

# Ultra-Broadband Absorber Based on Metasurfaces in the Infrared Regime



Vijay Laxmi, Abida Parveen, Deepika Tyagi, and Zhengbiao Ouyang

**Abstract** An ultra-broadband metasurface absorber is proposed that falls in the terahertz regime cover a wide spectrum. Here we theoretically demonstrate the novel design of angular and polarization-insensitive ultra-broadband multi-metasurfaces-based absorber (MMBA) on a metallic substrate in the infrared spectrum of wavelength 1.5–6  $\mu\text{m}$ . The proposed device is composed of germanium and gold slabs arranged periodically to work as a metasurface on a metallic substrate. A metal–dielectric interface has been repeated to enhance the absorption. A circular top layer is used to reduce the dips in absorption peak and for broadband spectrum consequently, absorption improved up to 95% covering broadband from 2.5  $\mu\text{m}$  to 6  $\mu\text{m}$ . A systematic theoretical investigation about this model revealed that this absorber is insensitive to the incident angles and polarization of light with excellent performance for an s-polarized and p-polarized plane wave. The metamaterial (MM)-based absorber received significant attention due to their promising properties and have the potential for many applications such as thermal emitters, high-speed communication, imaging, optoelectronic devices.

**Keywords** Metamaterials · Absorber · Ultra-broadband · Metasurfaces · Angle insensitivity

## 1 Introduction

Recently, metamaterial (MM) absorbers have gained considerable attraction due to their outstanding properties in the field of nanoelectronics and nanophotonics [1–4].

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MM-based absorbers cover a very broad range including a few GHz to 10 THz and have auspicious applications in various fields from medical to communication. MMs can be defined as artificial material, composed of periodically arranged subwavelength microstructure. Their properties strongly depend on their designed nano-structure instead of the composition of materials. MMs exhibit many unusual phenomena such as cloaking, double negative index, anomalous light bending, superlens [5, 6] and MMs also display perfect electromagnetic absorption. The first metamaterial absorber was fabricated in 2008, with the help of two resonators [7]. After this discovery, many theoretical investigations have been published over metamaterials perfect absorber [8–12]. And their simplest structure makes them an excellent candidate to fabricate and commercialize in many daily life applications such as superlens, thermal emitters, wireless communications, sensing, light manipulation, and imaging [13–17]. Their macroscopic electromagnetic properties arise at a subwavelength scale due to the collective response of the individual structure. For future electronics, MM-based absorber plays a significant role in further improving the performance of the optoelectronics devices such as thermal emitters, thermal radiators, solar cells, and detection [4, 18]. To obtain a near-unity absorption is still a bottleneck for a perfect MM absorber (MMA). Nevertheless, with the help of MMs, it is somehow possible to reach the boundary of maximum absorption. Near-unity absorption with ultra-broadband is still an issue to resolve. Moreover, MMA falls in the THz regime leads to many attractive branches of terahertz devices because of their scalable features. Many multi-layer structures have been realized and experimentally demonstrated to gain the maximum absorption and expand the bandwidth, including five-layered [19] and three-layered [2] terahertz metamaterials. This multi-layer structure can be the composition of periodically arranged dielectric layers, metallic patterns, and a metal/dielectric, metal/dielectric/metal, and metal/insulator/metal (MIM). As it is previously mentioned that their properties are defined according to their structure therefore MMAs are typically designed of a tri-layer structure in the infrared or visible region [1, 20]. In recent years, MMAs have been effectively utilized to clarify and anticipate the resonances in metallic grating film structure [21, 22], narrow slit array [23, 24], double-layer nanoslit array [25], and deep grating [25, 26]. Usually, extreme absorptance reaches its limit when the effective impedance of the proposed structure matches with the impedance of the free space. Numerous efforts have been made to enlarge the absorption bandwidth of MMAs, such as, by joining two different resonators into one-unit, dual-band absorption [10, 27]. However, the average absorptivity efficiency is still not very high because those absorption spectra are composed of discrete peaks. While the single band MMA is not appropriate in certain zones, for example, phase imaging, spectroscopic detection where distinct absorption peaks are required, most MMAs generally require unit cells with complex geometries, including complex structure and cost of manufacture. Moreover, previous designs are incident angle and polarization-sensitive which may unblock numerous practical applications [28].

Here, we have theoretically designed and simulated this MMA which is incident angle and polarization insensitive (s-polarization and p-polarization). This broadband multi-layer metasurface-based absorber (MMBA) operates in a broad spectrum

ranging from 1.5 to 6  $\mu\text{m}$ . The MMBA is designed by five layers in which semiconductor and metals layers are arranged alternatively in a periodic manner with perfect electric conductor (PEC, or metallic substrate) on the ground plane. Three benchmarks are studied to reveal the novelty of our work which includes usage of a resonator multi-structure, a dual-layered multi resonator for better absorption, and a metallic substrate. In this paper, an ultra-broadband absorber based on a metasurface is presented for the infrared spectrum in the terahertz (THz) region. The absorption bandwidth increased much significantly in our proposed absorber. The simulated total absorption increased more than 90% by using a multi-layered single structure. Besides, the results show that the absorption bandwidth is significantly enlarged by using multi-layers of the metasurface, also known as a dual-layered absorber. The top layer is used circularly to reduce the dips in absorption peak and expand the bandwidth of absorption by using multi-mode resonance absorption in the circular ring resonator. In addition, an angle-dependent study has been done which accomplishes that MMBA is angle insensitive and polarization-insensitive. This MMBA is an excellent contender for many applications such as spectroscopic imaging, thermal emitters, as well as thermal detectors due to its exceptional properties. For further improvement in the device, the unit cell keeps on repeating up to 12 square patches to design a dual-layered MIM structure within a subwavelength period, and consequently, the absorption exceeds up to 95% for a broad range spectrum. The dual-layered absorber has improved the bandwidth more than two times in contrast with the single resonator.

The absorptivity  $A(\omega)$  is calculated from the Eq. (1):

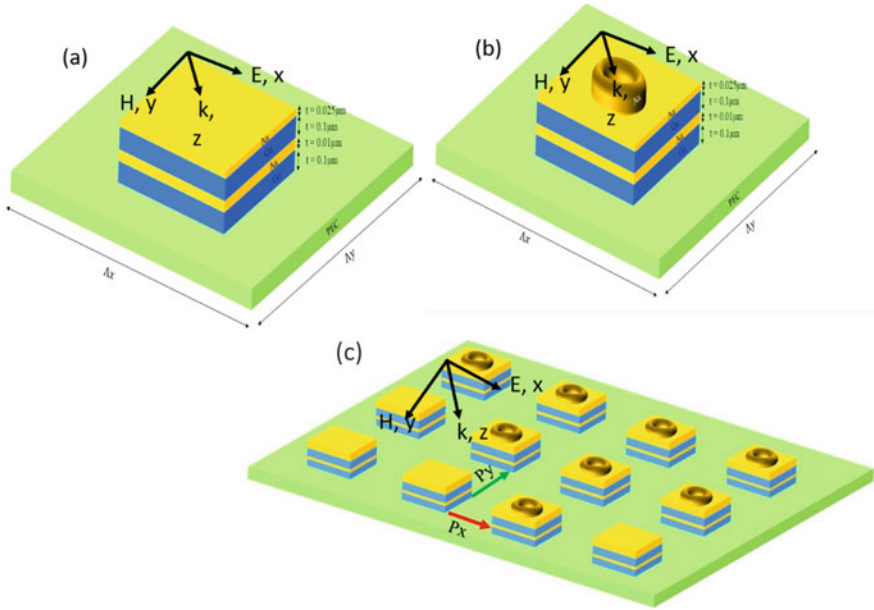
$$A = 1 - R(\omega) - T(\omega), \quad (1)$$

where  $R(\omega)$  and  $T(\omega)$  are reflectivity and transmissivity as functions of frequency  $\omega$ , respectively.

## 2 Device Design and Simulation

Generally, the geometric configuration and the geometrical parameters are considered the special factor in determining the resonance frequency. Multiple resonators of the same size and shapes are designed and fabricated to achieve unity absorption with maximized bandwidth. Typically, they are arranged periodically in a two-dimensional plane to form a metasurface. Here, a multi-metasurface broadband absorber (MMBBA) is theoretically demonstrated and simulated. This MMBBA is made of twelve metallic square patches of different geometric parameters, as shown in Fig. 1a. Previously reported absorbers are generally designed along the side with arranging of different sized subunits into one-unit cells or vertically stacking multi-layer structures, to get numerous absorption peaks [3].

Multi-layers and other parameters such as thickness, materials, and stacking, help to occur many resonant peaks during excitation and survived due to resonance

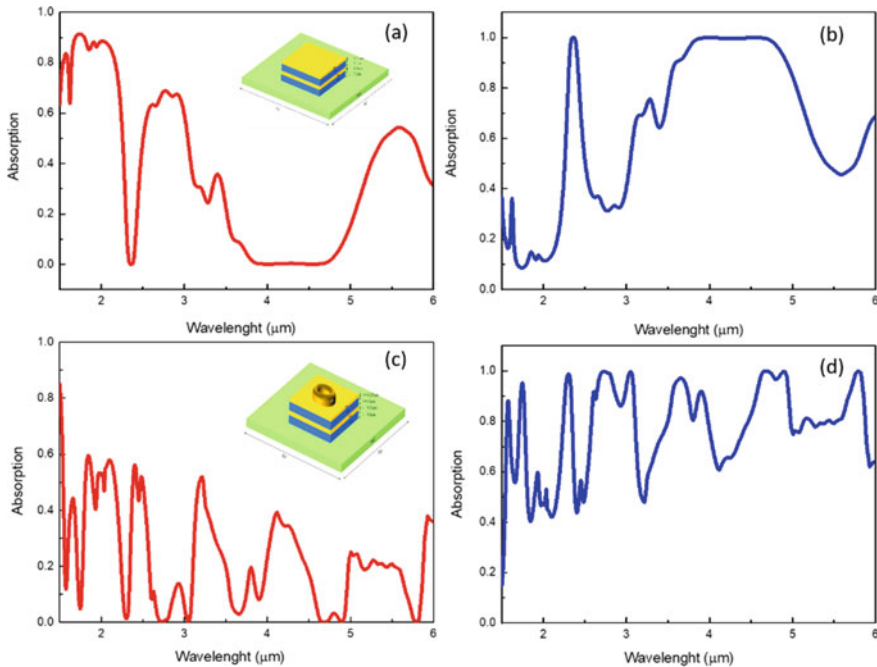


**Fig. 1** Proposed devices; **a** perspective view of the single resonator (square patch) multi-structure metasurfaces arranged periodically, **b** a circular ring has been placed as the top layer, **c** the repeated unit cell of MMBBA with a complete structure made of twelve metallic square patches of different geometric parameters

independence. Initially, a single unit cell of a multi-layered resonator is examined to understand the concept of multi-band absorption as mentioned in Fig. 1a. A multi-surface absorber is designed with three different materials, the ground plane is made of the perfect electric conductor (PEC) and then a square slab has chosen over it, of a little smaller size. The conductivity of gold is  $4.10 \times 10^7$  S/m. The next layer is an insulator made of germanium (Ge) with a refractive index of 4. An s-polarized and p-polarized plane wave enlightened the proposed device structure. The metal and dielectric are arranged periodically in the same manner with identical widths and height over the surface of PEC with a period of  $\Delta_x = 3.6 \mu\text{m}$  with equal widths  $\Delta_y = 1 \mu\text{m}$ . The thickness of Ge is  $0.1 \mu\text{m}$  throughout the whole structure. The top metallic layer of gold has thickness  $t_{\text{Au}} = 0.025 \mu\text{m}$  and the bottom layer of gold has thickness  $t_{\text{Au}} = 0.01 \mu\text{m}$ . The refractive index of Ge becomes 0.0000000005 inside the measured frequency range. The substrate has a thickness of  $t_{\text{PEC}} = 0.1 \mu\text{m}$ . For further improvement in absorption peak over broadband, A ring resonator of gold metal is designed on the top which has an outer radius of  $R_1 = 0.2 \mu\text{m}$  and an inner radius of  $R_2 = 0.1 \mu\text{m}$  shown in Fig. 1b. Figure 1c shows the perspective view of wide-band multi-sized resonators at normal incidence with identical spacing distance to neighbor resonators  $P_x = 0.05 \mu\text{m}$ , and  $P_y = 0.05 \mu\text{m}$ .

To examine the performance of the design in Fig. 1a, a full-wave simulation was completed using the finite-difference time-domain (FDTD) method. In the simulation arrangement, the PML boundary condition was set along the z-direction, and the periodical boundary conditions were set alongside the x- and y-directions. The presented Cartesian coordinate system shows that the propagation vector is along the z-direction while electric field ( $\mathbf{E}$ ) is in x-direction with normal to magnetic field ( $\mathbf{H}$ ) displayed with each structure. As it is mentioned in Fig. 1, a multi-layered single band absorber is investigated theoretically and the proposed structure is elucidated with all parameters. Figure 1b shows a similar structure with placing a gold ring resonator as a top layer of the device. The presented MMBBA has a high absorption peak of about 95% with covering 1.5–6  $\mu\text{m}$ . Further information is revealed in Fig. 2. Figures 2a, b show the reflection and absorption spectra of the multi-layer single absorber with inset showing the corresponding structure. Using Eq. (1), it is seen that reflection works opposite of absorption and which concludes that the absorption peak is maximum at few wavelengths. Figure 2c depicted the reflection spectra of similar multi-metasurfaces with a gold ring as a top layer.

As it is apparent in Fig. 2d the number of absorption peaks enhanced after placing the top layer as a circular ring because the ring serves as a resonator and there is



**Fig. 2** Simulated reflection and absorption characteristics of the proposed device with inset of their proposed structures; **a** reflection spectra for multi-meta surfaces (single resonator), **b** absorption spectra for multi-meta surfaces (single resonator), **c** reflection spectra with a top layer as circular, **d** absorption spectra with top layer as circular

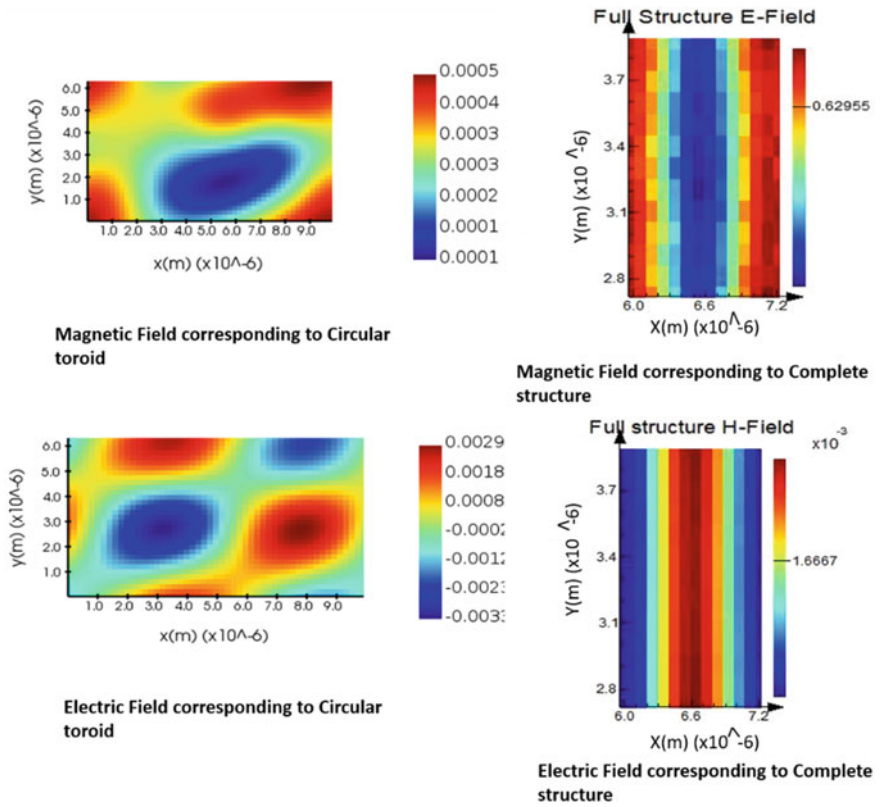
multi-mode resonance absorption in the resonator and this multi-mode resonance absorption greatly enhanced the absorption. While in Fig. 2a, from 1  $\mu\text{m}$  to 4  $\mu\text{m}$  there is no proper absorption peak. After placing the top layer circular, various absorption peaks are observed in a single resonator at wavelengths = 1.6  $\mu\text{m}$ , 2.5  $\mu\text{m}$ , 3.5  $\mu\text{m}$ , etc., as shown in Fig. 2c. Moreover, an absorption spectrum is calculated with the gold ring resonator to clarify the above information. Figure 2d displays the absorption spectra ranging from 1.5  $\mu\text{m}$  to 6  $\mu\text{m}$ . A significant improvement is there. Nevertheless, these peaks occur due to distinct resonant peaks in a narrow band at their resonant frequencies.

To clear the concepts, a complete display of reflection spectra concerning the electric field and magnetic field as a function of wavelength is specified in Fig. 3. The four sub figures give the information about electric and magnetic field corresponding complete structure and across the circular top layer. This accomplishes that the electric field is focused on both sides of the metallic patch. The strong intensity of the electric field is high because of large charge accumulation over the metallic patches and this concludes the excitation of electric dipole resonance. For s-polarization mode, most energy is consumed by the metallic resonator. Figure 3 represents E and H for s-polarization mode, and p-polarization mode is not presented for brevity. Therefore, the required power stays in between the dielectric layers typically the upper layer. Electromagnetic waves start moving back and forth between dielectric and so metallic slab. Consequently, resonant absorption of Fabry–Perot induced mode occurred. It is reasonable that at corresponding resonance wavelength, the structure can efficiently confine the incident electromagnetic waves.

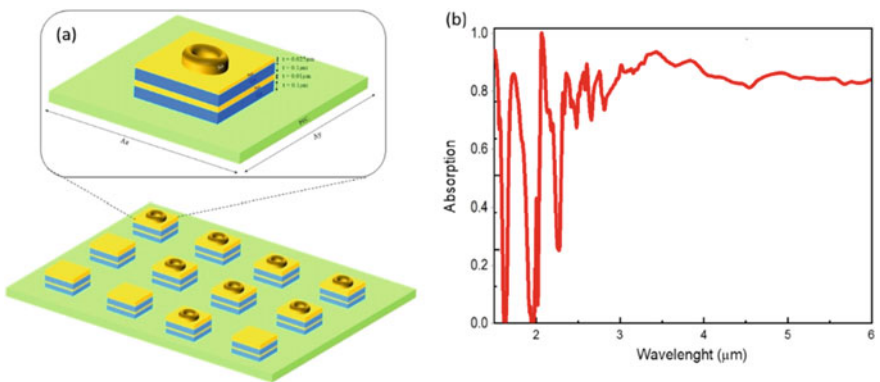
This MMA is theoretically designed and simulated to accomplish high absorption bandwidth and ultra-broadband. The multi-metasurface single band resonator with a circular top layer is repeated as a unit cell. As it was mentioned in Fig. 2d, the broadband resonance consists of several distinct resonances. Ultimately, a multi-layered dual-broadband absorber is designed by repeating the initial structure depicted in Fig. 4a and corresponding absorption spectra are demonstrated in Fig. 4b. Maximum absorption has been grasped at wavelength 2.25  $\mu\text{m}$  and beyond this point, and it gradually decreases with a minimum value at 2.4  $\mu\text{m}$  with very small dips [3]. Figure 4b also clarifies that individual resonant peaks are combined and a maximum absorption peak covers a broad spectrum range from 50 to 200 THz.

### 3 The Absorption Characteristics

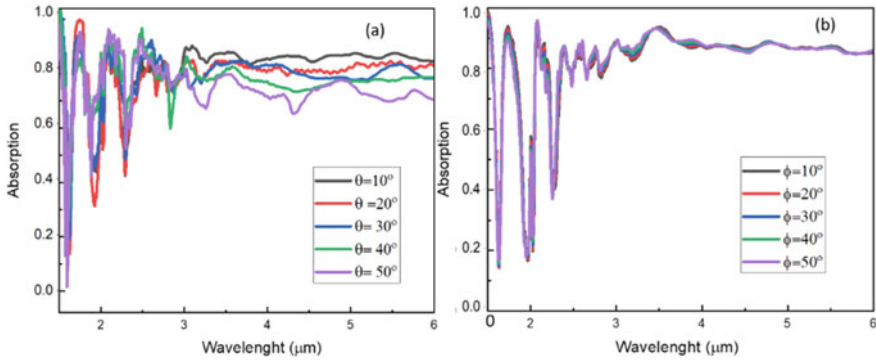
Recently, many efforts have been made to design polarization-insensitive absorption or wide-angle absorption (only in the incident plane with a fixed azimuthal angle). They have many potential applications such as thermal detectors, thermal emitters, and solar cells. To make our device superior, the absorption spectra at different incident angle 10°, 20°, 30°, and 40°, 50° is calculated. While the azimuthal angle remains fixed, i.e.,  $\varphi = 0^\circ$  shown in Fig. 5. The absorption spectra as a function of incident angle are also inspected at a fixed azimuthal angle ( $\varphi = 0^\circ$ ) and then incident angles



**Fig. 3** Distribution map of electric field and magnetic field intensity for the reflection spectra. The four sub figures include electric and magnetic field across the complete structure and across the top circular ring



**Fig. 4** Schematic diagram of the proposed dual-layered MMBBA-based absorber with same parameters; **a** unit cell of MMBBA with a complete structure, **b** the corresponding absorption spectrum

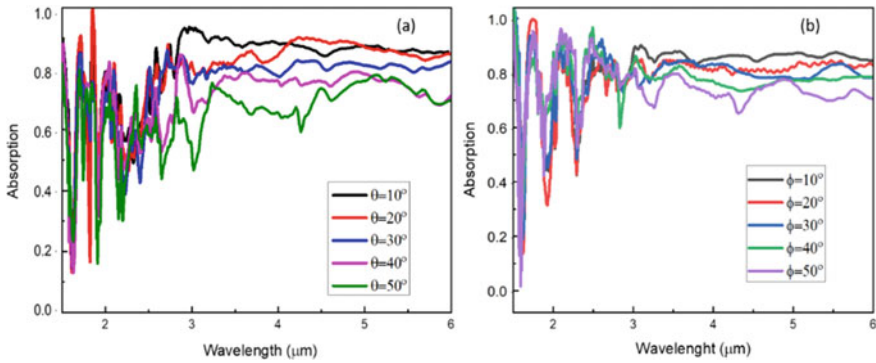


**Fig. 5** Absorption spectra of MMBBA for p-polarized radiation; **a** absorption spectra of multi-structure at different incident angles, **b** at different azimuthal angles

keeps constant at  $0^\circ$  and azimuthal angle  $\varphi$  is changed and different absorption peak is calculated for p-polarization at angle ( $\Phi = 0^\circ$ ) as depicted in Fig. 5. Different incident angles make very slight difference in the absorption spectrum. The small peaks happened in between the broad spectrum are due to the surface plasmon polariton resonance was not able to excite the peaks. Therefore, absorption dips arise due to a limited number of resonance modes and the condition of destructive interference is less satisfied. Consequently, the complete absorption spectrum remains unchanged at a different incident angle. This means, the proposed absorber is incident angle insensitive.

Additionally, the absorption spectra are investigated as a function of azimuthal angle ( $\varphi$ ) at a fixed incident angle ( $\theta = 0^\circ$ ) and vice versa with polarization angle ( $\Phi = 90^\circ$ ) also known as s-polarization revealed in Figs. 6a, b), where the angle " $\theta$ " is the angle of propagation, in degrees, with respect to the injection axis of the source and angle  $\varphi$  (azimuthal angle of propagation), rotated about the injection axis of the source in a right-hand context. The angle  $\Phi$  defines different polarization angle includes orientation of the injected electric field, and is measured with respect to the plane formed by the direction of propagation and the normal to the injection plane. A polarization angle of zero degrees defines p-polarized radiation, regardless of the direction of propagation while a polarization angle of 90 degrees defines s-polarized radiation. Figure 6a represented the absorption spectra at  $\varphi = 10^\circ, 20^\circ, 30^\circ, 40^\circ, 50^\circ$  and vice versa for incident angles for the p-polarization ( $\Phi = 90^\circ$ ). The absorption spectra remain almost unchanged at these angles mentioned in Fig. 6a. Thus, the explored absorber shows a similar absorption mechanism as that for  $\Phi = 0^\circ$  and  $90^\circ$ , i.e., it is an omnidirectional and s- and p-polarization-insensitive perfect absorber. For metamaterials, (s and p) polarization-insensitivity is an essential factor for their practical application. Investigation of a polarization-independent absorber for the polarization angle and absorption spectra are plotted at different polarization angles as shown in Figs. 5 and 6, respected to the proposed light absorber. The absorber



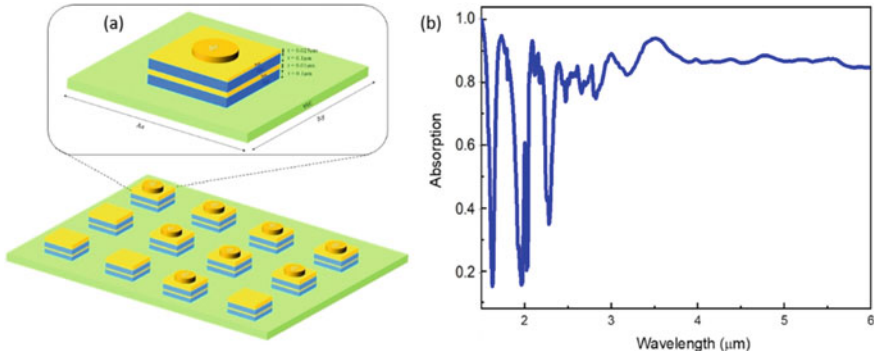


**Fig. 6** Absorption spectra of MMBBA for S-polarized radiation for **a** at different  $\theta$  of the incident angles and **b** at different azimuthal angle  $\phi$  of the incident angle

shows similar bandwidth from 2.5  $\mu\text{m}$  to 6.0  $\mu\text{m}$  for S- and P-polarized light. This signifies the polarization-insensitivity of the proposed absorber.

The MMBBA is not showing any changes at angles because the surface is not even and because there is a metallic substrate, so the incident light of any polarization or any propagation angle looks basically the same for the metasurface and localization is enhanced between the metasurface and metallic substrate, and therefore the incident wave can interact with the metasurface effectively regardless of the directions of polarization and propagation. That is, the incident light wave can be converted to a plasmonic wave along the metasurface effectively and finally absorbed by the metasurface through plasmonic resonance absorption insensitive to the directions of polarization and propagation. Another reason is that the plasmonic resonance greatly enhanced the absorption so that any polarized or incident wave of any propagation can be effectively absorbed by the metasurface.

From the fabrication point of view, the top layer is replaced with a circle of radius  $R = 0.1 \mu\text{m}$  and thickness  $t = 0.2 \mu\text{m}$  displayed in Fig. 7a. And corresponding absorption spectra have been simulated and presented in Fig. 7b. This shows there is no change in absorption in comparison to previous structure. This helps to make it practical and the final proposed structure of the device, is easy to fabricate without compromising its properties. When the multi resonators are combined into a one-unit cell with a subwavelength period, the total absorption exceeds 90% from 2  $\mu\text{m}$  to 6  $\mu\text{m}$ . The absorption is high from 1.5  $\mu\text{m}$  to 2.25  $\mu\text{m}$  comes with peaks not continuous due to some metal loss which affects the device performance. But increased more than 95% from 1.5  $\mu\text{m}$  to 2.25  $\mu\text{m}$  because of germanium. Germanium has excellent optical properties and creates a great impact on the device. Recently, numerous devices have been proposed using Ge. And a paper based on absorber application using Tu/Ge is published in 2017 [29, 30]. Again, declining at 2  $\mu\text{m}$  and starting cumulative up to 2.25  $\mu\text{m}$  after that it remains constant till 6  $\mu\text{m}$ , these falls are coming due to the superimposition of several peaks over the



**Fig. 7** **a** Perspective view of multi-metasurfaces absorber with gold disc on top having thickness  $t = 0.2 \mu\text{m}$  and radius  $r = 0.1 \mu\text{m}$ , all the patches are of same parameters, **b** corresponding absorption spectra of MMBBA

absorption's phenomena [3]. For dual-layered structure, 95% absorptance is realized approximately near-unity in  $1.5 \mu\text{m}$  to  $6 \mu\text{m}$  spectral range.

## 4 Conclusion

This simplest and thinnest model of MMA has been realized in all aspects. An infrared broadband absorber with multi-metasurface has been designed and simulated using FDTD simulation. At first, a multi-structure single resonator with the same dielectric spacing layer is used, and then a dual-band multi-layer structure of the same thickness and dielectric spacing layer is used for further enhancement. The absorption is increased meaningfully and reaches a near-unity value by using a dual-band multi-layer structure, i.e., the absorption FWHM of single-layered is 50% and 95% (from  $1.5 \mu\text{m}$  to  $6 \mu\text{m}$ ) for multi-layered structure, i.e., the absorption FWHM of single-layered is 50% and 95% (from  $1.5 \mu\text{m}$  to  $6 \mu\text{m}$ ) for multi-layered structure. This MMA accomplishes outstanding results with previously reported MMAs [31, 32]. This absorption is very robust to the incident angle, azimuthal angle, and polarization angle.

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