Active Control of Terahertz Toroidal Excitations in a Hybrid Metasurface with an Electrically Biased Silicon Layer

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The active control of artificially structured metasurfaces is a promising route for solving the operation bandwidth limitation of metasurfaces due to their resonant nature. Herein, the active tunability of the toroidal response in a terahertz hybrid metasurface is proposed and experimentally demonstrated. The top metallic layer of the metasurface has a toroidal configuration and is coupled to an electrically biased phase-change silicon layer, whose conductive thickness and conductivity can be changed significantly when applying increased external current. The electrically biased hybrid metasurface shows high efficiency and complete electrical switching on the toroidal response in a broadband manner. Also, the optoelectronic metasurfaces modulated by biased currents are much easier to integrate in on-chip optical devices. The hybrid metasurface taking advantage of the silicon layer with insulating-state to conductive-state transition in optical conductivity may facilitate the development of high-performance active photonic applications in, for example, smart sensing in the terahertz regime.

1. Introduction

Metamaterials, and their 2D counterpart metasurfaces, made of a number of artificial micro/nanostructures with subwavelength dimensions, have attracted increasing interest due to the extraordinary capability for exterior light manipulation. The subwavelength thickness of metasurfaces along the propagating direction is helpful for the miniaturization of optical systems and improving the efficiency of photonic devices. As for light manipulation, one important application is the optical field localization, which is traditionally done with Fabry–Perot cavities or some echo wall modes. However, their dimensions are usually comparable to the wavelength. If the optical field can be further localized in a subwavelength scale, or the optical field can be compressed in both the spatial and time domains, it would be very beneficial for nonlinear optical devices. The investigation on metasurfaces with resonant building blocks has inspired rapid development for subwavelength optics, in which metasurfaces are used for novel wavefront engineering and extreme optical localization. Various plasmonic and Mie metasurfaces have been proposed for enhancing light–matter interactions and localizing light fields in a subwavelength volume, which is usually accompanied by the generation of high-Q-factor resonances; for example, the high-Q “trapped mode” with a sharp spectral response has been exploited for applications, including ultrasensitive sensing, high-Q filtering, and optical switching. Recently, metasurfaces/metamaterials with strong toroidal excitations have been demonstrated as a novel route for realizing extreme optical field localization and higher-Q optical responses. Different from electric and magnetic excitations in traditional multipole expansions, toroidal excitations arise from the decomposition of the momentum tensors with currents flowing on the surface of the torus along its meridians. The toroidal excitations taking advantage of weak free-space coupling properties are beneficial for achieving ultra-high-Q response in a metamaterial, which has inspired numerous applications such as metaswitches, photodetectors, metamodulators, metasensors, and nonlinear harmonic signal generators. Their unique field localization configuration is also helpful for...
avoiding the huge Ohmic dissipation on a metal surface and thus low-power nonlinear processing.\cite{44} Recently, metasurfaces with sharp spectra response arising from a distortion of bound states in the continuum (BICs) have been widely reported for the realization of extremely high-Q resonances.\cite{15-17,45} Theoretically, the $Q$-factors of BICs show infinite values in ideal conditions.\cite{38} However, in realistic material systems, only a quasi-BIC with a limited $Q$-factor can be realized due to the inevitable materials’ absorption and other perturbations.\cite{39}

Metasurfaces with high-$Q$ responses can only operate in a narrow frequency band due to their locally resonant nature. From the view of practical photonic applications, it is highly desirable to dynamically modulate the metamaterials in the subwavelength unit cells by incorporating active inclusions such as lumped elements,\cite{40} graphene,\cite{41-43} phase-change materials,\cite{44,45} and semiconductors.\cite{46,47} On the other hand, some works have proposed reconfigurable metamaterial design with Kirigami patterns or micro/nanoelectromechanical systems (MEMS) for active manipulation of electromagnetic waves.\cite{48,49} In this article, we experimentally demonstrated electrically tunable toroidal excitations in a hybrid metasurface incorporated with an active silicon layer. The enhanced toroidal dipolar response originates from the excitation of the coupled magnetic dipoles a head-to-tail configuration of the paired split ring resonators. It is found that the sharp toroidal-dominated Fano resonance can be completely switched off by active control of the carriers on the surface of the silicon layer and the conductive layer thickness. It is also found that the sharp high-$Q$ trapped toroidal mode can be understood as the distortion of the BIC. The proposed electrically controlled toroidal metasurface shows high-efficiency and complete electrical switching on the toroidal response in a broadband manner. The optoelectronic metasurface is much easier to embed into integrated chips, and it is compatible with the current established micro–nanofabrication process, which is promising for developing novel and low-cost terahertz photonic devices.

2. Results and Discussion

Figure 1 shows the proposed hybrid metasurface composed of a metallic top layer and biased silicon layer. The detailed dimensions of the metallic structure are marked with arrows in the zoomed unit cell. In the design, the terahertz wave with an electric field polarizing along the $\gamma$-direction is normally incident on the metasurface. The top metallic layer of the metasurface is with toroidal configuration on a silicon substrate. The toroidal metamolecule is composed of an I-shaped cut wire coupled with a pair of mirror-symmetrical split ring resonators, forming an enlarged double-ring resonator (DRR) with four split gaps. To realize the tunable toroidal resonance, interdigitated electrodes (30 $\mu$m wire width) are incorporated to dynamically excite the charge carriers inside the silicon substrate. The silicon carrier layer can be changed from insulating state to conductive state and thus the terahertz transmitted pulse can be significantly modulated, in which the optical properties of the tuned silicon layer perform similarly to those of phase-change materials such as VO$_2$ and germanium antimony telluride (GST).\cite{50,51} We will show later that the hybrid metasurface can be actively controlled by electrically biasing the conductivity and the thickness of the conductive layer of the phase-change silicon layer. The metallic patterns are fabricated by thermally depositing 200 nm thick platinum (Pt) on a 2000 $\mu$m thick high-resistance silicon (n-doped, 8 $\Omega$cm) substrate. A layer of 10 nm thick titanium (Ti) is deposited between Pt and silicon substrate to increase the adhesion.

We first studied the terahertz response of the hybrid metasurface of toroidal geometry considering the silicon layer not biased. A home-built finite-difference time domain (FDTD) method based electromagnetic solver was used to investigate the transmission spectrum of the proposed metasurface. In the simulations, periodic boundary conditions were set along the $x$- and $\gamma$-directions to simulate an infinite periodic array, and the UPMs were set along the $z$-direction. A plane wave was normally incident to the top surface of the proposed metasurface with a $\gamma$-polarized electric field. The permittivity of the silicon substrate is 11.9 and the DC conductivity of the Pt metal is $9.56 \times 10^6$ S m$^{-1}$. The simulated transmission spectrum of the metasurface shows an asymmetric Fano-shaped profile with a sharp change between the dip and peak (Figure 2a). A typical symmetric Lorentz-type electric dipole mode appears at higher frequency (around 0.688 THz), while another antisymmetric toroidal dipole mode occurs at lower frequency (around 0.438 THz). The near-field interference between the electric dipole (as a broadband continuum mode) and toroidal dipole (as a sharp discrete mode) results in the sharp Fano-type resonance. The inset artistic diagram in Figure 2a shows the formation of the toroidal dipolar mode under proper coupling of the magnetic response of DRRs. To excite the toroidal dipole and suppress the unwanted multipole for a high-$Q$ mode, the structural asymmetry of the DRR is introduced to ensure the excitation of the magnetic dipoles with two joint metallic loops. The currents in the two loops oscillate in opposite directions, which makes the in-plane magnetic dipoles oscillate in opposite phase. The coupling of the induced magnetic dipoles results in a toroidal dipole with a head-to-tail configuration, forming a significant enhancement of the toroidal mode. The toroidal mode is
confined in the free space and weakly couples with the incident electromagnetic field, resulting in the low radiative loss and the sharp resonance dip with a high quality factor.\(^\text{[52]}\)

To quantitatively evaluate the contributions of the multipole scatterings, we calculate the radiating power magnitude for various multipole moments induced in the toroidal metasurface. The magnitudes of relative radiating power of induced multipoles of the metasurface can be quantitatively evaluated with the multipole decomposition formula\(^\text{[15]}\) by integrating the spatially distributed current density inside a metamolecule extracted from the simulation. For simplicity, three main contributed multipoles, including electric dipole \(P_y\), toroidal dipole \(T_y\), and magnetic quadrupole \(M_{zx}\), are shown in Figure 2b.

It can be found that the electric dipole \(P_y\) shows strong scattering over the entire frequency band, indicating that the metasurface is excited by the \(y\)-polarized electric field component of the incident wave. Around the asymmetric Fano-resonant frequencies (orange region in Figure 2), the radiating power of the toroidal dipole \(T_y\) shows a considerable enhancement, which reveals the strong excitation of the toroidal mode in our metasurface. It is worth noting that the \(T_y\) plays a dominant role around the transmission peak frequency 0.458 THz when compared with all other multipoles, even stronger than the electric dipole moment \(P_y\). The constructive or destructive interferences between the \(T_y\) and \(P_y\) lead to the typically asymmetric Fano-type transmission spectrum and the sharp change between a dip and a peak. The radiating power of the magnetic quadrupole \(M_{zx}\) shows a similar frequency-dependence trend on the toroidal dipole \(T_y\), whereas the radiating intensity of the \(T_y\) is ten times bigger than \(M_{zx}\), which should be attributed to their similar coupling configurations of the magnetic dipoles on the \(zx\) plane but different radiation patterns.

To actively control the toroidal excitation, a DC current source was applied to excite charge carriers inside the n-doped silicon substrate; the surface layer of silicon can be changed from insulating state to conductive state for tunable terahertz response of the hybrid metasurface. The dynamic modulation of the hybrid metasurface and the physical picture are shown in Figure 3. The measured normalized terahertz time domain (THz TD) signals with different bias currents ranging from 0 to 2.7 A are shown in Figure 3a and the inset shows a scanning electron micrograph (SEM) photo of the fabricated metasurface. The transmission spectra of the metasurface were obtained by \(\left| |H(\omega)| = E_r(\omega)/E_i(\omega)\right|\), where \(E_r(\omega)\) and \(E_i(\omega)\) are the electric amplitudes transmitted through the metasurface and silicon substrate, respectively. Figure 3b shows the corresponding terahertz transmission spectra with the current varying from 0 to 2.7 A. When the DC current is 0 A, a typical symmetric Lorentz-type electric dipole resonance appears at higher frequency (around 0.675 THz), and an antisymmetric toroidal dipole resonance occurs at lower frequency (around 0.458 THz), which agrees well with our simulated results shown in Figure 2a. The interference between the toroidal and electric dipolar modes leads to this sharp asymmetric Fano-type transmission spectrum. When the current is less than 1.4 A, the terahertz transmission spectrum barely changes because both the thickness and conductivity of the silicon carrier layer is not large enough (behaves like an insulator) to effectively change the spectrum. Once the current exceeds a certain threshold value (about 1.4 A), the transmission spectrum changes dramatically with further increased current (see Figure 3b), which is due to the amount of carrier being so large that it can significantly increase the surface layer’s conductivity (behaves like a conductor) and the conductive layer thickness. When the current is increased to 2.7 A, the toroidal dipole mode is completely switched off and the transmittance is suppressed. The input current is high and there exists heating in experiments. This efficient terahertz wave control capability implies that our metasurface can perform as a terahertz transmission amplitude modulator with high modulation depth. For example, at frequency 0.3 THz, the transmission amplitude decreases from 96.2% to 3.0% as the current increases from 0 to 2.7 A, showing a large drop off of 93.2%.

The remarkable transmission modulation performance is due to the phase change (in its optical property) of the silicon carrier layer from insulating state to conductive state on top of the silicon substrate when applying electrically bias current, where a large number of charge carriers are excited. For simplicity, we consider the charge carriers uniformly distributed on top
of the silicon substrate with a thickness of $h$ and a conductivity of $\sigma$ (see Figure 3c). To estimate the thickness and conductivity of the carrier layer under different current biases, we first extracted the current-dependent transmission amplitude and Fano resonance intensity from the experimentally measured results. The transmission amplitude is chosen at frequency of 0.3 THz because it is far from the resonant region. The Fano resonance intensity is obtained using $(t_p - t_d)/t_p$, where $t_d$ and $t_p$ are the transmission dip and peak of the Fano resonance, respectively. We then performed numerical simulations to simulate this current-dependent trend (including terahertz transmission amplitude changes and Fano resonance intensity changes) by simultaneously changing the thickness $h$ and conductivity $\sigma$. The optimized calculated results are shown in Figure 3d. We note that the measured transmission spectrum is different from the simulated results under zero bias current. This is because the incident light is not a perfect linear polarized light along the $y$-direction and there will be mixing in the measured result with different components. Also, the experimental sample is not exactly the same as the designed perfect structure due to errors in fabrication processing, and the material loss or dispersion in real experiments may bring difference in measured and simulated spectra. However, the general features of the measured spectra and the changing trend of experimental results agree well with the numerical simulation. When the biased current was 2.7 A, we found that the average thickness and conductivity of the silicon carrier layer reached about 1000 $\mu$m and 62 S m$^{-1}$, respectively, showing the excellent modulation performance of our metasurface.

The unique property of the hybrid metasurface is the sharp high-$Q$ trapped mode due to the special toroidal configuration and coupling mechanism. In fact, this kind of high-$Q$ resonance originating from the coupling between two modes has attracted much interest in recent years, and can also be understood as one case of the bound states in the continuum (Friedrich–Wintgen BIC). In the studied metasurface, the asymmetric Fano resonance profile is originating from the constructive or destructive interference between a sharp resonance (discrete state) and the continuum (background), and the parameter $d$ is crucial for constructing the high-$Q$ trapped mode. We analyzed the influence of the crucial parameter $d$ on the terahertz transmission amplitude (see Figure 4a), which exhibits similar pictures to the BIC. The
simulated transmission amplitude with different $d$ ranging from 0 to 40 $\mu$m is shown in Figure 4a. As $d$ increases, the toroidal resonance first disappears ($d = 22 \mu$m) and then reappears, and in the meantime the line width of the toroidal resonance first decreases to 0 and then increases, showing a similar trend toward BIC. Note that the transverse $T_y$ cannot be easily coupled to the normal incidence. Figure 4b shows the radiating power $T_y$ with respect to the parameter $d$ from 8 to 36 $\mu$m. We can see that the $T_y$ is greatly suppressed when $d$ is 22 $\mu$m, whereas it is significantly enhanced when $d$ deviates from 22 $\mu$m within the frequency band of interest. When further optimizing the parameter $d$ to 29 $\mu$m, $T_y$ reaches a large value, even exceeding $P_y$.

To show the influence of the crucial parameter on the $Q$-factor and dephasing time $\tau$, we calculated the $Q$-factors and $\tau$ with different $d$. The $Q$-factors of the asymmetric Fano resonance can be calculated from the ratio of the central frequency to the full width at half maxima (FWHM). Here we extracted the $Q$-factor using the characteristic frequencies of the Fano resonance (dip frequency $f_d$ and peak frequency $f_p$). The frequencies $f_d$ and $f_p$ correspond to the constructive and destructive interferences, respectively. The central frequency of the Fano resonance could be $(f_d + f_p)/2$ and the FWHM would be $|f_d - f_p|/2$. The $Q$-factor of the Fano resonance can be obtained as follows

$$Q = \frac{f_d + f_p}{|f_d - f_p|}$$

The dephasing time is another important parameter measuring the resonant mode. The dephasing time of the toroidal dipole can be calculated by $\tau = 2/|f_d - f_p|$. $Q$-factor/dephasing time as a function of the parameter $d$.

3. Conclusion

In summary, we have experimentally demonstrated the electrical tunability of the toroidal response in a terahertz hybrid metasurface composed of a top metallic layer with toroidal configuration coupled to an electrically biased phase-change silicon layer. The sharp toroidal-dominated Fano resonance can be dynamically modulated by incorporating interdigitated electrodes to excite the charge carriers inside the silicon substrate and thus change the silicon carrier layer from insulating state to conductive state. It was found that the significantly enhanced toroidal mode was excited in our metasurface and its physical insight was uncovered by the multipole decomposition. It was also found that the sharp high-$Q$ trapped toroidal mode can be understood as a distortion of the BIC. The demonstrated hybrid metasurface exploiting phase change (in optical conductivity) of the silicon layer is promising for promoting the development of high-performance active photonic applications in the terahertz regime.

4. Experimental Section

**Sample Fabrication:** A standard photolithography technique was used to fabricate the hybrid metasurface. After the silicon substrate was cleaned with acetone and isopropyl alcohol, it was dried at 100 °C for 10 min on a hot plate, and a 1.5 $\mu$m thick positive photoresist was coated on the substrate. A positive mask composed of metal patterns was aligned on the photoresist and was exposed to ultraviolet light after prebaking at 105 °C. Then it was soaked in the developer solution to develop the pattern. Later, 10 nm titanium and 200 nm platinum were deposited through the thermal evaporation method followed by the liftoff process in acetone to remove the resist.

**Experimental Measurements:** The terahertz transmission measurements were conducted using the conventional GaAs photoconductive switch-based THz-TDS system. The metasurface was located at the focus of the terahertz beam. We used a DC constant-current source to connect the interdigitated electrodes. Under various current biases, the transmitted terahertz pulses through the metasurface and the blank silicon reference were captured using the terahertz detector connected to the lock-in amplifier, and thus time-varying electric fields of the terahertz radiation were recorded. The transmission amplitude spectra were obtained by...
performing fast Fourier transformation (FFT) of the time-domain signals and normalized to those of the reference.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

high Q, phase-change metasurfaces, toroidal excitations, tunable metasurfaces

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