

A Flexible Metamaterial Terahertz Perfect Absorber

X R Chen^{1,2}, Y W Zheng^{1,2}, L M Qin^{1,2}, G C Wei^{1,2}, Z P Qin^{1,2}, N G Zhang^{1,2}, K Liu^{1,2}, S Z Li^{1,2} and S X Wang^{1,2,*}

¹ School of Electronic and Electrical Engineering, Wuhan Textile University, Wuhan, Hubei, 430073 People's Republic of China

² State Key Laboratory for Hubei New Textile Materials and Advanced Processing Technology, Wuhan Textile University, Wuhan, 430020, P. R. China

*Email: shxwang@wtu.edu.cn

Abstract. We designed a THz metamaterial absorber using metallic wires (MWs) and split resonant rings (SRRs). This metamaterial absorber exhibits perfect absorption which up to 96% at 4.03 THz and is capable of wrapped around objects because of flexible polyimide dielectric substrate.

1. Introduction

The metamaterial consists of artificially designed cell units are capable of exhibiting exotic properties that natural materials cannot achieve at operating wavelengths that are much smaller than the unit structure dimension. This unit cells resemble the molecules of natural materials and behave different properties by adjusting the properties of the unit cell. With the rapid progress of metamaterial research, the practical application of metamaterials in from microwave, infrared to optical frequency regions has attracted enormous interest [1-3].

Terahertz range is a particularly interesting band which refers to the frequency in the range of from 0.1 THz to 10 THz. Due to the lack of high efficient terahertz source and detection equipment, the development of THz applications is almost blank and commonly known as "THz gap". Terahertz wave exhibits many unique properties[4, 5]. A large amount of nonpolar molecules cannot absorb terahertz waves, so terahertz waves have strong penetrability for many materials and can be used at security field. In addition, the terahertz wave photon energy is so less than that of the traditional X-ray so that the damage of terahertz wave to the detected object is much smaller relatively. The highly flexible polyimide substrate can be used on non-planar devices because it can be easily wrapped around objects with a diameter of millimeters[6].

The metamaterial structure based on a polyimide substrate with nearly perfect absorption characteristics in terahertz frequency regime can be applied to non-planar device and these results serve as an important step forward in constructing a functional THz cloak[7-9]. In this paper, we designed a metamaterial based on polyimide flexible substrate with perfect absorption which up to 96% at 4.03 THz.

2. Design and simulation

We designed a compact multi-layer absorber which is illustrated in Figure1. The unit cell of the metamaterial consists of four alternating metal structure and dielectric layer. The two-layer



intermediate dielectric layer is composed of polyimide and the dielectric constant of which is $\varepsilon = 2.4 + i0.005$ in the interested frequency[10]. Patterned metallic structure is a combination of metallic wire and split resonant rings and it is made of Au. The upper and lower layers split resonant rings is mirror symmetrical along the horizontal axis. The repeat period metamaterial parameters is illustrated in the inset of Figure 1 in top-right corner and specific dimension is $P_y=125\text{ }\mu\text{m}$, $P_x=106\text{ }\mu\text{m}$, $R_y=28\text{ }\mu\text{m}$, $R_x=27.5\text{ }\mu\text{m}$, $R=19.5\text{ }\mu\text{m}$, $r=14.5\text{ }\mu\text{m}$, $d=5\text{ }\mu\text{m}$, $w=10\text{ }\mu\text{m}$, $L=110\text{ }\mu\text{m}$, $l=100\text{ }\mu\text{m}$. The thickness of polyimide dielectric layer and patterned metal structure are $5\text{ }\mu\text{m}$ and 500 nm , respectively.

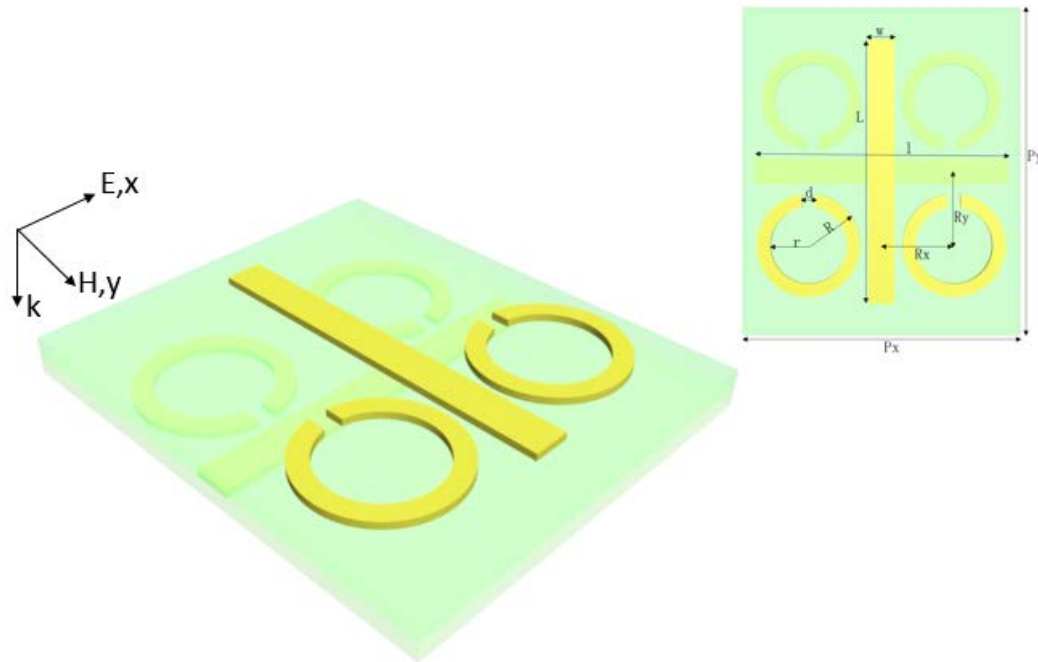


Figure 1. The unit schematic of the designed metamaterial structure and the inset in top-right shows the structure parameters of the designed unit cell of the metamaterial.

We implemented the simulation through finite element calculation, which incident plane wave from port is perpendicular to the structure plane. The direction of electric component of incident electromagnetic wave is parallel to x-axis as that of the magnetic component parallel to y-axis. The transmission parameter S_{21} and the reflection parameter S_{11} are used to describe the transmission and reflection characteristics of the entire model structure. The absorption of the terahertz electromagnetic wave is given by $A = 1 - |T| - |R|$.

On the other hand, we have simulated the absorption of the different components of the metamaterial interacting with the terahertz electromagnetic wave. As it shows in Figure 2, the dominant absorptivity of the structure lies in the split resonant rings of which the absorption curve is highly coincident with the unit structure.

3. Discussion

We designed the metamaterial structure with perfect absorption characteristics in terahertz region. The absorptivity spectra in Figure 3 reveal resonance peak with the absorption efficiency up to 96% at the frequency of 4.03 THz, which could be potentially applied for the subsequent development of metamaterial devices. It's worth noting that Figure 3 also illustrate two drastic changing absorption peak at 3.26 THz and 4.44 THz. To figure out the nature of these two peaks, we extract the distribution of the electric field in the x-direction and shown in Figure 4. It can be seen that the enhancement effect of the electric field mainly concentrates on the gaps of the split of the SRRs. It is well known that the split resonant ring structure can be equivalent to an inductance-capacitance (LC) circuit, and the equivalent inductance and capacitance have a great influence on the resonant frequency.

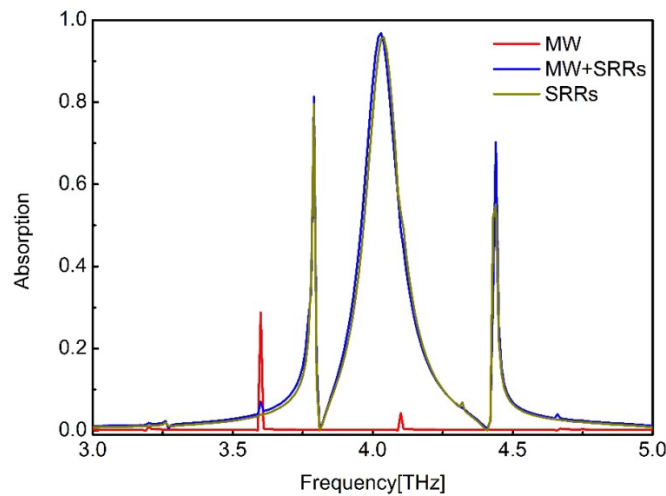


Figure 2. The absorption of different components of the unit metamaterial structure

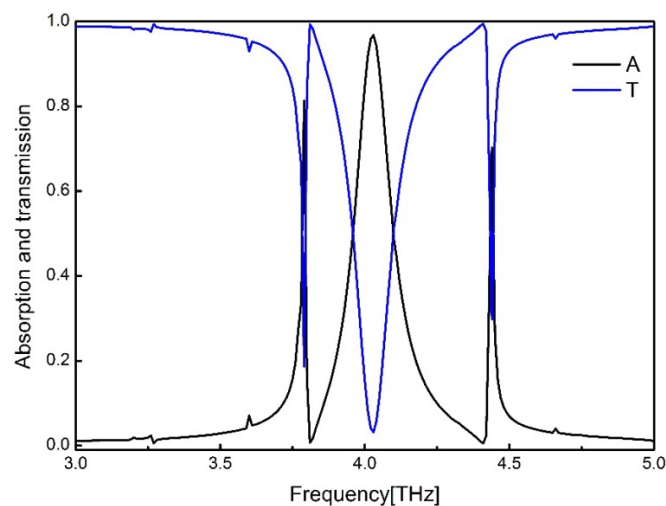


Figure 3. The absorption and transmission curve of the unit structure reacting with terahertz electromagnetic wave.

The distribution of current density inside the split resonant ring at 4.03 and 4.44 THz are displayed in Figure 5. The relatively weak current density portion of SRRs accompanied with enhanced electric field in adjacent dielectric is shown in Figure 5. It is easy to make it clear that the absorption peak at 4.03 THz is due to resonance and the absorption peaks at 4.44 THz and 3.26 THz have the same mechanism. It is remarkable that the fluctuation of the charges density distribution leads to the generation of singular absorption peaks and its physical mechanism is consistent with the main peak. On the other hand, the full width at half maximum (FWHM) of this metamaterial device is 0.15 THz which is adequate to practical application.

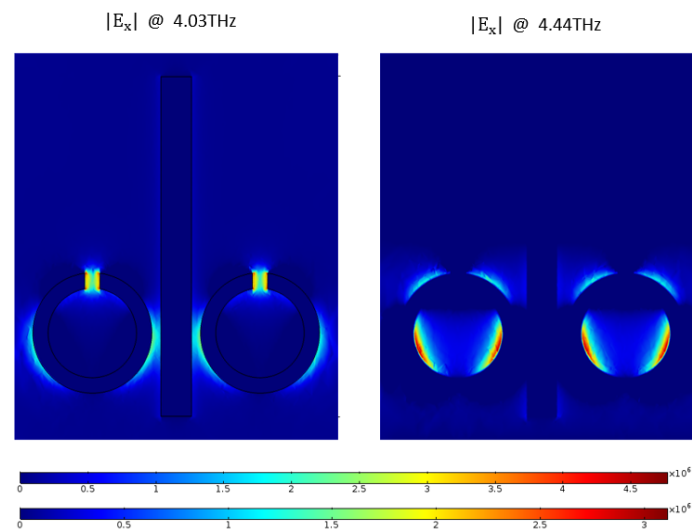


Figure 4. The distribution of electric field component and the upper legend corresponds to the electric field distribution at 4.03THz.

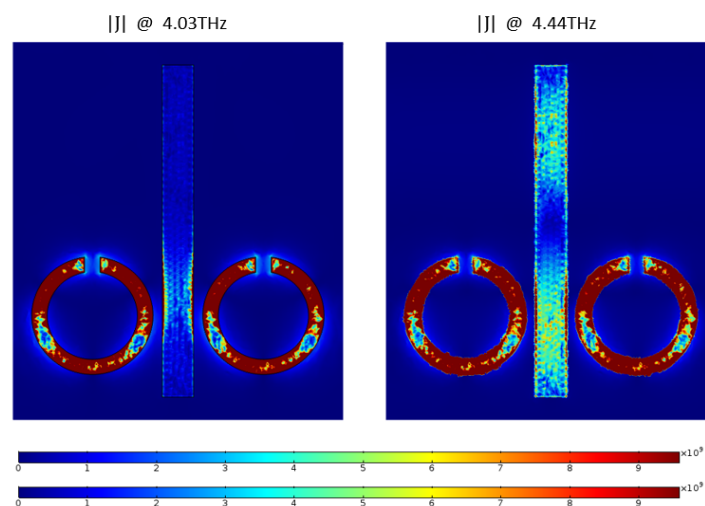


Figure 5. The distribution of current density and the upper legend corresponds to the current density at 4.03THz.

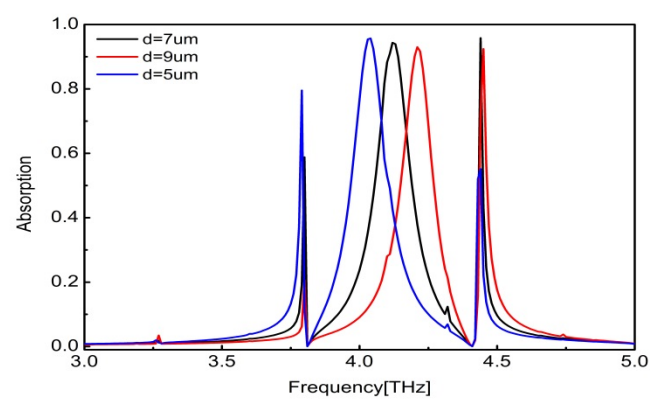


Figure 6. The influence of different split width of SRRs on the absorptivity of the unit metamaterial structure

As mentioned, the split resonant rings has a decisive effect on the absorption of electromagnetic waves. To further study the absorption characteristics of the split resonant rings, we simulate the effect of changing the width of the split of SRRs. The results are shown in Figure 6. As the split width increased, the resonant absorption becomes smaller and blue shift of resonant frequency occurs. The peak value of the singular peak on the left side descends and the peak value of the singular peak on the right increases. The split width of split resonant rings can be equivalent to the capacitance of the LC circuit as described above, so the change of split width affect the capacity of equivalent capacitor and the blue-shift occurs in addition with the maximum of absorption efficiency declining. However, another method with the same effect is to alter the inner and outer diameters of the split resonant rings[11].

4. Conclusions

In conclusion, we have proposed a THz metamaterial absorber could be applied for perfect absorption in THz region and be capable of wrapped around objects due to flexible polyimide dielectric substrates. The absorption intensity reaches 96% at 4.03 THz. We further explored the effects of the different components of the metal structure on the absorption and found that the metal split resonant rings had a decisive influence on the absorption. The distributions of electric field component are used to illustrate the nature of singular peak at 3.26 THz and 4.44 THz. The absorption peak can be adjusted by changing the structure of the metamaterial. This perfect flexible metamaterial absorber will be applied as candidate materials for a functional THz thermal detector or imaging application [12-15].

Acknowledgements

This study was supported by National Natural Science Foundation of China (51302196) and State Key Laboratory for Hubei New Textile Materials and Advanced Processing Technology (ZDSYS201711).

References

- [1] Bingham C M, Tao H, Landy N I, Averitt R D, Padilla W J and Zhang X 2008 A metamaterial absorber for the terahertz regime: Design, fabrication and characterization *Opt. Express* **16** 7181.
- [2] Grant J, Escorcia-Carranza I, Li C, McCrindle I J H, Gough J and Cumming D R S 2013 A monolithic resonant terahertz sensor element comprising a metamaterial absorber and micro - bolometer *Laser & Photonics Reviews* **7** 1043-8.
- [3] Cheng Y, Gong R and Cheng Z 2016 A photoexcited broadband switchable metamaterial absorber with polarization-insensitive and wide-angle absorption for terahertz waves *Opt. Commun.* **361** 41-6.
- [4] Li E P, Lim H C, Federici J F, Hor Y L and Szabó Z 2010 Terahertz response of microfluidic-jetted three-dimensional flexible metamaterials *Appl. Opt.* **49** 1179.
- [5] Tao H, Bingham C M, Pilon D, Fan K, Strikwerda A C, Shrekenhamer D, Padilla W J, Zhang X and Averitt R D 2010 A dual band terahertz metamaterial absorber *Journal of Physics D Applied Physics* **43** 225102.
- [6] Tao H, Bingham C M, Strikwerda A C, Pilon D, Shrekenhamer D, Y N I L, Fan K, Zhang X, Padilla W J and Averitt R D 2008 Highly flexible wide angle of incidence terahertz metamaterial absorber: Design, fabrication, and characterization *Physics* **78** 1879-82.
- [7] Chen H, Wu B I, Zhang B and Kong J A 2007 Electromagnetic wave interactions with a metamaterial cloak *Phys. Rev. Lett.* **99** 063903.
- [8] Wang B X, Wang L L, Wang G Z, Huang W Q, Li X F and Zhai X 2014 A broadband, polarisation-insensitive and wide-angle coplanar terahertz metamaterial absorber *The European Physical Journal B* **87**.
- [9] Yao J Q 2017 Solid analyte and aqueous solutions sensing based on a flexible terahertz dual-band metamaterial absorber *Optical Engineering* **56** 027104.

- [10] Wang B-X, Wang L-L, Wang G-Z, Huang W-Q, Li X-F and Zhai X 2013 A simple design of ultra-broadband and polarization insensitive terahertz metamaterial absorber *Appl. Phys. A* **115** 1187-92.
- [11] Ye Q, Liu Y, Lin H, Li M and Yang H 2012 Multi-band metamaterial absorber made of multi-gap SRRs structure *Appl. Phys. A* **107** 155-60.
- [12] Grant J, Ma Y, Saha S, Khalid A and Cumming D R 2011 Polarization insensitive, broadband terahertz metamaterial absorber *Opt. Lett.* **36** 3476-8.
- [13] Ma Y, Chen Q, Grant J, Saha S C, Khalid A and Cumming D R S 2011 A terahertz polarization insensitive dual band metamaterial absorber *Opt. Lett.* **36** 945.
- [14] Withayachumnankul W, Shah C M, Fumeaux C, Ung B S Y, Padilla W J, Bhaskaran M, Abbott D and Sriram S 2014 Plasmonic Resonance toward Terahertz Perfect Absorbers *Acs Photonics* **1** 625-30.
- [15] Cong L, Tan S, Yahiaoui R, Yan F, Zhang W and Singh R 2015 Experimental demonstration of ultrasensitive sensing with terahertz metamaterial absorbers: A comparison with the metasurfaces *Appl. Phys. Lett.* **106** 26