

2.1. Structure and Design. Figure 1a shows an illustration of the PMA structure, which consists of a square array of all-dielectric rings and cylindrical disks. A scanning electron microscopy (SEM) image of the PMA structure is illustrated in Figure 1b; the grating consists of a ring (r and r1 are the outer and inner radii, respectively) and a cylinder (the radius is r2), which are deeply etched onto a silicon wafer that has been N-doped with a carrier density of $4.63 \times 10^{17}$ cm$^{-3}$. The repeat period of the grating is $p = 200 \mu$m, the dielectric substrate thickness is $t_1 = 300 \mu$m, and the metamaterial layer thickness is $t_2 = 50 \mu$m. Under these conditions, we design two types of split-ring resonators (SRRs) with different geometries and the same carrier density in the micrometer region. We set the parameters of the first grating of the broadband PMA as follows: the outer radius and the inner radius of the ring are $r = 75 \mu$m and $r_1 = 60 \mu$m and the radius of the cylinder is $r_2 = 34 \mu$m. The outer radius and the inner radius of the ring are $r = 90 \mu$m and $r_1 = 70 \mu$m and the radius of the cylinder $r_2 = 55 \mu$m for the dual-band PMA. To design and optimize the grating structures, we used the commercial software CST (a commercial electromagnetic solver), in which the permittivity of the highly doped Si is treated using the Drude dispersion model:

$$
\varepsilon = \varepsilon_0 - \frac{\omega_p^2}{\omega^2 + i\gamma \omega}
$$

where $\varepsilon_0 = 11.7$ is the intrinsic silicon dielectric constant, $\gamma = 1.72 \times 10^{13}$ s$^{-1}$ is the Drude collision frequency, $\omega_p = \sqrt{n^2e^2/m_0\varepsilon_0}$ is the plasma frequency, $n$ is the doped carrier density of silicon, and $m_0 = 0.26m_e$ is the effective mass of the carriers, which includes the contributions from the N-doped electrons. The unit cell was subject to periodic boundary conditions in the x and y planes and was open in the z direction in the free space environment. To investigate the resonant behavior of these absorbers, we obtained the transmittance ($T_{11}$) and reflectance ($R_{11}$) parameters of the metamaterials with the two different geometries and calculated their absorption ($A$) values using the equation $A = 1 - |S_{11}|^2 - |S_{21}|^2 (S_{21} \approx 0)$. The results in Figure 1c show that the narrow gap can be used to achieve double-band absorption, while the broader gap leads to broadband absorption. The performance

Figure 1. (a) Schematic of all-dielectric THz plasmonic metamaterial absorbers (PMAs). (b) SEM image of the designed PMAs. (c) Simulated transmission, reflection, and absorption characteristics of the broadband and dual-band devices. (d) Absorption spectrum as a function of gap size and frequency.
of the structure with a periodicity of 200 μm and \( r = 75 \mu m \) has been shown for the different gap parameters in Figure 1d, which presents the absorption spectrum as a function of both the gap width between the ring and the cylinder and the frequency. The dotted black line in Figure 1d indicates how the resonance bandwidth changes as the gap width increases. We chose a gap width of 26 μm, which gives rise to a broadband absorption (≥90%) of width of 1.05 THz, corresponding to 72.4% of the center frequency of 1.45 THz. The results in Figure 1d also show that the double narrow bandwidths absorption can be achieved by reducing the gap width. From a macroscopic point of view, the metamaterial layer on a Si substrate realizes the function of antireflection coating, which can reduce reflection. At the same time, the carrier density of Si is about \( 10^{17} \text{ cm}^{-3} \); such a heavily doped Si have metallic property. The THz transmittance is almost zero (Figure 1c). Thus, it can lead to a perfect absorption.

2.2. Absorption Characteristics of the PMAs. Left side panels in Figure 2a,b show the unit cell of the PMAs with different gaps. The calculated and experimental absorption spectra of the proposed broadband absorber at a 25° angle of incidence are shown in Figure 2a. The absorber can achieve more than 90% absorption over the range from 0.95 to 2.0 THz, which gives a bandwidth of 1.05 THz. The absorption peaks (∼99%) occur at 1.03, 1.45, and 1.77 THz, and the absorption is nearly 100% at three resonant peaks. It is obvious from Figure 2b that the dual-band absorber has two discrete absorption peaks located at approximately 0.96 THz (\( f_1 \)) and 1.92 THz (\( f_2 \)), which each have absorption values of more than 99.6%. The dual-band PMAs has Q factors of 1.1 (\( f_1 \)) and 1.88 (\( f_2 \)), which are 4.6 and 7.8 times larger than the Q factor of the broadband PMAs, respectively. The difference in size caused by the PMA manufacturing process, or the error caused by the measurement itself, is the cause of inconsistency between the experimental results and the simulation results. It is apparent that the change of bandwidth depends on the gap width. The broadband operation can be obtained by lowering the Q factor value, which can be achieved through overlapping multiple resonant modes by changing the inner radius of the ring and the radius of the cylinder.

2.3. Electric and Magnetic Field Profiles. Electromagnetic simulations are performed to resolve the spatially distributed losses in the cavity at the resonance frequency. These simulations can be computed using a frequency-domain solver to simulate an infinite array. Figure 3 clearly shows that the electric field of the broadband PMAs reaches a maximum at resonance at 1.45 THz. It can be inferred from Figure 3c that at resonance most of the incident energy is absorbed by the center pillar because of the strong current induction associated with the coaxial SPP mode. A relatively weak electric field can be observed along the narrowed cavity edges. To provide a clear understanding of the nature of the dual-band absorption in the designed structure, the calculated electric field and magnetic field (in the plane where \( z = 0 \)) distributions corresponding to the two absorption maxima (\( f_1 \) and \( f_2 \)) are presented in Figure 4. As shown in Figure 4a, the distributions of the electric field in mode \( f_1 \) are mainly focused on the dielectric layer of the absorber, which means that mode \( f_1 \) is the fundamental resonance mode of the proposed structure. For mode \( f_2 \), we see that the electric field (Figure 4b) is...
distributed over both the center of the unit cell area between the units and on the dielectric layer, where the resonance is weaker than that of \( f_1 \). Comparing the magnetic field distributions of Figure 4c,d, for a higher frequency at 1.92 THz, the absorption peaks are derived from the coupling of multiple modes of the resonator.

2.4. Dispersion Behavior of the PMAs. Further insights into the responses of these cavities can be gained from examination of the dispersion behavior of coaxial plasmonic waveguides. We derive an approximate dispersion equation to establish an explicit connection between a structure with a coaxial cross section, which thus has a concentric geometry, and a semiconductor–insulator–semiconductor (SIS) structure with a simpler planar geometry. The proposed method has broad applicability and can also be extended to provide further insights into more complex concentric waveguide structures. Consider a SIS structure that is formed using the same metals and dielectric materials as the coaxial structure and with a gap \( g \ll r_1, r_2 \); the approximate dispersion model of this structure can be expressed in the form \(^2\)

\[
\tan h \frac{k_y g}{2} = -\frac{k_x \varepsilon_1}{k_x \varepsilon_2}
\]

where \( \varepsilon_1 = \varepsilon_1(\omega) \) represents the dielectric function of the semiconductor and \( \varepsilon_2 \) is the positive, real dielectric constant of the insulator. \( k_x = \sqrt{(\beta_{\text{SIS}}^2 - \varepsilon_1 k_0^2)^2}, i = 1, 2 \), where \( k_0 \) is the wave vector of free space. For these coaxial plasmonic waveguides, we assume that the propagating mode has a total wave vector that is determined by the SIS dispersion relation given in ref \(^2\)

\[
\beta^2 + k_y^2 = \beta_{\text{SIS}}^2
\]

\[
k_y 2\pi r = 2\pi \mu
\]

where \( \beta \) is the wave vector component along the propagation axis (perpendicular to the cross-sectional plane) and \( k_y \) is the transverse component in the cross-sectional plane. In the above expression, \( r = (r_1 + r_2)/2 \) and \( \mu \) is an integer that represents the angular momentum. By combining eqs 2–4, we obtain the dispersion of the coaxial plasmonic waveguides as follows

\[
\tan h \left( \beta_{\text{SI}}^2 + \left( \frac{\mu}{r} \right)^2 - k_y^2 \frac{g}{2} \right) = -\frac{\varepsilon_1 \sqrt{\beta_{N}^2 + (\mu/r)^2 - k_y^2 \varepsilon_2}}{\varepsilon_1 \sqrt{\beta_{N}^2 + (\mu/r)^2 - k_y^2 \varepsilon_2}}
\]

This expression allows us to estimate all features of the dispersion behavior of the deep subwavelength modes that are supported by the coaxial structure. The condition for plasmonic resonance can be approximated as \( \beta_N = (2N + m)\pi/2t_4 \) \((N = 0, 1, 2, ...), \) where \( t_4 \) is the cavity depth and \( m \) represents the phase change upon reflection at both ends of the cavity \((m = \{0, 9, 1\}) \) for the plasmonic and perfect electric conductor (PEC) boundaries, respectively. Based on the resonance condition and the dispersion relation, these cavities are expected to exhibit their fundamental resonance at a wavenumber of \( \beta_0 = 2.826 \times 10^4 \) rad/m. Because of the strong field confinement, the dispersion curve of the plasmonic waveguide \( \beta \) lies to the right of the PEC waveguide dispersion curve. From Figure 5, the above wavenumber corresponds to a frequency of 1.36 THz, which is in good agreement with the resonance frequency observed from both the experimental and numerical results. For the absorbers, resonant frequencies corresponding to eight different thicknesses are selected to correspond to the theoretically calculated values. In Figure 5, triangles represent the resonant frequency of the double narrow-band absorber and circles represent the results for the broadband absorber. Figure 5 shows that the three absorption peaks of the broadband device correspond to the lines at \( \mu = 0, 1 \) and PEC \( \mu = 1 \), respectively, while for the narrow-band absorber, the first absorption peak corresponds to \( \mu_1 = 0 \) and the second absorption peak corresponds to the line where PEC \( \mu_1 = 2 \). This means that the third peak of the broadband absorber and the second absorption peak of the narrow-band absorber have the same resonance mode, similar to metal absorbers. \(^3\)

2.5. Photoexcitation of the All-Dielectric PMAs. To ease the understanding of the phototunable capabilities of the proposed absorbers, we perform full-wave electromagnetic simulations. Analysis of the carrier density distribution indicates that we are unable to excite the all-dielectric PMA structure homogeneously using the pump beam, which thus necessitates consideration of the carrier density gradient in our simulation. \(^3\) Therefore, we divide the grating layer into 10 slices, where each slice has a thickness of 5 \( \mu m \), as shown in the graph inset in Figure 6b. The carrier density distribution in silicon along the z direction is calculated using

\[
n_\text{d}(z) = \frac{1}{E_\text{ph}} \times \frac{df(z)}{dz} = \alpha f_0 e^{-\alpha z}
\]

where \( \alpha = 1020 \text{ cm}^{-1} \) is the linear absorption coefficient, \( f_0 \) is the incident fluence when assuming a circular cross-section shape for the Gaussian beam, \( E_\text{ph} \) is the photon energy of the pump beam, and \( z \) is the depth in the silicon, where \( z = 0 \) at the top surface. The simulated results for the broadband absorber and dual-band absorber under optical excitation are given in Figure 6a,b, respectively. For simplicity, we use the Drude model to describe the frequency and the carrier density; the carrier density variation in the top layer is related linearly to the pump fluence, as illustrated in the graph inset in Figure 6a. Regardless of whether the broadband PMAs or the dual-band PMAs are considered, the 90% bandwidth and the peak
absorption both show a strong dependence on increasing optical power, as shown in Figure 6c,d.

2.6. Sensing Properties of PMAs for High-Sensitivity Sensors. A schematic representation of the experiments in which the PMAs operate as sensors is shown in Figure 7a. We measured the changes in the THz radiation spectra absorbed through the metamaterials following deposition of chlorpyrifos (CPS) and demonstrated that the all-dielectric metamaterial absorbers operating at terahertz frequencies act as high-sensitivity sensors. We now describe the THz absorption experiments when 100 μL of CPS solution was dropped on the surface of the PMAs at concentrations ranging from 0.1 to 100 ppm; the solutions were prepared by dissolving appropriate amounts of CPS powder in a petroleum ether solvent. It could be found that there was a clear change of spectrum by adding chlorpyrifos solutions onto the surface of the metamaterial absorber. Although, as reported, three absorption peaks of chlorpyrifos were located at 1.47, 1.93, and 2.73 THz,32 they were not around the peaks of the metamaterial at 0.93 and 1.33 THz. However, chlorpyrifos located in the gratings induce a change in the dielectric properties of the metamaterials. As a result, changes of the amplitude and frequency in the absorption peak could be observed. Figure 7b,c shows the experimentally measured changes in the CPS (molecular formula shown in the inset in Figure 7b) solutions on the PMAs and show that the deposition location can change the absorption properties of the PMAs. For CPS concentrations ranging from 0.1 to 100 ppm, the peak absorption amplitude increased as the CPS concentration increased; we attributed this increasing peak absorption amplitude to the behavior of the antireflection coatings, which reduce the surface reflection and thus cause increased absorption. To observe these changes clearly, we partially magnified the absorption of the PMAs, with results as shown in the insets in Figure 7d–f. As shown in Figure 7d–f, the blue circle indicates the absorption coefficient detected by the pesticide at each concentration on the absorber and the red line shows that the resonant absorption shift can be approximated as a linear response that increases with the PMAs absorbance increasing. These results showed that the peak spectral intensity had good resonances with the CPS concentrations ranging from 0.1 to 100 ppm that were deposited on the surface of a semiconductor metamaterial. The regression coefficients achieved at the peak intensity were 0.8437, 0.8966, and 0.9331, as shown in Figure 7d–f, respectively. The increase in the resonant absorption is observed more clearly in the narrow-band absorber than in the broadband device because of the higher Q factors. As a consequence, the Q values for the resonance frequencies centered at \( f_1 \) and \( f_2 \) are 4.6 and 7.8 times larger than those of the broadband PMAs, which solved the problem of poor sensitivity of broadband PMA.

To summarize, we have theoretically and experimentally demonstrated the feasibility of THz-level sensing based on metamaterials for deposition detection and CPS is selected as an example target substance. THz metamaterial sensing is a universal method because it is based on dielectric sensing, while selective detection can also be made possible by functionalizing the substrates using antibodies that are specific to the target substances. The approach presented here is likely to constitute an important step toward the fabrication of high-sensitivity biosensors and lab-on-a-chip devices, thus enabling high-speed on-site detection of hazardous substances in a variety of environments.

3. CONCLUSIONS

In conclusion, we have proposed two all-dielectric terahertz plasmonic metamaterial absorbers that were formed using the same heavily doped silicon but with different geometric parameters. It was found that in addition to a broadband perfect absorber with a broad gap, a narrow-band absorber
with dual-band characteristics and high resonance absorption peaks was also fabricated. When compared with the broadband absorber, the dual-band absorber has a higher $Q$ factor, which means that the proposed absorber has significant potential for use in sensor applications. Using these metamaterial absorbers, we experimentally observed clear shifts in the absorption following the deposition of CPS (where concentrations down to 0.1 ppm could be detected). Furthermore, we proposed and studied the optical tunability of these two types of absorbers via simulations, which highlighted a new strategy for control of dielectric metamaterials and demonstrates a potential approach to achieve device reconfigurability for future applications.

4. EXPERIMENTAL SECTION

4.1. Fabrication of the All-Dielectric PMAs. The all-dielectric terahertz PMAs were fabricated on an n-type doped silicon wafer using conventional photolithography and deep reactive-ion etching based on the large-scale microfabrication techniques. After cleaning the silicon wafers with acetone followed by dehydration baking, a 4 μm-thick layer of photoresist (AZ6130) was spin-coated on top of the wafer. Photolithography is used to achieve the pattern of the microstructure after soft-baking on a hotplate. Then, the sample was exposed to light at an optical density of 10 mJ/cm$^2$ for 3 s. The exposed wafer was developed for 40 s to create openings for the etching, and a mixture of SF$_6$ (450 sccm) and C$_4$F$_8$ (190 sccm) gases was alternatively permitted into a high vacuum chamber and ionized by applying radio frequency power toward the silicon wafer to create deep and smooth trenches in the silicon wafer. Finally, the wafer was cleaned with acetone to remove the photoresist and polymer residue.

4.2. Pesticide Sample Preparation. CPS standard substances were in the form of solid powder (analytical grade, $\geq 99.0\%$), homogenized in an agate mortar, and sieved with 100 mesh; CPS and petroleum ether were used as a solute and solvent, respectively. First, a CPS sample in solution with a concentration of 100 ppm in petroleum ether was prepared by mixing 5 mg of solid-state powder of CPS standard with 50 mL of petroleum ether. Then, the CPS solutions in concentrations of 0.1, 1, 10, 50, and 100 were prepared by dilution with the 100 ppm solvent. Finally, the prepared CPS solutions were uniformly mixed by a centrifugal oscillator.

4.3. Characterization of the All-Dielectric PMAs. The THz absorption coefficient and refractive index spectra in the frequencies of 0.2–3 THz were characterized using terahertz time-domain spectroscopy (THz-TDS) based on photo-
conductive antennas. CTT-1800 (China Communication Technology Co., Ltd., Shenzhen, China) consists of an ultrashort pulse fiber laser, a laser-gated photoconductive semiconductor emitter, and a laser-gated photoconductive semiconductor receiver. It uses the ultrafast laser sources and semiconductor-based detection systems. The central wavelength of the ultrashort pulse fiber laser is 780 nm, the pulse width is 54 ps, and the scanning precision is 1 μm. Experiments were conducted at room temperature of 15–30°C, and dry nitrogen was filled into the sample bin to avoid the influence of moisture. The average spectrum of 900 time-domain scans with PE as a reference is obtained as the spectrum of the tested sample. PE is an ideal mixture because it has extremely low absorption of THz radiation and therefore has no effect on the location of absorption peaks of the pesticides.

**AUTHOR INFORMATION**

**Corresponding Author**
*E-mail: wangyue2017@xaut.edu.cn.*

**ORCID**
Yue Wang: 0000-0003-2232-2783

**Author Contributions**
D.Z. and Z.C. contributed equally.

**Notes**
The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

The authors acknowledge financial support from the National Natural Science Foundation of China (NSFC) (61975163, 61575161), the Open Project of Key Laboratory of Engineering Dielectrics and Its Application, Ministry of Education (KEY1805), and the Postdoctoral Scientific Research Development Fund of Hefei University of Science and Technology, China (LBH-Q16119). The authors acknowledge Dr. Bo Wang (Institute of Physics, Chinese Academy of Sciences) and Dr. Yi Pan (Shenzhen Institute of Terahertz technology and Innovation) for the technical support.

**REFERENCES**

1. Engheta, N.; Ziolkowski, R. Electromagnetic Metamaterials: Physics and Engineering Explorations. *IEEE Antennas Propag. Mag.* 2006, 49, 137.
2. Shi, H. A. Metamaterials: a personal view. *Radio Eng.* 2009, 18, 90.
3. Pendry, J. B. Negative refraction makes a perfect lens. *Phys. Rev. Lett.* 2000, 85, 3966–3969.
4. Schurig, D.; Mock, J. J.; Justice, B. J.; Cummer, S. A.; Pendry, J. B.; Starr, A. F.; Smith, D. R. Metamaterial electromagnetic cloak at microwave frequencies. *Science* 2006, 314, 987–980.
5. Mccoy, J.; Engheta, N.; Hoorfar, A. High impedance metamaterial surfaces using Hilbert-curve inclusions. *IEEE Microwave Wireless Compon. Lett.* 2004, 14, 130–132.
6. Giannini, V.; Berrier, A.; Maior, S. A.; José, S.; Jaime, G. R. Scattering efficiency and near field enhancement of active semiconductor plasmonic antennas at terahertz frequencies. *Opt. Express* 2010, 18, 2870–2874.
7. Qin, J.; Xie, L.; Ying, Y. A High-Sensitivity Terahertz Spectroscopy Technology for Tetracycline Hydrochloride Detection using Metamaterials. *Food Chem.* 2016, 211, 300–305.
8. Liu, N.; Mesch, M.; Weiss, T.; Hentschel, M.; Giessen, H. Infrared Perfect Absorber and Its Application As Plasmonic Sensor. *Nano Lett.* 2010, 10, 2342–2348.
9. Zhu, W. M.; Liu, A. Q.; Bourrouina, T.; Tsai, D. P.; Teng, J. H.; Zhang, X. H.; Lo, G. Q.; Kwong, D. L.; Zheludev, N. I. Microelectromechanical Maltese-cross metamaterial with tunable terahertz anisotropy. *Nat. Commun.* 2012, 3, No. 1274.
10. Tao, H.; Bingham, C. M.; Pilon, D.; Fan, K.; Strikwerda, A. C.; Shrekenhamer, D.; Padilla, W. J.; Zhang, X.; Averitt, R. D. A dual band terahertz metamaterial absorber. *J. Phys. D: Appl. Phys.* 2010, 43, No. 225102.
11. Ye, L. F.; Zeng, F.; Zhang, Y.; Liu, Q. H. Composite graphene-metal microstructures for enhanced multiband absorption covering the entire terahertz range. *Carbon* 2019, 148, 317–325.
12. Ye, L. F.; Chen, X.; Cai, G. X.; Zhu, J. F.; Liu, N.; Liu, Q. H. Electrically tunable broadband terahertz absorption with hyperbolic-patterned graphene metasurfaces. *Nanomaterials* 2018, 8, No. 562.
13. Singh, R.; Cao, W.; Al-Naib, I.; Cong, L.; Withayachumnankul, W.; Zhang, W. Ultrahighly efficient terahertz sensing with high-Q Fano resonances in metasurfaces. *Appl. Phys. Lett.* 2014, 105, No. 171101.
14. Khurgin, J. B.; Sun, G. Practicality of compensating the loss in the plasmonic waveguides using semiconductor gain medium. *Appl. Phys. Lett.* 2012, 100, No. 011105.
15. Fan, K.; Suen, J. Y.; Liu, X.; Padilla, W. J. All-dielectric metasurface absorbers for uncooled terahertz imaging. *Optica* 2017, 4, 601.
16. Lan, C.; Bi, K.; Li, B.; Zhao, Y. J.; Qu, Z. W. Flexible all-dielectric metamaterials in terahertz range based on ceramic microsphere/PMDS composite. *Opt. Express* 2017, 25, 29155.
17. Howes, A.; Wang, W.; Kravchenko, I.; Valentine, J. Dynamic transmission control based on all-dielectric Huygens metasurfaces. *Optica* 2018, 5, 787.
18. Gu, Y.; Xu, X. D.; Wang, F.; Zhang, M. G.; Cheng, X. M.; Jiang, Y. D.; Fan, T.; Xu, J. Salisbury Screen Terahertz Absorber Formed with an Insulator: 4-N,N-Dimethylamino-4′-N-methyl-stilbazolium Tosylate (DAST). *ACS Omega* 2019, 4, 9204–9210.
19. Ye, L. F.; Chen, Y.; Cai, G. X.; Liu, N.; Zhu, J. F.; Song, Z. Y.; Liu, Q. H. Broadband absorber with periodically sinusoidally-patterned graphene layer in terahertz range. *Opt. Express* 2017, 25, 11223–11322.
20. Deng, Y.; Wang, X.; Gong, Z.; Dong, C.; Lou, S.; Pegard, N.; Kyle, B. T.; et al. All-Silicon Broadband Ultraviolet Metasurfaces. *Adv. Mater.* 2018, 30, No. 1802632.
21. Li, Y.; An, B.; Jiang, S.; Gao, J.; Chen, Y.; Pan, S. Plasmonic induced triple-band absorber for sensor application. *Opt. Express* 2015, 23, 17607.
22. Vora, A.; Gwamuri, J.; Pala, N.; Kulkarni, A.; Joshua, M. P.; Durdu, O. G. Exchanging Ohmic Losses in Metamaterial Absorbers with Useful Optical Absorption for Photovoltaics. *Sci. Rep.* 2014, 4, No. 4901.
23. Wang, D.; Zhu, W.; Best, M. D.; Camden, J. P.; Crozier, K. B. Wafer-scale metalloconducive for total power absorption, local field enhancement and single molecule Raman spectroscopy. *Sci. Rep.* 2013, 3, No. 2867.
24. King, N. S.; Liu, L.; Yang, X.; Cerjan, B.; Everitt, H. O.; Nordlander, P.; Halas, N. J. Fano resonant aluminum nanoclusters for plasmonic colorimetric sensing. *ACS Nano* 2015, 9, 10628.
25. Li, G.; Chen, X.; Li, O.; Shao, C.; Jiang, Y.; Huang, L.; Ni, B.; Hu, W.; Wei, L. A novel plasmonic resonance sensor based on an infrared perfect absorber. *J. Phys. D: Appl. Phys.* 2012, 45, No. 205102.
26. Ye, J.; Dorpe, P. V. Improvement of Figure of Merit for Gold Nanobar Array Plasmonic Sensors. *Plasmonics* 2011, 6, 665–671.
27. Enkrich, C.; Wegener, M.; Pöllmann, S.; Burger, S.; Zschiedrich, L.; Schmidt, M.; Zhou, J. F.; Koschny, T.; Soukoulis, C. M. Magnetic metamaterials at telecommunication and visible frequencies. *Phys. Rev. Lett.* 2008, 95, No. 203901.
28. Maier, S. A. Plasmonic: Fundamentals and Applications; Springer: Academic Press: New York, 2007; pp 38–51.
29. Cattys, P. B.; Fan, S. Understanding the dispersion of coaxial plasmonic structures through a connection with the planar metal-insulator-metal geometry. *Appl. Phys. Lett.* 2009, 94, No. 231111.
(30) Withayachumnankul, W.; Shah, C. M.; Fumeaux, C.; Kaltenecker, K.; Walther, M.; Fischer, B. M.; Abbott, D.; Bhaskaran, M.; Sriram, S. Terahertz Localized Surface Plasmon Resonances in Coaxial Microcavities. Advanced Optical Materials. Adv. Opt. Mater. 2013, 1, 443–448.

(31) Zhao, X.; Wang, Y.; Schalch, J.; Duan, G.; Cremin, K.; Zhang, J.; Chen, C.; Averitt, R. D.; Zhang, X. Optically Modulated Ultra-Broadband All-Silicon Metamaterial Terahertz Absorbers. ACS Photonics 2019, 6, 830.

(32) Qu, F.; Lin, L.; He, Y.; Nie, P. C.; Cai, C. Y.; Dong, T.; Pan, Y.; Tang, P.; Luo, X. M. Spectral characterization and molecular dynamics simulation of pesticides based on terahertz time-domain spectra analyses and density functional theory (dft) calculations. Molecules 2018, 23, No. 1607.