Research Article

Simulation and Experimental Study of Terahertz Wave Transmission Characteristics Based on Periodic Metal Open Resonant Ring Structures

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Different open resonant ring structures with substrate of polyimide were designed. The transmission characteristics of the structures for terahertz wave were investigated by simulation and experiment. The results show that the transmission peak of the structures moves to high frequency with increase of thickness of the metal layer. With increase of substrate thickness, the transmission peak moved to low frequency and the transmissivity decreased. The influence of number of “C” shape open resonant rings in the unit structure on the transmission characteristics of terahertz wave was also studied. It is found that when the number of “C” shape open resonant rings increases from one to two, more transmission peaks appeared in the frequency of 0.2–2 THz. The transmissivity of the designed structures was tested by terahertz time-domain spectrometer (THz-TDS). The experimental results showed good agreement to the simulation results.

1. Introduction

Terahertz (THz) waves are electromagnetic waves with frequencies between 0.1 THz and 10 THz (wavelength between 30 μm and 3 mm) [1, 2]. Terahertz wave is located in the transition region from radio wave to infrared light in the electromagnetic spectrum [3]. It is the last band in the electromagnetic spectrum which has not been fully recognized and utilized. The basic characteristics of terahertz wave are high transmissivity, low energy, and fingerprint spectrum. In recent years, due to the development of ultrafast optoelectronic technology, various works have been carried out due to important values of terahertz waves [4–6]. With the rapid development of terahertz technology, a variety of terahertz instruments have been widely applied in medicine, military, aviation, and other fields [7–10], so the demand for high performance terahertz devices is more and more urgent.

Metamaterials and metasurfaces are effective to make modulations to terahertz waves and have drawn intensive interests of investigators for years. The terahertz metamaterial generally consists of periodic metal open resonant ring structure arrays, which have a resonant electromagnetic response [11, 12]. With this characteristic, specific terahertz wave sensors can be designed. In 1998, Ebbesen found in experiments that when a beam of light is vertically incident to a subwavelength metal hole array structure, the transmission enhancement appears in a specific wavelength range, which is contrary to the traditional classical theory of optical surgery [13]. Since then, researchers have conducted a series of simulations and experiments to modulate electromagnetic waves by using different designs, including terahertz waves. It is found that the dielectric constant of the subwavelength metal structure has a great influence on the resonant transmission frequency [14]. Sun et al. measured the refractive index of 200 μm thick copper film and 500 μm

thick aluminum film on silicon substrate by using the terahertz time-domain reflection system and found that the refractive index decreased with increase of THz frequency [15]. Ma et al. studied the transmission property of terahertz wave and dielectric response of ZnO conductive film by using THz time-domain spectrometer (THz-TDS) and obtained the frequency-related conductivity curve and refractive index curve of the film [16]. Carretero-Palacios et al. revealed the influence of thickness of metal films and dielectric constants of substrates on the transmission characteristics of porous metal mesh structures [17]. Currently, most research studies on the transmission characteristics of terahertz wave focus on the influence of different substrates on the transmission characteristics of periodic metal mesh structures [18] and the influence of the thickness of metal film on the transmission characteristics of array structures [19, 20]. However, it is found that the transmissivity of periodic metal open resonant structures still needs further improvement.

At present, most research studies focus on the realization and regulation of high transmissivity in a single frequency band which limits the applications of terahertz devices. Yen et al. designed a monolayer open resonant ring array and realized the electromagnetic resonance response. The electromagnetic resonance effect of the split-ring resonator (SRR) array was called magnetic plasmon resonance [21]. Xia et al. realized the dual frequency transmission enhancement by employing metal ring arrays [22]. There are majority works that study broadband transmissions of metasurfaces. Compared with visible light, the analysis results of wide terahertz band have important reference significance for the design and preparation of surface plasma devices, such as filters, polarizers and micronano devices.

In this study, different open resonant ring structures based on polyimide substrates are designed. The influence of the structure parameters on the transmission characteristics of the array structure was studied by simulation. The optimal structure parameters obtained from the simulation were employed to fabricate the structures. The experimental results were in good agreement with the simulation results.

2. Simulation Models

The different open resonant ring structures were designed as shown in Figure 1. The yellow area is filled with metal, and the rest is polyimide. Figures 1(a), 1(b), and 1(d) are top view of the structures and Figures 1(c) and 1(e) are side view of corresponding structures. The coordinate system for simulation is also set as in Figure 1. The thickness of the metal layer and the substrate is t and d , respectively. The other parameters of the structures can be found in Figures 1(a), 1(b), and 1(d). Copper was chosen as the metal layer because it has relatively stable chemical properties and low cost, and polyimide was chosen as the substrate.

3. Simulation Results and Discussion

3.1. Numerical Simulation. The numerical simulation was completed by using commercial software CST 2018 based on

the time-domain finite integration method. The unit structure models were established in the CST software as shown in Figure 2. The terahertz wave frequency range was set as 0.2–2 THz, which is convenient to compare the results from experiments. The background condition was selected as vacuum. The X -axis is along the direction of magnetic field or electric field, the Y -axis is along the direction of electric field or magnetic field, and the Z -axis is along the incident direction of terahertz wave, which is vertical to the unit structure surface. Periodic boundary conditions are set to make the element extend into an infinite plane with the same period in X and Y directions. The terahertz signal serves as the excitation source.

3.2. Results and Discussion. The influence of metal layer thickness on the transmission characteristics of terahertz wave was first studied. The thickness t is set as from 0.2 μm to 8 μm , and the thickness d of substrate is set as $d = 10 \mu\text{m}$. The simulation results are shown in Figure 3.

As shown in Figures 3(a), 3(b), and 3(c), with increase of metal thickness, the position of transmission peak of three structures moved to high frequency gradually and the transmissivity slightly decreased. The specific information of transmission peaks for different metal thickness is given in Table 1.

As given in Table 1, it can be found that when the metal thickness is increased from 0.2 μm to 8 μm , the movement of transmission peak is only 7 GHz, 19 GHz, and 9 GHz, respectively, for three structures. The transmissivity only decreases 0.4%, 0.11%, and 0.11%, respectively. This is because when the metal thickness is bigger than the skin depth, the resonance enhancement will be saturated according to R. Singh's study [23]. The skin depth can be calculated from following equation [23, 24]:

$$\delta = \frac{1}{\sqrt{\pi f \mu_0 \sigma_{dc}}}, \quad (1)$$

where f is the frequency at which the skin depth is defined, μ_0 is the vacuum permeability, and σ_{dc} is the DC conductivity of metal. For copper, its skin depth is 85.2 nm at 0.6 THz which is much smaller than the metal thickness, so the transmission peak moves little when the metal thickness is bigger than 1 μm .

The influence of substrate thickness on the transmission characteristics was also studied. The substrate thickness of three structures is changed from 5 μm to 25 μm , the metal thickness is selected as 0.2 μm , and the other parameters keep unchanged. The 12.5 μm was selected to compare with experimental results.

The simulation results are shown in Figure 4, and the specific information for the peaks is given in Table 2.

As given in Table 2, it can be found that for single "C" resonant ring, the transmission peaks shifted to left of 13.2 GHz from 0.672 THz to 0.540 THz when substrate thickness is increased from 5 μm to 25 μm . The transmissivity is decreased from 99.45% to 98.94%. For double "C" resonant ring, the transmission peaks shifted to left of 12.8 GHz from 0.643 THz to 0.515 THz when substrate

FIGURE 1: Schematic and dimension of open resonant ring structures with unit of μm . (a) Top view of single “C” resonant ring structure. (b) Top view of double “C” resonant ring structure. (c) Side view of “C” resonant ring structures. (d) Top view of square resonant ring structure. (e) Side view of square resonant ring structure.

FIGURE 2: Schematic of the simulation model. (a) Single “C” resonant ring structure. (b) Double “C” resonant ring structure. (c) Square resonant ring structure.

thickness is increased from $5\mu\text{m}$ to $25\mu\text{m}$. The transmissivity is decreased from 98.99% to 97.34%. For square resonant ring, the transmission peaks shifted to left of 10 GHz from 0.694 THz to 0.594 THz when substrate

thickness is increased from $5\mu\text{m}$ to $25\mu\text{m}$. The transmission rate is decreased from 99.51% to 98.82%.

It is shown that when a terahertz wave is perpendicularly incident to a specific surface structure, the excitation

FIGURE 3: Transmission spectrum for different thickness of metal layer. (a) Single “C” resonant ring structure. (b) Double “C” resonant ring structure. (c) Square resonant ring structure.

TABLE 1: Transmission peak of resonant ring with different metal layer thickness.

Structure	Thickness of metal layer (μm)	Transmission peak frequency (THz)	Transmissivity (%)
Single “C” resonant ring	0.2	0.610	99.33
	1	0.614	99.21
	4	0.615	99.16
	8	0.617	98.92
Double “C” resonant ring	0.2	0.573	98.78
	1	0.574	98.61
	4	0.583	98.58
	8	0.592	98.67
Square resonant ring	0.2	0.623	99.43
	1	0.625	99.45
	4	0.628	99.39
	8	0.632	99.32

FIGURE 4: Transmission spectrum for different thickness of substrate. (a) Single “C” resonant ring structure. (b) Double “C” resonant ring structure. (c) Square resonant ring structure.

TABLE 2: Transmission of resonant ring with different substrate thickness.

Structure	Thickness of substrate (μm)	Transmission peak frequency (THz)	Transmissivity (%)
Single "C" resonant ring	5	0.672	99.45
	10	0.610	99.33
	12.5	0.592	99.29
	15	0.573	99.25
	20	0.555	99.06
	25	0.540	98.94
Double "C" resonant ring	5	0.643	98.99
	10	0.573	98.92
	12.5	0.567	98.88
	15	0.544	98.40
	20	0.529	97.82
	25	0.515	97.34
Square resonant ring	5	0.694	99.51
	10	0.668	99.37
	12.5	0.643	99.43
	15	0.636	99.55
	20	0.614	99.22
	25	0.594	98.82

wavelength of plasmon resonance in the metal array with holes is approximate [25].

$$\lambda_{SP} = \frac{L}{\sqrt{m^2 + k^2}} \sqrt{\frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2}}. \quad (2)$$

In this formula, ϵ_1 represents the effective dielectric constant of the surrounding medium, L is the lattice constant, m and k represent the different modes of light, and their values are integers. $\epsilon_2 = \epsilon_{r2} + \epsilon_{i2}$ is the dielectric constant of the metal, and ϵ_{r2} and ϵ_{i2} represent the real part and the imaginary part, respectively. The real and imaginary parts are related to the frequency of incident light, the period and size of the hole, the material of the metal, and other factors. In our actual application, the thickness of the substrate of a metal array structure is much smaller than (c/ω) with c of light speed and ω of frequency of incident light. So, the structures including substrate are generally considered as thin film. For films that are exposed to the air, the refractive index can be calculated by [26]

$$n(\omega) = \sqrt{2A(\omega) - 1}. \quad (3)$$

In this formula, $A(\omega) = (c/\omega d)|(E_{\text{film}}/E_{\text{ref}}) - 1|$. E_{film} and E_{ref} represent the electric field after the light wave penetrates the medium thin film and the reference electric field when the light wave propagates in the free space. $(E_{\text{film}}/E_{\text{ref}})$ represents the transmittance of light waves through a dielectric film, and this value is related to the thickness of the substrate film of the structure. In addition to the resonant transmission factors, the frequency selection effect of the subwavelength metal array with holes on the surface of terahertz wave will also change the transmission properties of the substrates of the structure. Considering $\epsilon(\omega) = n^2(\omega)$, which is the relation between transmittance and dielectric constant of substrate material, we can conclude that

$$\epsilon_1(\omega) = 2 \frac{c}{\omega d} \left| \frac{E_{\text{film}}}{E_{\text{ref}}} - 1 \right| - 1. \quad (4)$$

According to equation (4), the terahertz wave transmittance of the subwavelength metal array structure is directly related to the dielectric constant of the substrate as well as the thickness of the substrate as a whole, and changes in the thickness of the substrate d also leads to changes in ϵ_1 . According to equation (2), we can find that the change of ϵ_1 will cause the shift of subwavelength metal array structure of surface plasmon resonance wavelength. Numerical simulation for equations (2)–(4) is carried out to verify the reasoning, and the results are shown in Figure 5. It can be found that the transmission peak position of the metal hole array structure is subject to change with the change of substrate thickness d . When the thickness of the substrate increases, the position of the transmission peak moves to low frequency. Substrate thickness has great influence to the dielectric constant of metal microstructure. Due to this, the surface plasmon resonance wavelength will be changed and lead to the movement of the position of transmission peak.

Figure 5 shows the relationship between the frequency of transmission peak and the thickness of the substrate. It can be found that the frequency of transmission peak decreases nonlinearly. With increase of thickness of substrate, the frequency of transmission peak tends to be stable. According to the literature [27], the main reason to affect the resonance frequency is the interface plasma resonance between metal and substrate. If the substrate is thick enough, it will be like a half infinite medium, and the interface effect will have nothing to do with the transmission peak frequency. Due to this reason, the transmission peak frequency will tend to a stable position. In practical application, we can realize the modulation of terahertz wave by changing thickness of substrate in a certain range.

In order to better understand the transmission characteristics of the three proposed structures, the electric energy density of the unit structures at their respective resonant frequencies were studied and are shown in Figure 6. As

FIGURE 5: Relationship between frequency of peak transmission and substrate thickness. (a) Single “C” resonant ring structure. (b) Double “C” resonant ring structure. (c) Square resonant ring structure.

FIGURE 6: Electric energy density of the three structures. (a) Single “C” resonant ring structure ($f_1=0.592$ THz). (b) Double “C” resonant ring structure ($f_2=0.592$ THz). (c) Square resonant ring structure ($f_3=0.592$ THz).

shown in Figures 6(a) and 6(b), since the ring is hollow and the opening is metal, the energy of the incident terahertz wave is concentrated on both sides of the ring, revealing a stronger field confinement and THz wave capture [28, 29]. As shown in Figure 6(c), the electric field intensity is evenly and symmetrically distributed among the six openings, and this distribution is the formation of electric field dipole in the ring. Also, the energy density is not very high. This is because the opposite flow of the induced cycle on the surface cancels out the creation of magnetic dipoles.

The influence of the number of rings on transmission characteristics was studied. Single and double “C” resonant ring were selected for comparison. The metal layer thickness was $0.2\mu\text{m}$, and the substrate thickness was $12.5\mu\text{m}$.

As shown in Figure 7, for single “C” resonant ring structure, only one high transmission peak appears at 0.592 THz with transmissivity of 99.29% . The bandwidth with transmissivity above 90% is 0.117 THz. For double “C” resonant ring structure, four high transmission peaks of F1, F2, F3, and F4 appear at 0.567 THz, 1.218 THz, 1.421 THz, and 1.487 THz, respectively. For peaks F1 and F2, the bandwidth with transmissivity above 90% is 86 GHz and 72 GHz, respectively. For peaks F3 and F4, the corresponding bandwidth is too narrow to discuss. The detailed information for above simulation results is given in Table 3.

4. Experimental Results and Discussion

4.1. Experiment. According to the optimal parameters obtained from the previous simulation and considering the difficulty of the actual sample processing, copper with a thickness of $0.2\mu\text{m}$ was selected as the metal layer and polyimide with a thickness of $12.5\mu\text{m}$ as the substrate for the sample preparation.

Polyimide (PI) with thickness of $12.5\mu\text{m}$ was used as the substrate for the three structures in the experiment. First, a layer of polyimide with thickness of $12.5\mu\text{m}$ was coated on the silicon chip with thickness of $500\mu\text{m}$ by PI spinning. Then, the open resonant ring structures were formed on the PI substrate by positive photolithography through homogenization, predrying, preexposure, over-drying, overexposure, development, and other processes. The AZ5214 model was selected as the photoresist, and $0.2\mu\text{m}$ thick copper was plated on the PI by magnetron sputtering. After stripping, an open ring copper film was formed on the PI substrate. Disco cutting machine (Disco 641) with a hard knife was used to slice the samples into small pieces of $8\text{mm} \times 8\text{mm}$. The final samples were obtained after soaking in HF (40%) for 3 min and separated from the silicon wafers. The microstructures of final samples are shown in Figure 8.

The detection of transmission characteristics of the samples was carried on the THz-TDS system (Advantest,

FIGURE 7: Simulated transmission spectrum for single and double “C” resonant ring structure.

TABLE 3: The simulation of transmission peak of single and double “C” resonant ring.

Structure	Transmission peak	Transmission peak frequency (THz)	Transmissivity (%)
Single “C” resonant ring	F1	0.592	99.29
	F1	0.567	98.88
Double “C” resonant ring	F2	1.218	97.93
	F3	1.421	95.92
	F4	1.487	97.13

FIGURE 8: Microstructure of resonant ring structures. (a) Single “C” resonant ring structure. (b) Double “C” resonant ring structure. (c) Square resonant ring structure.

TAS7400). The system is mainly composed by a femtosecond laser, electric control device, and THz wave generating device. The Ti: sapphire femtosecond laser with pulse width of 100 fs, center wavelength of 800 nm, and repetition rate of 82 MHz is used as the light source. The femtosecond laser pulse is divided into two beams. One beam is used to generate terahertz pulse, and the other one acts as a probe beam to detect the terahertz pulse. The detection width of this system is 0.1–5 THz. The temperature is kept at 21°C during the experiment, and the humidity of the detection environment is controlled below 4% by the air dryer so as to

minimize the absorption of water to terahertz wave and increase the accuracy of the detection results.

The transmissivity can be calculated by following equation:

$$T(\nu) = \frac{\text{Power}_{\text{transmitted}}(\nu)}{\text{Power}_{\text{reference}}(\nu)}, \quad (5)$$

where $T(\nu)$ is the transmissivity, ν is the incident pulse frequency, $\text{Power}_{\text{reference}}(\nu)$ is the energy of incident pulse, and $\text{Power}_{\text{transmitted}}(\nu)$ is the energy of transmission pulse.

FIGURE 9: Comparison simulation and experimental results of transmission spectrum for three structures. (a) Single “C” resonant ring structure. (b) Double “C” resonant ring structure. (c) Square resonant ring structure.

FIGURE 10: Experimental transmission spectrum for single and double “C” resonant ring structures.

4.2. Results and Discussion. As shown in Figure 9(a), the transmission peak of the sample was at 0.56 THz with transmissivity of 85.9% for single “C” resonant structure. For double “C” resonant structure, the transmission peak showed up at 0.56 THz with transmissivity of 82.9%, as shown in Figure 9(b). As for the square resonant ring structure, the transmission peak was at 0.62 THz with transmissivity of 84.1%. As shown in Figure 9, it can be found that the transmission peak position has a very good match for the simulation and the experimental results. The difference of transmissivity is mainly due to the absorption of polyimide substrate for THz wave and the slight oxidation of the metal layer. Also, there are more transmission peaks in simulation than in experiment. The main reason is due to the absorption of polyimide substrate for THz wave and the slight oxidation of the metal layer. Besides, the size error of

the samples and the absorption of terahertz wave by water in the environment during detection process will also lead to a lower transmission compared to the ideal simulation results.

Figure 10 shows the comparison of transmission spectrum for single and double “C” resonant ring structures. Table 4 provides specific information for the peaks of experiment result. It can be seen from the diagram for the single “C” resonant ring structure, only one super-transmission peak appears within 0.2–2 THz. However, for the double “C” resonant ring structure, three transmission peaks show up at 0.561 THz, 1.232 THz, and 1.474 THz with transmissivity of 84.2%, 66.2%, and 28.1%, respectively. This is showing the potential to improve the sensitivity of THz detection devices by adding more resonant rings to the unit structure. In order to improve the transmissivity of the structures, other materials with low terahertz absorption

TABLE 4: The experiment of transmission peak of single and double “C” resonant ring.

Structure	Transmission peak	Transmission peak frequency (THz)	Transmissivity (%)
Single “C” resonant ring	F1	0.592	83.4
	F1	0.561	84.2
Double “C” resonant ring	F2	1.232	66.2
	F3	1.474	28.1

such as polyethylene [30] or low-density polyethylene [31] can be considered in the future study.

5. Conclusions

Three kinds of open ring structures were designed, and their transmission characteristics of THz waves were studied by simulation and experiments. The influence of metal layer thickness, substrate thickness, and number of open rings on the transmission characteristics was studied.

The results show that the transmissivity decreases with increase of thickness of metal layer and substrate. The transmission peaks have a redshift with increase of thickness of metal layer and substrate, and the influence from substrate is greater than that from metal layer. For single “C” and square open resonance ring structures, only one resonant transmission peak with transmissivity higher than 90% appears in the range of 0.2–2 THz. However, for double “C” open resonant ring structure, four transmission peaks with transmissivity higher than 90% appear in the range of 0.2–2 THz. According to the actual demand, by changing the thickness of the metal layer, as well as the thickness of the substrate, adjust the terahertz wave transmission and its transmission peak position, so as to achieve the desired purpose.

The transmission characteristics of three structures were studied experimentally. The results of position of transmission peaks have a good agreement with simulation. The transmissivity of experiments is lower than the simulation results which is mainly because the simulation was carried out in an ideal environment first, and the size error in the sample preparation process and the absorption of terahertz wave by water in the environment during the detection process were caused.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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