

Experimental Demonstration of Spoof Surface Plasmon Based THz Antennas for Huge Electric Field Enhancement

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Received: 2 November 2016 / Accepted: 9 February 2017 / Published online: 24 February 2017
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Abstract We experimentally demonstrate the fabrication and optical measurement of a novel terahertz antenna array due to the excitation of spoof surface plasmon modes. With the unit cell composed of ultrathin copper film corrugated with three rectangular grooves, the designed plasmonic antenna array fabricated on the quartz substrate clearly shows multiple plasmonic resonances, including the regular broadband dipolar-like and sharp Fano resonances. Terahertz time-domain measurements were performed and the transmission spectrum shows quite good agreement with full wave numerical simulations. These results provide direct evidence for the validity of the novel antenna design, which is expected to exhibit huge local field enhancement suggesting highly potential applications in terahertz sensing and detections.

Keywords Spoof surface plasmons · Field enhancement · Terahertz

In the optical frequencies, localized surface plasmons (LSPs), which are resonance modes existing around small metal nanoparticles [1], have been well investigated and widely employed in some technologies, e.g., surface enhanced Raman spectroscopy (SERS) [2] and surface enhanced infrared absorption spectroscopy (SEIAS) [3] by taking advantage of strong field enhancement in the near vicinity of metallic nanostructures. The excitation of the LSP modes is the key to the field enhancement at resonance, which can be tuned by the geometry of nanostructures in the shape of nanospheres,

nanorods [4], and nanoshells [5] and the dielectric environment. In the terahertz frequencies which is widely recognized as a promising regime for sensing applications and substance identifications using characteristic absorption, since the absorption cross sections of most molecules are far smaller than the terahertz (THz) wavelengths (a few hundred microns), the interactions between single molecules and THz radiations are extremely weak. It would benefit those applications a lot (e.g., enhance the sensing sensitivity and then a much smaller volume of sample is required) if the local electromagnetic field can be enhanced in a similar way as in optics and infrared. However, because metals behave more like a perfect electric conductor (PEC) and electromagnetic waves are loosely bounded to the metal-dielectric interface in the form of Zenneck wave in the THz band, regular LSPs cannot be realized using simple metallic geometries as in the optical frequencies. In order to generate highly confined surface waves with resonance mode at these lower frequencies, periodically textured closed surfaces [6] and cavities [7] have been proposed and experimentally demonstrated at microwave frequencies [8] supporting artificial surface waves termed as “localized spoof surface plasmon (LSSP)” [9] [10], which resemble the localized surface plasmons in the optical frequencies. However, due to the difficulty of using mechanical or laser-ablation methods to fabricate those curved structures working in terahertz regime in which the wavelength typically ranges from 30 μm to 3 mm, the fabrication of three-dimensional structures on metal surfaces and the use of them in practical THz photonic applications is limited.

Quite recently, we theoretically proposed a two-dimensional (2D) concept of retardation-based corrugated metal stripe antennas and numerically demonstrated that sharp spoof surface plasmon resonances with strongly local field enhancement can be achieved in the THz regime [11]. These spoof surface plasmon (SSP) based terahertz antennas can be

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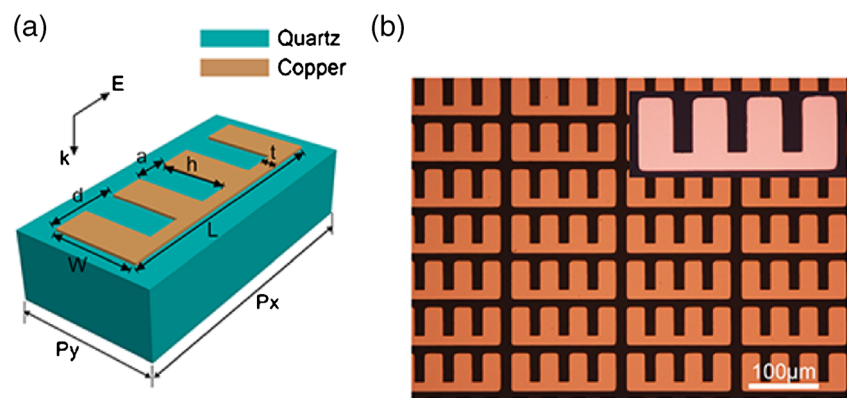
easily realized on very thin metal films that can be deposited using regular evaporation facilities. Rectangular grooves can be made perforating the metal layer and numerical simulations show that strong terahertz hotspots can be realized within these 3D antennas [12]. Further results also suggest the properties of these antennas are weakly affected by the metal thickness as long as it is larger than the metal skin depth at THz frequencies. For a single SSP antenna, the scattering from it is to all directions and it is hard to characterize this property of antenna in the terahertz regime due to the lack of integration sphere. A two-dimensional array of antennas will result in the scattering to be only in the backward and forward directions in the form of reflection and transmission, and can be easily measured by terahertz time-domain system (THz-TDS). Then, the array of SSP-based THz antennas can provide a perfect platform for THz sensing and other applications and one only needs to pay attention to the reflection/transmission spectra. In this paper, we experimentally demonstrate the fabrication of the antenna array on the quartz crystal substrate and the measurement of their transmission spectrum using a THz-TDS. The results agree quite well with the predictions from numerical simulations.

Figure 1a illustrates one unit-cell of the SSP antenna array on top of the quartz crystal substrate and it consists of a copper stripe corrugated with three rectangular grooves. The investigated THz plasmonic antenna array is top-cladded with air and the groove width is uniform in the direction normal to the substrate, which makes it very convenient for use in THz sensing since the specimen can be added onto the structure dropwise or by spin coating. The fabrication is quite straightforward and easy using regular microfabrication facilities. After spin coating of the photoresist on a 500 μm thick Z-cut quartz crystal substrate, the pattern of the antenna array was defined in the resist layer using a laser direct writing system. A copper layer with the thickness around 400 nm plus a 5 nm layer of chromium for adhesion were then thermally evaporated onto the sample, followed by the lift-off process in acetone and rinsing of the sample in isopropanol. Figure 1b

presents a typical optical microscopy image to show an overview of the fabricated structure and the inset gives an enlarged demonstration of one unit cell. The dimension of the antenna can be measured using the microscopy and the period of grooves is found to be 41.5 μm .

Before presenting the experimental results of the measured transmission spectrum for the fabricated structures, some numerical results are first shown to demonstrate their property. The transmission spectrum for the antenna array is calculated using a finite-element method (FEM) at a normal THz incidence with the polarization along the x direction and the result is shown in Fig. 2a. In the simulations, the period of groove d is set as 41.5 μm to be consistent with the fabricated structure while other geometrical parameters are related with d by the following equations $a = 0.5d$, $h = d$, $W = 1.2d$, and $L = 3.5d$. The period of antenna array along the x and y directions are chosen as $P_x = 4d$ and $P_y = 1.6d$ respectively so that one can get a near-zero transmission for the resonances of our interest. In calculations, the refractive index of quartz substrate is set as 2 and the thickness of copper film is 0.4 μm . It is clear that two resonances are supported, with one broader located at around 0.52 THz while the second resonance demonstrating a sharp Fano profile at 0.793 THz. These two resonances are consistent with the scattering property of a single SSP antenna which has been fully investigated [12]. The origin of the two resonances is due to the reflection of excited spoof surface plasmon modes propagating along the groove array and getting reflected at both termination ends. Different orders of Fabry-Perot (FP) modes are then formed depending on the length of the antenna. The insets of Fig. 2a, b shows the x component of electric field (E_x) and z component of magnetic field (H_z) at the central plane of copper film, which demonstrates the third order property of this mode. Further results also show that the broader resonance is the first order FP resonance exhibiting a dipolar-like mode profile. This is because the propagating constant of the SSP mode at lower frequencies is very close to that of THz waves in the dielectric [10] and the SSP antenna behaves like a regular metal stripe with no corrugations.

Fig. 1 **a** Schematic diagram of the SSP antenna unit-cell. **b** Optical microscopy image of the fabricated structure



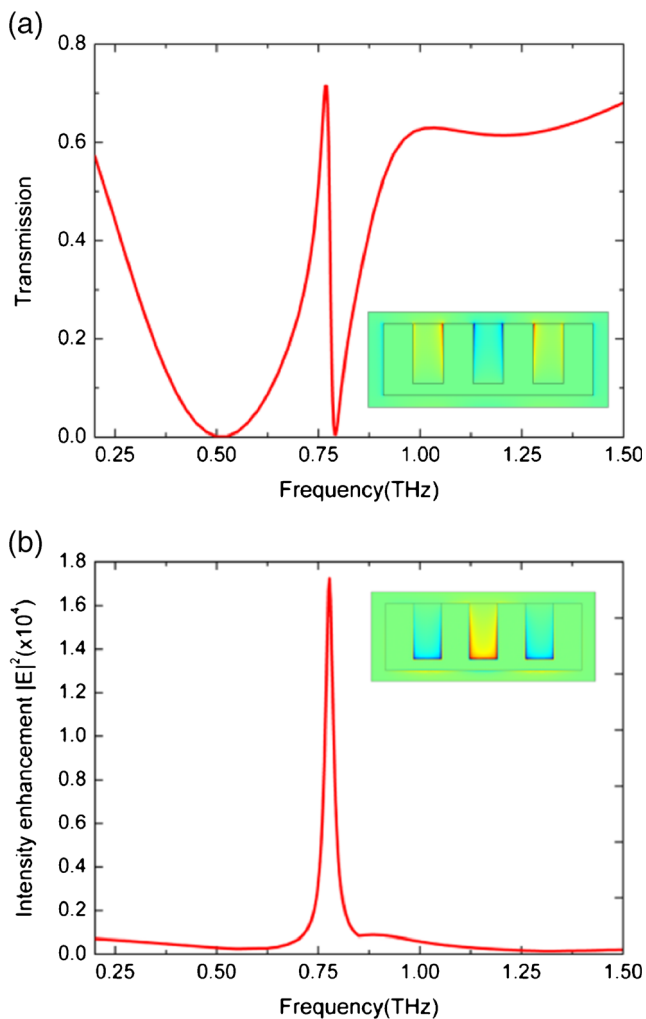


Fig. 2 FEM-calculated results for **a** transmission spectrum of the antenna array and **b** normalized electric field enhancement $|E|^2$ as a function of frequency. The insets in **a** and **b** show the distribution of electric field (E_x) and magnetic field (H_z) respectively at the central plane of copper film

The main characteristic of the SSP-based antenna is the large enhancement of electric field which will boost the interactions between terahertz radiation and substances. In reference [12], it was demonstrated that for a single SSP-based antenna, strong local field enhancement with the electric field intensity $|E|^2$ up to four orders of magnitude higher than that of the incident wave can be achieved. The maximum electric intensity for the antenna array is also calculated using the FEM method as a function of frequency and the result is shown in Fig. 2b. It is clear that at the second resonance the factor of field enhancement can reach up to 1.723×10^4 , very close to the value which can be achieved using a single antenna in a uniform dielectric environment. This huge E field enhancement is roughly at the same level in the whole copper layer, with the values slightly higher closer to the substrate due to its higher refractive index. It should be noted that for the first resonance around 0.52 THz which is a dipolar-like resonance, the field enhancement is much lower.

The smallest feature in the design is the narrow copper bar starting from the bottom of grooves to the edge of copper stripe (see Fig. 1a, the part with width labeled t). This narrow metal region provides the reflection for the transverse electromagnetic (TEM) modes propagating in individual grooves to form cavity modes which is required for the spoof surface plasmon modes [9, 10]. During the fabrication process, the bar width t can be easily affected by the exposure parameters. So, we further investigate whether the change of t will affect the properties of SSP antenna array. The transmission and electric field enhancement spectra for three different t as $0.1d$, $0.2d$, and $0.3d$ are calculated and presented in Fig. 3. It is found that for the transmission spectrum, the lower dipolar-like resonance behaves a red shift as t increases while the Fano resonance remains at almost the same position. This is because the SSP mode at the higher resonance is tightly confined within the grooves and then is less vulnerable to the geometry perturbations. It can also be seen that as t decreases and

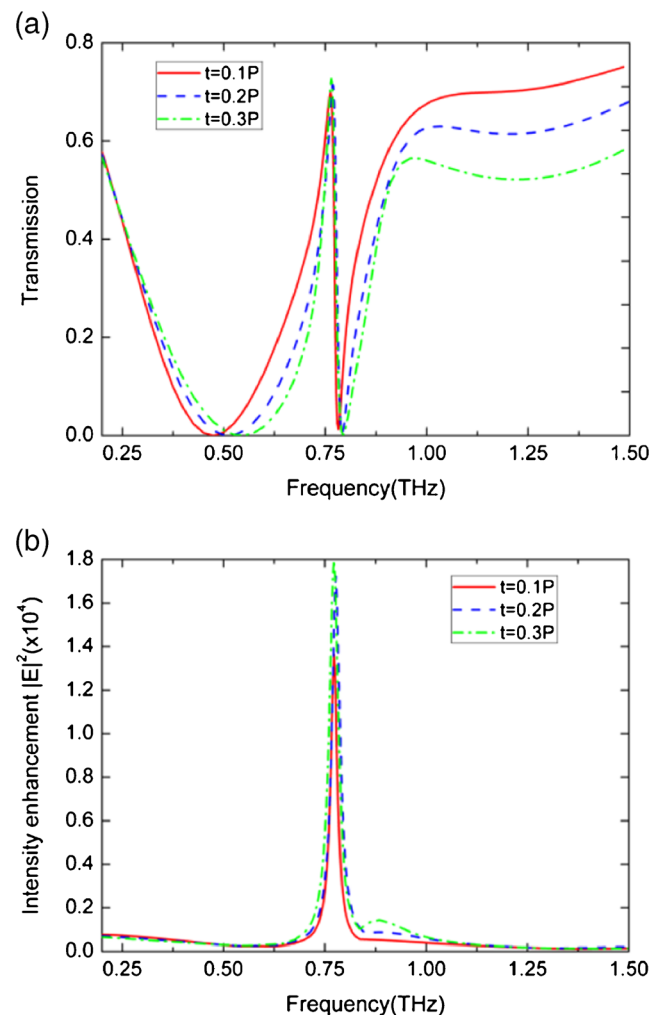


Fig. 3 **a** Transmission spectrum of periodic terahertz antenna with different remaining width of t . **b** Electric field enhancement as a function of frequency with different remaining thickness of t

increases into $0.1d$ and $0.3d$ respectively from $0.2d$, the factor of electric field enhancement at the second resonance changes from originally 1.72×10^4 to 1.36×10^4 and 1.80×10^4 . We can conclude that although the change of bar width does have some influence to the properties of SSP antenna, the effect is not very significant. So in our fabrications we simply choose a value of $t = 0.2d$, although the measured t shown in Fig. 1b turned out to be larger than that.

For the fabricated antenna array shown in Fig. 1b, a commercial THz-TDS system (Z2 from Zomega Terahertz Corp, USA) was used to measure the transmission spectrum through the sample. The Fourier-transformed spectral power of the time-domain terahertz pulse through the sample was normalized to that directly from the THz emitter to the detector, and the result was presented as the black line in Fig. 4. The red line is the FEM-calculated transmission spectrum from the SSP antenna array into the substrate whose thickness is considered as infinite. Note that the quartz crystal substrate used in our experiment has a finite thickness of $500 \mu\text{m}$ and multiple reflections happen at the top interface between air/antenna array and lower interface between quartz/air. So, the measured transmission spectrum takes into account the interference phenomenon and can be governed by the following equation:

$$T(f) = \left| \frac{t_1(f)t_2(f)}{1-r_1(f)r_2(f)e^{j2nT}} \right|^2 \quad (1)$$

where $t_1(f)$ is the frequency-dependent transmission coefficient between top air cladding and the SSP antenna array on

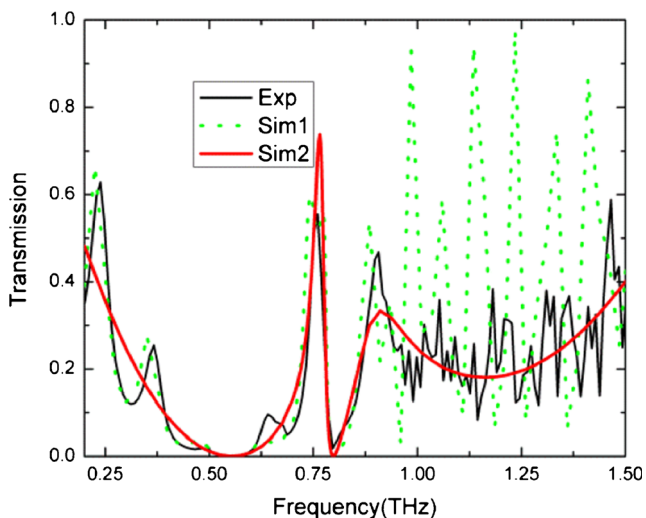


Fig. 4 Simulations (Sim1 corresponds to the results when the quartz crystal thickness of $500 \mu\text{m}$ is considered while Sim2 is for the case when quartz crystal is assumed to be infinitely thick) and experiment measurement of a terahertz antenna with measured parameters as $d = 41.5 \mu\text{m}$, $a = 14.75 \mu\text{m}$, $h = 41.5 \mu\text{m}$, $t = 14.03 \mu\text{m}$, and $L = 151.25 \mu\text{m}$

infinite-thick quartz substrate and $r_1(f)$ account for the reflection coefficient at this interface, $r_2(f)$ and $t_2(f)$ are the reflection and transmission coefficients at the quartz/air interface and n/T is the refractive index/thickness of the quartz substrate. The fringes in the black curve in Fig. 4 arise from the term of e^{j2nT} due to the reflections between the two surfaces of quartz substrate, which can be confirmed by the free spectral range (FSR) values of those fringes. We have also presented in Fig. 4 the numerical results of transmission spectrum when the thickness of the quartz crystal substrate is assumed to be $500 \mu\text{m}$. One can see similar fringes in the simulated results are also present, which further supports our conclusion about the origin of these fringes. The observable shift in the frequencies of the fringes between the numerical results and experimental results is attributed to the slight difference in the quartz crystal index used in our simulation compared to the real values. Except these fringes, the agreement between the experimentally measured transmission spectrum and numerical results is quite good, especially in the resonance frequency, bandwidth and the overall level of transmission. In practice, the fringes can be eliminated using thickness quartz crystal substrates so that the FSR is so small to be beyond the frequency resolution of THz-TDS systems. One may also notice the decrease of transmission in the higher frequency region. That is because of the small detector size in the THz-TDS system and only the normal transmitted power can be collected. In the simulations, the higher orders of diffractions are also not considered intentionally to be consistent with the experimental conditions.

The direct characterization of the local electric field enhancement that can be achieved using the investigated antennas is more complicated and requires the use of near-field probes into the vicinity of the antennas. So, we believe that an experimental measurement of the transmission spectrum showing good agreement with the numerical results can work as the proof to show the validity of the design. As a result, the high local electric field enhancement that are predicted numerically can also be expected, which will work as the basis for many applications in the context that the interactions between THz radiations and matters can be significantly improved.

As a conclusion, we fabricated in this paper the SSP based THz antenna array and measured the transmission spectrum using a THz-TDS system. Both the broad dipolar-like and sharp Fano resonances in the calculated transmission spectrum are found in the experimental results, in good agreement with the numerical results in both the resonant frequency and bandwidth. This agreement verifies our original design of the novel terahertz plasmonic antenna based on the excitation of localized spoof surface plasmon. The huge local field enhancement that can be expected from these antennas could provide the foundation for the investigation of THz nonlinear optics and light-molecular interactions [13] even when the THz radiation power is not strong enough.

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