

# Dual-band absorber for multispectral plasmon-enhanced infrared photodetection

Peng Yu<sup>a\*</sup>, Jiang Wu<sup>b</sup>, Eric Ashalley<sup>a</sup>, Alexander Govorov<sup>c</sup>, Zhiming Wang<sup>a\*</sup>

<sup>a</sup>*Institute of Fundamental and Frontier Science, University of Electronic Science and Technology of China, Chengdu 610054, P. R. China.*

<sup>b</sup>*Department of Electronic and Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, United Kingdom.*

<sup>c</sup>*Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA*

\*Corresponding author: [Azarisyu@gmail.com](mailto:Azarisyu@gmail.com); [zhmwang@uestc.edu.cn](mailto:zhmwang@uestc.edu.cn)

## ABSTRACT

For most of the reported metamaterial absorbers, the peak absorption only occurs at one single wavelength. Here, we investigated a dual-band absorber which is based on simple gold nano-rings. Two absorption peaks can be readily achieved in 3-5  $\mu\text{m}$  and 8-14  $\mu\text{m}$  via tuning the width and radius of gold nano-rings and dielectric constant. The average maximum absorption of two bands can be as high as 95.1% (-0.22 dB). Based on the simulation results, the perfect absorber with nano-rings demonstrates great flexibility to create dual-band or triple-band absorption, and thus holds potential for further applications in thermophotovoltaics, multicolor infrared focal plane arrays, optical filters, and biological sensing applications.

**Keywords:** Metamaterials, Dual-band, Plasmonics, Infrared detector, Perfect absorber, FDTD.

## 1. Introduction

Artificial metamaterials (MMs) are widely studied for their exotic properties i.e. negative refractive index [1], and potential device-applications such as perfect lenses[2] and invisibility cloaks[3,4]. Composite optical MMs are innovative structures for customizing electric and magnetic properties for specific applications, which are based on fundamental resonance of the resonators. For the last ten years, researchers have presented MMs with the state-of-the-art performances from radio[5,6], microwave[7,8], mm-Wave[9-11], THz[12,9,13], FIR[14], MIR[15-17], NIR[18,19], to optical spectrum[20,21]. Specifically, metamaterial perfect absorber (MMPA), first demonstrated by Landy *et al.*[22], shows the merits of MMs such as highly absorptive characteristics, tunable resonant frequencies, and undemanding manufacturability for a high Q-factor. Intrigued by MMPA and possibility for near unity absorbance, MMPAs have become attractive for various optoelectronic applications, including detectors[23,24], emitters[25], imaging devices[26], solar cells[27], etc.

Extensive efforts have been made to harness energy harvesting applications. For infrared (IR) detector application, to provide perfect signal-to-noise performance and an extremely fast response, traditional methods and materials require cryogenic cooling, sacrificing their convenience and scalability and makes them bulky, heavy, pricy. The IV-VI materials demonstrate available low gap and were fully studied, but with poor mechanical property and large permittivity. The III-V materials has matured dopants and fabrication technology and possible monolithic integration, but they demonstrate heteroepitaxy with large lattice mismatch. Recently, quantum dot and quantum well were used in the photodetection [28]. However, the weak absorption of quantum dots / well, challenge in achieving a uniform quantum structure size and low operating temperatures have not been addressed yet. Selective emitters using luminescent bands of rare earth oxides are limited in scarcity of materials and complication of controlling compounds [29,30]. Additionally, nonresonant nature of photonic crystal emitters impose restrictions on boosting efficiencies [31].

The MMPAs with hundreds of nanometers present perfect absorption at specific wavelengths, consuming less material and lessening fabricate process. The pivotal focus for MMPA design is to minimize reflection and transmission while balancing electric and magnetic resonances to maximize absorption. Although rapid progress has been made in terahertz frequency domain [32-36], most MMPA designs are single-band at specific frequency with limited applications. Compared with the single-band absorbers, the dual-band devices have many advantages such as better image contrast, longer detecting distance and higher spatial resolution at targeted wavelengths. However, traditional dual-band detectors have low signal response with low responsivity and poor detection characteristics because of their multi-surface and complex components of materials. Recently, researchers have demonstrated multiband MMPAs with two or more well-defined absorption peaks [37-42]. For instance, triple-band polarization-independent metamaterial absorber are reported for GHz absorption based on millimeter-sized square strips [42]. The general structure is comprised of a highly conductive and geometrically shaped metallic resonator, i.e. gold and copper, and metal-dielectric layers with various arrangements, which oscillate electrons in a unit cell. Physically, engineered impedance matching  $Z_{eff} = (\mu_{eff}/\epsilon_{eff})^{1/2}$ , complex electric permittivity and complex magnetic permittivity need to be taken into account. If the  $Z_{eff} = 1$ , then the bulk effective impedance of MMs matches the  $Z_{eff}$  of free space medium such as air and vacuum. By tuning  $\epsilon$  and  $\mu$  simultaneously, the reflectance weakens approximately to zero; indicating full light absorption and thus no penetrating radiation and no reflection.

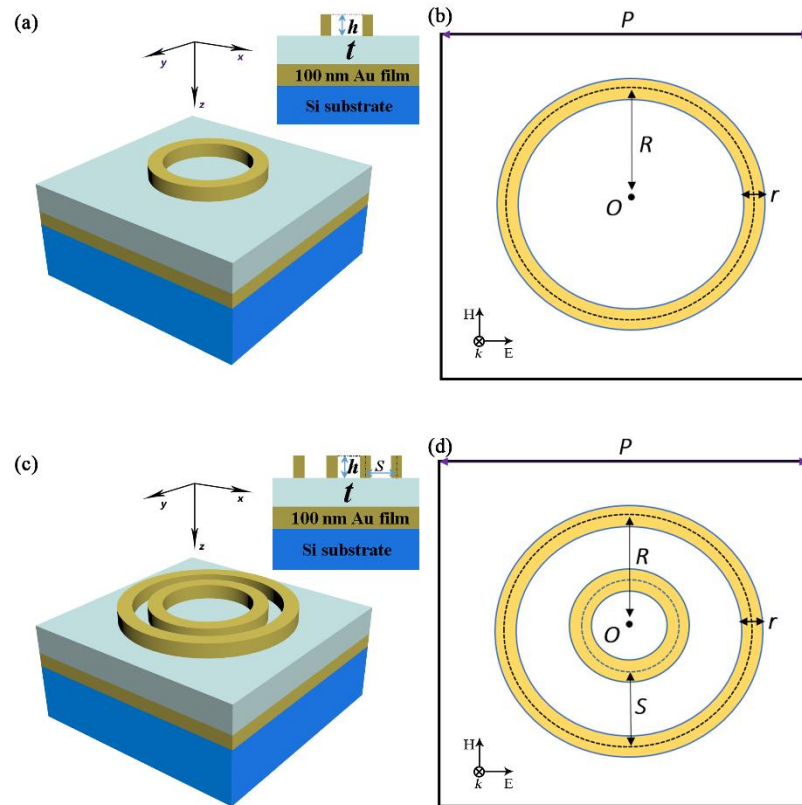
Here we present a design of MMPA with a double-ring geometry that is insensitive to the polarization of light. Here we used a single unit cell in the propagation direction achieving two maximum absorptions

as high as average 95.1% (-0.22 dB) with a much smaller thickness than the resonant wavelengths. The scalability with wavelengths permits applications for bolometric pixel elements and pyroelectric detectors. Our design can be especially useful for bolometers with a narrow band response; such bolometers are used as focal plane array (FPA) detectors for imaging. Meanwhile, the proposed detector also has potential use for combustible, toxic and harmful gases, such as  $\text{CH}_4$ ,  $\text{CO}$ ,  $\text{C}_2\text{H}_6$  in MIR region,  $\text{SO}_2\text{F}_2$  and  $\text{SF}_6$  in FIR, thermographic cameras, hyperspectral imaging, meteorology, free space light communication, remote sensing, laser, and identification biological compounds, etc.

## 2. Simulation methodology

Fig. 1 shows MMPA structures proposed in this study, demonstrating the 3D construction of the structure which includes a thick Si substrate at the bottom, a layer of gold thin film with fixed thickness, a dielectric spacer layer and a gold nanoresonator at the top respectively. In this structure, the thickness of gold film is much larger than typical skin depth so that the  $A(\omega)$  can be simplified as  $1 - R(\omega)$ , where  $A(\omega)$  and  $R(\omega)$  are absorptivity and reflectance respectively. Fig. 1b demonstrates the top view of the surface which is incorporated with a nano-ring as a coupler to trap light in. The ring is 100 nm thick and capable of altering by tuning parameters of  $R$  and  $r$ , while the lattice constant is defined as  $P$ . The performance of this single-band MMPA extremely counts on these variates.

Enlightened by the single band absorber, we designed the dual-band MMPA based on two concentric rings. Fig. 1c exhibits the dual-band MMPA including almost identical structure with the single-band structure. The only distinction is the addition of another concentric ring; the separation distance between two rings is defined as  $S$ . While the absorption of the device is relevant with geometrical parameters in single-band, the dual-band MMPA can also be engineered through the  $S$ , component also crucial for non-loss absorption at specific frequencies, as illustrated in Fig. 1d.



**Fig. 1** Schematic illustration of a periodic single-band MMPA. **a** Side view of the

1  
2  
3  
4 structure with a gold-ring of the height  $h = 100$  nm, dielectric spacer with a thickness  
5  $t$ , 100 nm gold film and silicon substrate. **b** Top view of the ring resonator with a width  
6  $r$ , lattice constant  $P$  and radius  $R$ . **c** Side view of the structure incorporating paired gold  
7 concentric rings with height  $h = 100$  nm, dielectric spacer with a thickness  $t$ , 100 nm  
8 gold film, distance  $S$  between two rings, and silicon substrate from top to bottom. **d**  
9 Top view of the double ring structure with the parameters: The ring widths  $r$ , lattice  
10 constant  $P$ , radius  $R$  and distance between two rings  $S$ . The surface of dielectric spacer  
11 is set as 0 in  $Z$  direction  
12  
13  
14

15 To design such structure, the overriding criteria is to certify the availability and reliability. Finite  
16 difference time domain (FDTD) method, based on Maxwell equation for theoretical study, shows its  
17 flexibility on design, analysis and optimization for photonic devices and materials. It provides a route to  
18 reducing dependence upon costly experimental prototypes, and breeds quicker assessment of designs  
19 [43,22,44]. Here, we simulated MMPAs with gold-ring placed on the top to provide dual-band  
20 absorptions at targeted frequencies while upholding tunability and flexibility. By altering corresponding  
21 parameters, maximum absorptions at desired frequencies between 3-5  $\mu\text{m}$  (middle infrared, MIR) and 8-  
22 14 (far infrared, FIR)  $\mu\text{m}$  can be realized. A single unit cell was simulated with appropriate boundary  
23 conditions as illustrated in Fig. 1. The wave vector  $k$  propagates through the  $Z$  direction with perfect  
24 magnetic field in  $y$ - $z$  plane and perfect electric field in  $x$ - $z$  plan. Perfectly matched layers (PML) was  
25 applied in the propagation direction in order to eliminate nonphysical reflections at domain boundaries  
26 and the periodic boundary condition (PBC) is adopted to simulate a structure which is periodic in one  
27 direction but not necessarily in other directions. The refractive index of materials are modelled using  
28 fitted optical data Au[45], silicon[46] and silicon dioxide[46]. Ideal dielectric spacer with different  
29 refractive indexes to replace  $\text{SiO}_2$  is investigated. According to the proposed structure, the TEM wave is  
30 reflected and absorbed when the incident radiation is perpendicular to the surface. So, the absorption  
31 hinges on Eq. (1)  
32  
33  
34  
35  
36  
37

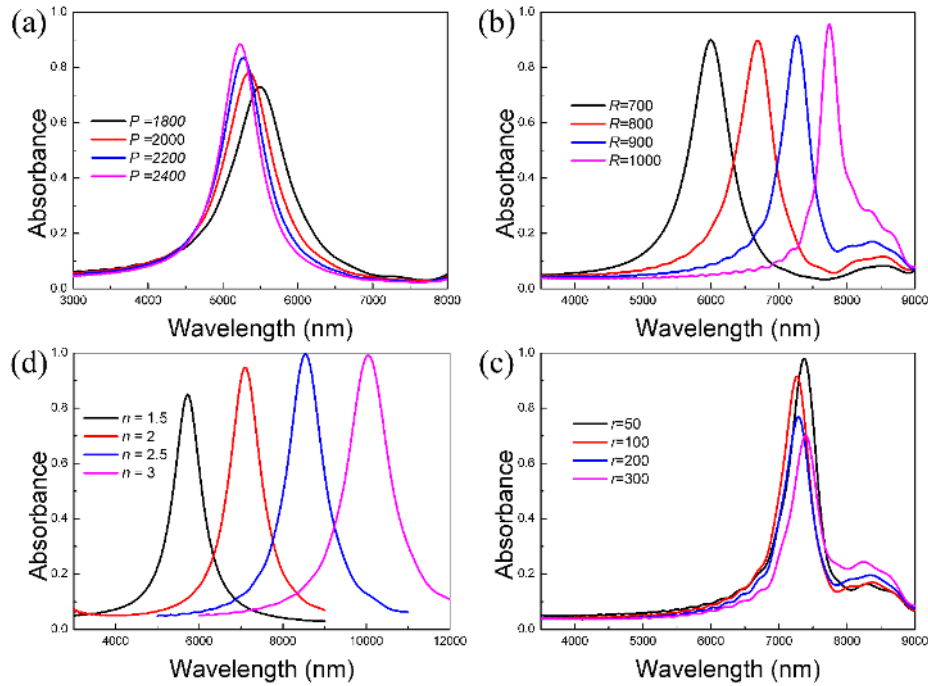
$$38 \quad A(\omega) = 1 - |S_{21}(\omega)|^2 - |S_{11}(\omega)|^2 = 1 - T(\omega) - R(\omega) \quad (1)$$

39  
40 where  $|S_{11}(\omega)|$  and  $|S_{21}(\omega)|$  are the complex reflection and transmission coefficients  
41 respectively, which determine  $R(\omega)$  and  $T(\omega)$ . Because of the existence of semi-infinite Au film,  
42 transmission vanished in the substrate, and the equation can be simplified as  $A(\omega) = 1 - R(\omega)$ .  
43  
44  
45

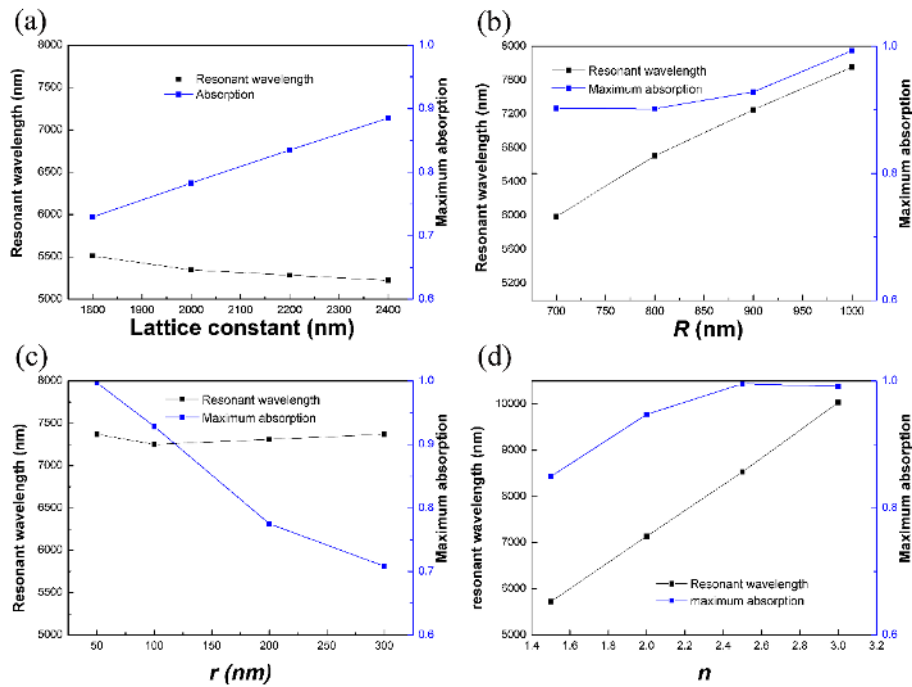
### 46 3. Results and discussion

47 As shown in Fig. 2, the proposed structure composing of a single ring atop exhibits narrow  
48 electromagnetic absorption peak centered at MIR and FIR region. The ring on the top creates a resonant  
49 response as a function of wavelength, while the Au film functions together with the spacer to generate  
50 strong coupling to magnetic component of the normal incident plane source. The lattice constant  $P$  has  
51 linear dependency with resonant wavelength and peaked absorption (features critical for light harvesting).  
52 As the  $P$  increases, the peak shifts to shorter wavelength, where plasmon resonances are excited. Full  
53 width at half maximum (FWHM) narrows down linearly as the  $P$  increase, giving rise to high  
54 distinguishability. While the resonant wavelengths respond sensitively to  $R$  and  $n$  with linear positive  
55 correlations, it is negligible for  $P$  and  $r$ , as indicated in Fig. 3. On the other hand, maximum absorptions  
56 are positively correlated with  $P$ ,  $R$ ,  $n$  and negatively correlated with ring width  $r$ . This phenomena are  
57 mainly attributed to the electromagnetic coupling efficiency. Smaller  $r$  with sharp edge have stronger  
58  
59  
60

near field enhancement than the larger  $r$ , thus coupling more energy. Larger  $P$  and  $R$  can concentrate more energy in a unit cell and avoid out-coupling. Besides, Ohmic losses contribute partially to the non-perfect absorption.

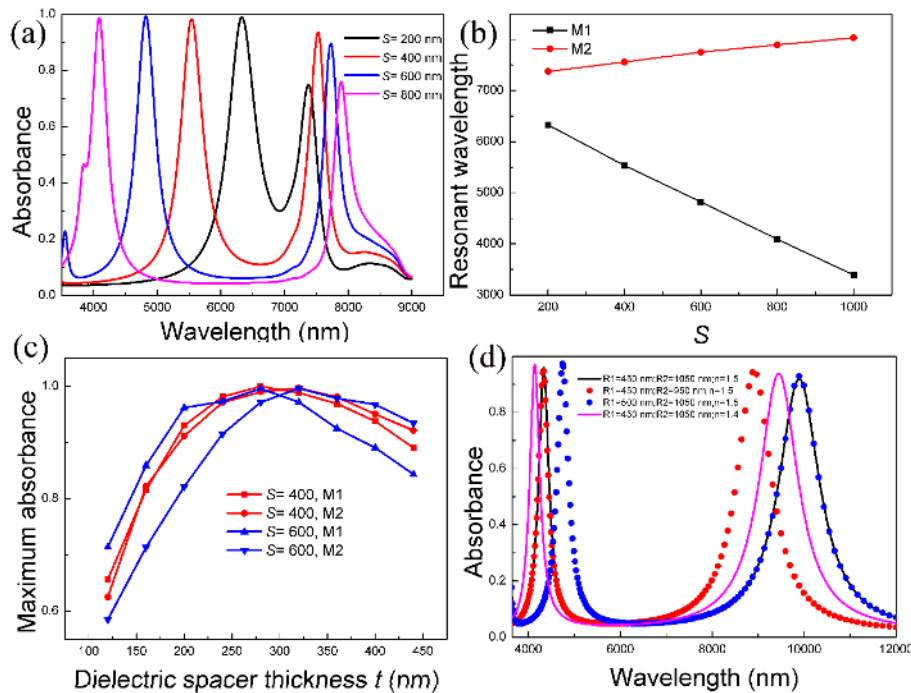


**Fig. 2** Absorbance properties of single-ring MMPA with different parameters. **a** Variation of lattice constant  $P$ . **b** Variation of radius of ring  $R$ . **c** Variation of refractive index  $n$ . **d** Variation of ring width  $r$ . The dielectric spacer is silicon dioxide



**Fig. 3** Resonant wavelength and maximum absorption dependence of single-ring MMPA with different parameters, matching with Fig. 2. **a** Lattice constant  $P$ . **b** Radius of ring  $R$ . **c** Ring width  $r$ . **d** Refractive index  $n$ . The dielectric spacer is silicon dioxide

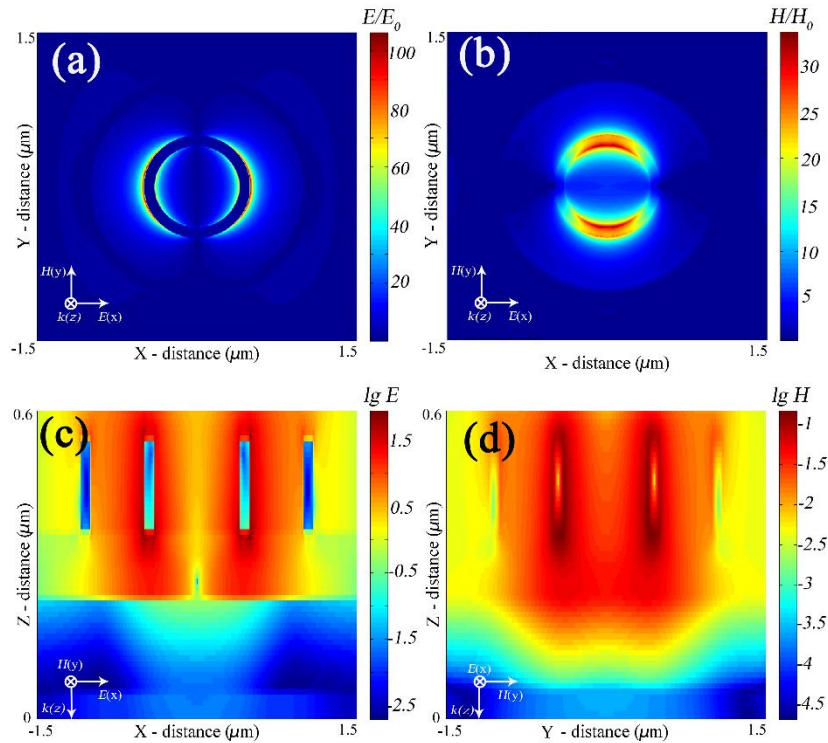
To the end, we demonstrate a dual-band MMPA with considerable signal-to-noise ratio by using this ring-shaped resonator after investigating the properties of the single band. The data from simulations dovetail with our expectation. The two ring-shaped resonators support two resonances at targeted wavelength bands distributed in MIR and FIR respectively with different ring radii. As shown in Fig. 4, the two first-order resonant modes, M1 (short-wavelength) and M2 (long-wavelength), appear at MIR and FIR. Fig. 4a, b and c clarify the relationship between  $S$  and  $t$ . The  $S$  and the absorption curves are demonstrated in Fig. 4 a. It can be seen that the larger  $S$  pushes two bands toward MIR and FIR and the two bands have almost similar FWHM. In Fig. 4 (b), while the resonance mode M1 shifts linearly to blue, the M2 shifts to red. Dielectric spacer is also critical for optimization during design consideration because the spacer thickness controls radiation damping. As shown in Fig. 4c, for  $S = 400$  nm and 600 nm, the optimum absorption can be achieved when  $t = 290$  nm and deviation from this value dwarfs the peaks. Contrary to one's research with different optimum  $t$  for various offset [43], our result shows same optimum  $t$  for different  $S$ . Their cross-shaped structure reaches maximum absorbance at different MgF<sub>2</sub> thickness due to the coupling strength of two modes brought about by asymmetry. Owing to the symmetry in our simulation, this ring-shaped structure have potential on practical application with simplification. To achieve average maximum absorbance above 80%, the  $t$  can be tuned from 150~550 nm for  $S = 400$  nm and 175~550 nm for  $S = 600$ , allowing deviation with fabrication flexibility. Fig. 4d demonstrates peaks in MIR and FIR with tunability at interested wavelengths. The two clearly resolved absorption peaks were selected arbitrarily within 3-5 and 8-14  $\mu\text{m}$  for our proof-of-concept by modifying  $R$  and  $n$ . For ideal dielectric spacer, the resonant wavelength is only influenced by radius of ring. It is worth noting that the individual ring leads to blueshift of the resonant frequency, different from presence of two rings simultaneously. This phenomenon can be attribute to the anti-parallel surface current oscillation in the neighboring rings and can be relieved by increasing the ring distance  $S$ . However, modification of one ring has no effect on another resonant band for two rings structure.



**Fig. 4** Resonant wavelength and maximum absorption dependence of dual-band MMPA with  $S$ ,  $R$  and  $t$ . **a** Absorbance spectra with increasing  $S$  at  $t = 280$  nm. **b** Relationship between two excited modes with increasing  $S$ . **c** Relationship between

maximum absorbance and  $t$ . **d**  $R$  and  $n$  for customizing at  $t = 250$  nm. For **a-c**, dielectric spacer is silicon dioxide and for **d**, the  $n$  of spacer is set to 1.4 and 1.5

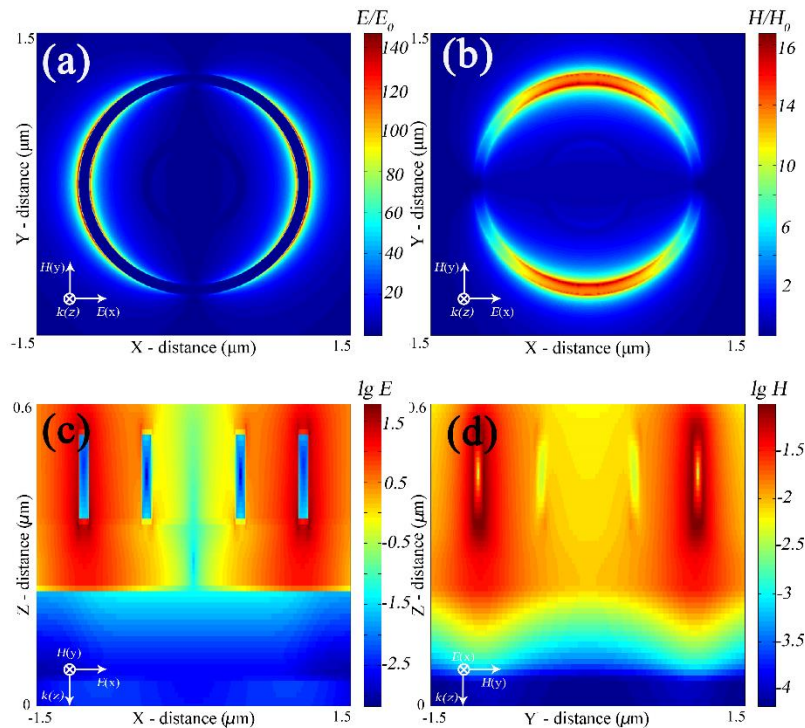
To interpret the mechanism behind this enhancement, Fig. 5 and Fig. 6 show the spatial distribution of electric ( $E$ ) and magnetic ( $H$ ) fields for structure plotted in Fig. 4d (black line). The enhancement factor,  $E/E_0$  and  $H/H_0$ , provides insight into the mechanism behind the enhancement where  $E$  and  $H$ ,  $E_0$  and  $H_0$  are the intensity of electric field and magnetic field respectively at given position and that would occur at the same position in the absence of gold ring. It can be seen from Fig. 5 and Fig. 6 that magnetic field and electric field are enhanced dramatically at resonant wavelengths 4332 nm and 9890 nm respectively. The local field intensity is even 20~140 times larger than the ring-absent structure. The electric component of the plane wave can couple the electric field strongly because two gold rings afford local surface plasmon resonances (LSPRs) and surface plasmon polaritons (SPPs). For magnetic component, it gives rise to antiparallel surface current on the rings and the ground metal plane, leading to the magnetic coupling and the response, as shown in Fig. 7. Utilizing the surface plasmon (SP) mode, various nanostructured absorbers have been achieved, such as nano-apertures [47], nano-antennas [43], micro-scale cavity [44], nano shaped resonator/grating [35] and convex groove [48].



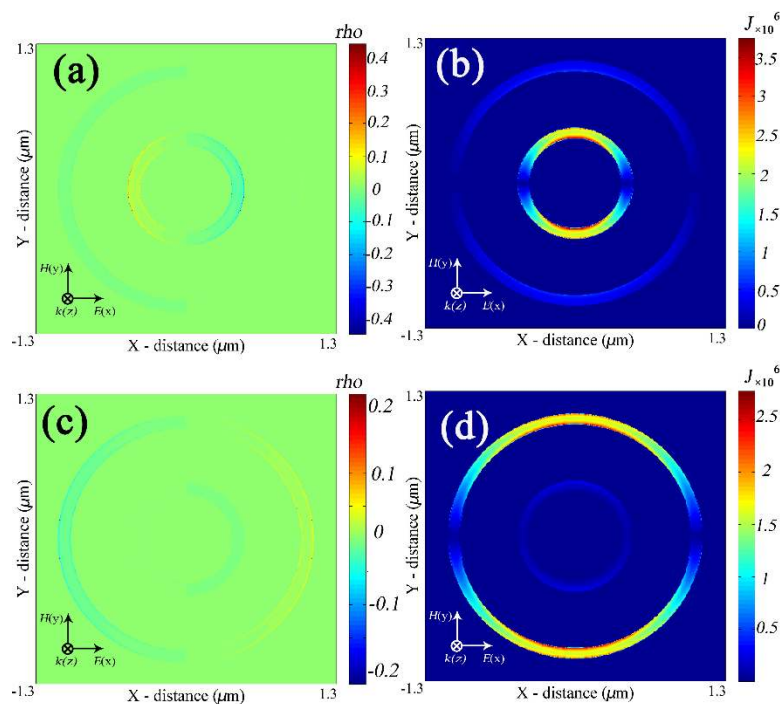
**Fig. 5** Maps of electric and magnetic fields at resonant mode (M1) corresponding to **Fig. 4 d** (black line). **a** Enhancement factor,  $E/E_0$  in the x-y plane at  $z = 5$  nm. **b** Enhancement factor,  $H/H_0$  in the x-y plane at  $z = 5$  nm. **c** Spatial map of logarithmic electric intensity. **d** Spatial map of logarithmic magnetic intensity

Fig. 5c and d (also in Fig. 6) show the logarithmic electric and magnetic field intensity. It mirrors the energy field distribution around the rings. For the M1 resonance, electric and magnetic field are squeezed in the inner ring and the gap between two rings. Unlike the M1 resonance, the M2 resonance has slight distinction. Electric and magnetic field are confined in the gap between two rings while opened on the outside of the external ring for M2. This explained that the M2 peak (0.929 or -0.32 dB) is slightly

weaker than M1 (0.973 or -0.12 dB) because of the out-coupling of M2. At M1 resonance, most of the energy is focused in the inner ring. Therefore, the FWHM of M1 is sharper than M2. The  $E$  and  $H$  distribution reveal that the energy of the incidence is almost absorbed by the rings structure as illustrated by the marked color map.



**Fig. 6** Maps of electric and magnetic fields at resonant mode (M2) corresponding to **Fig. 4 d** (black line). **a** Enhancement factor,  $E/E_0$  in the x-y plane at  $z = 5$  nm. **b** Enhancement factor,  $H/H_0$  in the x-y plane at  $z = 5$  nm. **c** Spatial map of logarithmic electric intensity. **d** Spatial map of logarithmic magnetic intensity

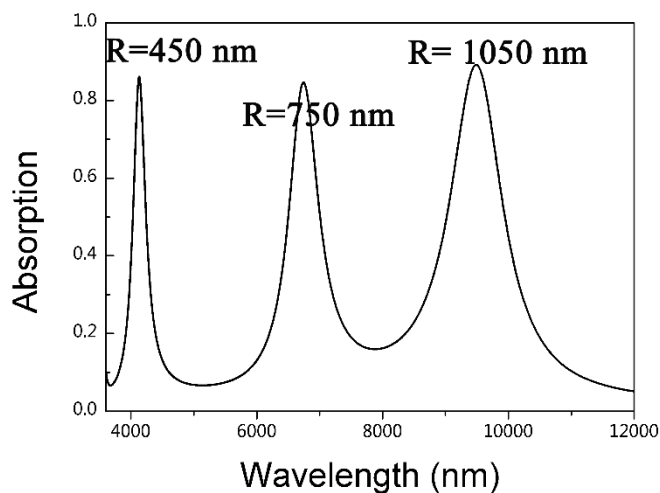




**Fig. 7** Charge density and current density distribution of  $x$ - $y$  plane at  $z = 100$  nm depths at two resonant modes corresponding to **Fig. 4 d** (black line). **a, b** for M1. **c, d** for M2

For the M1 mode the current flow is confined almost entirely in the inner ring and region under ring, while the M2 mode is mainly associated with the external ring, as shown in Fig. 7b and d. The current underneath the excited ring (not shown in figure) is caused by image charge, which forms the loops and further triggers magnetic response. This means that two absorption peaks are caused by ohmic loss and dielectric loss. Such phenomenon is observed in fishnet-shaped [49], cross-shaped [43] and H-shaped [15] structure. Fig. 7a and c illustrate the charge density of  $x$ - $y$  plane at  $z = 100$  nm. They are agree with the near-field enhancement as plotted in Fig. 5 and Fig. 6 with strong charge buildup at two sides of the ring, confined to the edge of the metal. The current flow in ring and gold film is generated by magnetic response while the leakage current in spacer is caused by electric field. Thus electric and magnetic response depicts the perfect absorption of majority of energy with  $x$ -polarized electric field and  $y$ -polarized magnetic field. This suggests that symmetrical ring couples the electromagnetic wave with no energy loss at resonant frequency by large near-field enhancement capacitance provide by the gap between two rings for electric filed component and anti-parallel current flow for magnetic field component.

Though other resonators, such as patches, discs, demonstrate high absorptivity with polarization-nearly insensitive performance, they lack of scalability. In some cases, most of the possible light containing arbitrarily polarized components needs to be absorbed. The proposed split-ring resonator is completely polarization-independent because of its symmetry. Additionally, in our structure, adding an extra ring to achieve three absorption peaks are plotted in Fig. 8 a. Three peaks are distributed in MIR and FIR region, slightly influenced with each other. Therefore, it is flexible with tunable absorption peaks via controlling the number of the rings.



**Fig. 8** Absorption spectra of the triple-band absorber

#### 4. Conclusion

Overall, the MMPA structure incorporating the nano-rings achieves high absorptivity at targeted frequencies greater than 90% or -0.46 dB for a plane wave and is polarization-insensitive. Numerical full-wavelength FDTD simulations reveals that incident light is strongly absorbed within the two

1  
2  
3 resonant bands. The plasmonic nano-ring provides a large near-field enhancement which is 20~140 times  
4 larger than the non-plasmonic case. The work exhibits a significant progress toward achieving high-  
5 efficiency MMPAs that suppress the reflection at multiple bands within MIR and FIR region, though  
6 with trade-off between FWHM and desired wavelength. Our calculations show that the double-ring  
7 MMPA design is promising for MIR and FIR applications and exhibits excellent tunability over a broad  
8 spectral region, especially for multi-color photodetectors.  
9

### 12 Acknowledgments

13  
14 Authors appreciate the financial supports by the National Program on Key Basic Research Project (973  
15 Program) No. 2013CB933301, National Program on Key Basic Research Project (973 Program) No.  
16 2015CB358600.  
17

### 18 References

- 19 1. Smith DR, Padilla WJ, Vier DC, Nemat-Nasser SC, Schultz S (2000) Composite medium with  
20 simultaneously negative permeability and permittivity. *Physical Review Letters* 84 (18):4184-4187.  
21 doi:10.1103/PhysRevLett.84.4184
- 22 2. Pendry JB (2000) Negative refraction makes a perfect lens. *Physical Review Letters* 85 (18):3966-  
23 3969. doi:10.1103/PhysRevLett.85.3966
- 24 3. Valentine J, Li JS, Zentgraf T, Bartal G, Zhang X (2009) An optical cloak made of dielectrics. *Nature*  
25 *Materials* 8 (7):568-571. doi:10.1038/nmat2461
- 26 4. Schurig D, Mock JJ, Justice BJ, Cummer SA, Pendry JB, Starr AF, Smith DR (2006) Metamaterial  
27 electromagnetic cloak at microwave frequencies. *Science* 314 (5801):977-980.  
28 doi:10.1126/science.1133628
- 29 5. Kurter C, Abrahams J, Anlage SM (2010) Miniaturized superconducting metamaterials for radio  
30 frequencies. *Applied Physics Letters* 96 (25):3. doi:10.1063/1.3456524
- 31 6. Kante B, Ourir A, Burokur SN, Gadot F, de Lustrac A (2008) Metamaterials for optical and radio  
32 communications. *Comptes Rendus Physique* 9 (1):31-40. doi:10.1016/j.crhy.2007.10.004
- 33 7. Edwards B, Alu A, Young ME, Silveirinha M, Engheta N (2008) Experimental verification of epsilon-  
34 near-zero metamaterial coupling and energy squeezing using a microwave waveguide. *Physical Review*  
35 *Letters* 100 (3):4. doi:10.1103/PhysRevLett.100.033903
- 36 8. Shelby RA, Smith DR, Nemat-Nasser SC, Schultz S (2001) Microwave transmission through a two-  
37 dimensional, isotropic, left-handed metamaterial. *Applied Physics Letters* 78 (4):489-491.  
38 doi:10.1063/1.1343489
- 39 9. Paulish AG, Zagubisalo PS, Kuznetsov SA, Ieee (2013) High-Performance Metamaterial MM-to-IR  
40 Converter for MM-wave Imaging. 2013 38th International Conference on Infrared, Millimeter, and  
41 Terahertz Waves (Irmw-Thz)
- 42 10. Sajin G, Mocanu IA, Craciunoiu F (2013) MM-Wave Metamaterial Adjustable Antenna on  
43 Magnetically Biased Ferritic Substrate. *International Journal of Antennas and Propagation*.  
44 doi:10.1155/2013/696483
- 45 11. Zagubisalo PS, Paulish AG, Kuznetsov SA (2014) Simulation of Thermal Processes in Metamaterial  
46 MM-to-IR Converter for MM-wave Imager. 2nd International Conference on Mathematical Modeling in  
47 Physical Sciences 2013 (Ic-Msquare 2013) 490. doi:10.1088/1742-6596/490/1/012174
- 48 12. Neu J, Krolla B, Paul O, Reinhard B, Beigang R, Rahm M (2010) Metamaterial-based gradient index  
49 lens with strong focusing in the THz frequency range. *Optics Express* 18 (26):27748-27757.  
50 doi:10.1364/oe.18.027748  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

13. Scalari G, Maissen C, Turcinkova D, Hagenmueller D, De Liberato S, Ciuti C, Reichl C, Schuh D, Wegscheider W, Beck M, Faist J (2012) Ultrastrong Coupling of the Cyclotron Transition of a 2D Electron Gas to a THz Metamaterial. *Science* 335 (6074):1323-1326. doi:10.1126/science.1216022
14. Zolotovskii IO, Korobko DA, Minvaliev RN, Ostatochnikov VA (2014) A generator of far-infrared and terahertz radiation in nonlinear metamaterials exhibiting negative index of refraction. *Optics and Spectroscopy* 117 (5):822-831. doi:10.1134/s0030400x14110253
15. Jiang ZH, Yun S, Toor F, Werner DH, Mayer TS (2011) Conformal Dual-Band Near-Perfectly Absorbing Mid-Infrared Metamaterial Coating. *Acs Nano* 5 (6):4641-4647. doi:10.1021/nn2004603
16. Korobkin D, Urzhumov YA, Neuner B, III, Zorman C, Zhang Z, Mayergoyz ID, Shvets G (2007) Mid-infrared metamaterial based on perforated SiC membrane: engineering optical response using surface phonon polaritons. *Applied Physics a-Materials Science & Processing* 88 (4):605-609. doi:10.1007/s00339-007-4084-8
17. Yu Z, Veronis G, Fan S, Brongersma ML (2006) Design of midinfrared photodetectors enhanced by surface plasmons on grating structures. *Applied Physics Letters* 89 (15):151116. doi:10.1063/1.2360896
18. Helgert C, Menzel C, Rockstuhl C, Pshenay-Severin E, Kley EB, Chipouline A, Tuennermann A, Lederer F, Pertsch T (2009) Polarization-independent negative-index metamaterial in the near infrared. *Optics Letters* 34 (5):704-706
19. Sersic I, Frimmer M, Verhagen E, Koenderink AF (2009) Electric and Magnetic Dipole Coupling in Near-Infrared Split-Ring Metamaterial Arrays. *Physical Review Letters* 103 (21). doi:10.1103/PhysRevLett.103.213902
20. Christ A, Martin OJF, Ekinci Y, Gippius NA, Tikhodeev SG (2008) Symmetry breaking in a plasmonic metamaterial at optical wavelength. *Nano letters* 8 (8):2171-2175. doi:10.1021/nl0805559
21. Salandrino A, Engheta N (2006) Far-field subdiffraction optical microscopy using metamaterial crystals: Theory and simulations. *Physical Review B* 74 (7). doi:10.1103/PhysRevB.74.075103
22. Landy NI, Sajuyigbe S, Mock JJ, Smith DR, Padilla WJ (2008) Perfect metamaterial absorber. *Physical Review Letters* 100 (20):4. doi:10.1103/PhysRevLett.100.207402
23. Venkatesh S, Shrekenhamer D, Xu W, Sonkusale S, Padilla W, Schurig D (2013) Interferometric direction finding with a metamaterial detector. *Applied Physics Letters* 103 (25). doi:10.1063/1.4851936
24. Benz A, Krall M, Schwarz S, Dietze D, Detz H, Andrews AM, Schrenk W, Strasser G, Unterrainer K (2014) Resonant metamaterial detectors based on THz quantum-cascade structures. *Scientific Reports* 4:10. doi:10.1038/srep04269
25. Wang H, Yang Y, Wang LP (2014) Switchable wavelength-selective and diffuse metamaterial absorber/emitter with a phase transition spacer layer. *Applied Physics Letters* 105 (7):5. doi:10.1063/1.4893616
26. Kuznetsov SA, Paulish AG, Gelfand AV, Lazorskiy PA, Fedorinin VN (2012) MATRIX STRUCTURE OF METAMATERIAL ABSORBERS FOR MULTISPECTRAL TERAHERTZ IMAGING. *Prog Electromagn Res* 122:93-103. doi:10.2528/pier11101401
27. Wang Y, Sun TY, Paudel T, Zhang Y, Ren ZF, Kempa K (2012) Metamaterial-Plasmonic Absorber Structure for High Efficiency Amorphous Silicon Solar Cells. *Nano letters* 12 (1):440-445. doi:10.1021/nl203763k
28. Phillips J (2002) Evaluation of the fundamental properties of quantum dot infrared detectors. *Journal of Applied Physics* 91 (7):4590-4594. doi:10.1063/1.1455130
29. Guo B, Yang LQ, Hu WJ, Li WL, Wang HJ (2015) Effect of nano-sized cerium zirconium oxide solid solution on far-infrared emission properties of tourmaline powders. *Modern Physics Letters B* 29 (30):11.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

doi:10.1142/s0217984915501833

30. Xu GK, Liang JS, Wang LJ, Meng JP, Liang GC (2005) Effects on combustion of gasoline of rare earth composite materials for far infrared radiation. *J Rare Earths* 23:247-250

31. Mizeikis V, Seet KK, Juodkazis S, Misawa H (2004) Three-dimensional woodpile photonic crystal templates for the infrared spectral range. *Optics Letters* 29 (17):2061-2063. doi:10.1364/ol.29.002061

32. Grant J, Ma Y, Saha S, Lok LB, Khalid A, Cumming DRS (2011) Polarization insensitive terahertz metamaterial absorber. *Optics Letters* 36 (8):1524-1526

33. Tao H, Bingham CM, Pilon D, Fan K, Strikwerda AC, Shrekenhamer D, Padilla WJ, Zhang X, Averitt RD (2010) A dual band terahertz metamaterial absorber. *Journal of Physics D-Applied Physics* 43 (22). doi:10.1088/0022-3727/43/22/225102

34. Tao H, Bingham CM, Strikwerda AC, Pilon D, Shrekenhamer D, Landy NI, Fan K, Zhang X, Padilla WJ, Averitt RD (2008) Highly flexible wide angle of incidence terahertz metamaterial absorber: Design, fabrication, and characterization. *Physical Review B* 78 (24). doi:10.1103/PhysRevB.78.241103

35. Wen Q-Y, Zhang H-W, Xie Y-S, Yang Q-H, Liu Y-L (2009) Dual band terahertz metamaterial absorber: Design, fabrication, and characterization. *Applied Physics Letters* 95 (24). doi:10.1063/1.3276072

36. Grant J, Ma Y, Saha S, Khalid A, Cumming DRS (2011) Polarization insensitive, broadband terahertz metamaterial absorber. *Optics Letters* 36 (17):3476-3478

37. Cheng YZ, Nie Y, Gong RZ, Yang HL (2011) Multi-band metamaterial absorber using cave-cross resonator. *European Physical Journal-Applied Physics* 56 (3). doi:10.1051/epjap/2011110206

38. Dayal G, Ramakrishna SA (2013) Design of multi-band metamaterial perfect absorbers with stacked metal-dielectric disks. *Journal of Optics* 15 (5). doi:10.1088/2040-8978/15/5/055106

39. Huang L, Chen H (2011) MULTI-BAND AND POLARIZATION INSENSITIVE METAMATERIAL ABSORBER. *Prog Electromagn Res* 113:103-110. doi:10.2528/pier10122401

40. Ye Q, Liu Y, Lin H, Li M, Yang H (2012) Multi-band metamaterial absorber made of multi-gap SRRs structure. *Applied Physics a-Materials Science & Processing* 107 (1):155-160. doi:10.1007/s00339-012-6796-7

41. Zhang N, Zhou PH, Cheng DM, Weng XL, Xie JL, Deng LJ (2013) Dual-band absorption of mid-infrared metamaterial absorber based on distinct dielectric spacing layers. *Optics Letters* 38 (7):1125-1127

42. Shen X, Cui TJ, Zhao J, Ma HF, Jiang WX, Li H (2011) Polarization-independent wide-angle triple-band metamaterial absorber. *Opt Express* 19 (10):9401-9407. doi:10.1364/OE.19.009401

43. Chen K, Adato R, Altug H (2012) Dual-Band Perfect Absorber for Multispectral Plasmon-Enhanced Infrared Spectroscopy. *Acs Nano* 6 (9):7998-8006. doi:10.1021/nn3026468

44. Mao FL, Xie JJ, Xiao SY, Komiyama S, Lu W, Zhou L, An ZH (2013) Plasmonic light harvesting for multicolor infrared thermal detection. *Optics Express* 21 (1):295-304. doi:10.1364/oe.21.000295

45. Rakić AD, Djurišić AB, Elazar JM, Majewski ML (1998) Optical properties of metallic films for vertical-cavity optoelectronic devices. *Applied Optics* 37 (22):5271-5283. doi:10.1364/AO.37.005271

46. Palik ED (1985) *Handbook of optical constants of solids*. Academic Press, Orlando

47. Tang L, Miller DAB, Okyay AK, Matteo JA, Yuen Y, Saraswat KC, Hesselink L (2006) C-shaped nanoaperture-enhanced germanium photodetector. *Optics Letters* 31 (10):1519-1521. doi:10.1364/ol.31.001519

48. Beermann J, Eriksen RL, Sondergaard T, Holmgaard T, Pedersen K, Bozhevolnyi SI (2013) Plasmonic black metals by broadband light absorption in ultra-sharp convex grooves. *New Journal of*

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

Physics 15:16. doi:10.1088/1367-2630/15/7/073007

49. Kafesaki M, Tsiapa I, Katsarakis N, Koschny T, Soukoulis CM, Economou EN (2007) Left-handed metamaterials: The fishnet structure and its variations. *Physical Review B* 75 (23):235114