Design of multi-ellipse broadband metamaterial absorber

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Abstract. In this paper, two types of ellipse-pattern broadband metamaterial absorbers with high absorptivity are designed and analyzed. The single-ellipse periodic absorber can achieve more than 90% absorption in the range of 8.8 to 12.5 μm, and the average absorption in this range is 96.5%. Further exploration of its electromagnetic field’s distribution revealed that the coupling of propagating surface plasmon resonance and localized surface plasmon resonance is responsible for its character. An optimized four-ellipse periodic absorber can achieve 89.5% average absorption in the range of 8 to 15 μm, and the absorption is insensitive to the incident angle. The variations of absorption of the absorber under different polarization and incident angles are also discussed. This design has potential application value in uncooled infrared detectors and other fields.

1. Introduction
Infrared radiation is electromagnetic radiation between visible light and microwaves (wavelength between 0.76 μm and 600 μm) [1]. Objects that have a temperature higher than 0 K will emit thermally excited electromagnetic waves to their surroundings. The emitted radiation frequency depends on the temperature of the emitter and the size and shape of objects [2,3]. Infrared detectors are photoelectric devices that mainly work based on the infrared thermal effect (bolometers) or the photoelectric effect (photon detectors) [4]. Since expensive and relatively bulky refrigerant components limit photon detectors [5,6], thermal detectors, especially uncooled bolometers, are widely used in night vision [7], energy-saving, epidemic prevention [8], or other military and civilian fields [9-12].

According to the Wien law, the peak wavelength of human radiation is around 9.4 μm [13], and the thermal emission of most objects in the temperature range of 200-400 K is mainly distributed between 8 to 15 microns [14], which is called long-wavelength infrared range. The second atmospheric window is also located within this band, and it helps to achieve more extended distance detection by avoiding water vapor or carbon dioxide interference [15]. Therefore, requirements are put forward for high absorption and broadband absorption in the band mentioned above for the uncooled bolometer's absorber. The metamaterial absorber composed of metal and dielectric material by coupling specific structural parameters and patterns because of its excellent electromagnetic absorption and the relatively small size compared to an optical cavity has attracted numerous studies [16-18]. Luo [19] et al. designed several multi-layer broadband absorbers by flexibly combing four Ti-Ge cubes of different sizes to excite resonances at different wavelengths to achieve average absorption above 90% in the range of 6.3 μm to 14.8 μm. Tang [20] et al. designed a three-layer structure with a titanium disk embedded in the dielectric layer to achieve average absorption of 92.1% in the range of 8 μm to 12 μm.
and achieve another narrow-band high absorption at the same time by changing period. Li [21] et al. proposed a single-patterned three-layer structure of titanium metal block, which achieved an average absorption of 96.7% in the range of 8 μm to 13 μm by coupling propagation surface plasmon resonance and localized surface plasmon resonance. Inspired by previous studies, this paper uses a combination of the layered structure and multi-ellipse patterns to design a multi-layer periodic composite structure absorber with broad-spectrum and high absorption in the range of 8 μm to 15 μm. The spatial distribution of the absorber's photothermal conversion has been explored, and the manufacturing process of the structure is relatively easy.

2. Structure Design and Simulation

The absorber designed in this paper improves on the traditional Metal/Insulator/Metal (MIM) structure [22-24], and the middle dielectric layer is divided into two layers: a germanium layer and a doped silicon layer. Since the imaginary part of the germanium layer in the target band is 0, electromagnetic waves can be reflected in this layer without loss and then absorbed by other layers of the structure. The extinction coefficient of doped silicon in the target band can effectively increase the absorption. The titanium choice is because it is one of the metals with the best loss characteristics in the infrared band. The thinner top layer of titanium can reduce cavity loss and ensure significant coupling effects. The bottom layer uses a certain thickness of titanium to reduce transmission.

Fig. 1(a) shows the cell structure of a single-ellipse absorber with period $p = 2 \mu m$. The thickness of the titanium on the surface is $h_1 = 0.02 \mu m$. The lengths of the semi-major axis $a$ and semi-minor axis $b$ of the ellipse are 0.4 μm and 0.35 μm, respectively. The germanium layer with a thickness of $h_2 = 0.27 \mu m$. The thickness of the bottom titanium is $h_4 = 0.1 \mu m$, and the doping level of the N-doped silicon is $N = 10^{15} \text{cm}^{-3}$. The dielectric constants of titanium and germanium were obtained from Palik’s handbook [25], and parameters for doped-Si’s Drude model come from the literature [26].

![Figure 1](image)

Figure 1. (a) Schematic diagram of the proposed unit of single-ellipse periodic. (b) Absorption spectrum of single-ellipse absorber for TM polarization and TE polarization.

The absorber's absorption spectrum is calculated by the finite-difference time-domain (FDTD) method [27]. In the simulation, periodic boundary conditions are used in the $x$ and $y$ direction, and perfectly matched layer boundary conditions are used in the $z$-direction. It is worth mentioning that although the titanium layer of the bottom is set to prevent electromagnetic waves from passing through, it is found that the transmission monitor can still detect 1-2% of plane waves in the range of 7 to 10 μm after several pre-simulations. Therefore, the transmission cannot be neglected, and the total spectral absorption of the proposed absorber can be described by $A = 1 - R - T$, where $R$ is the spectral reflection and $T$ is the spectral transmission. Since the thickness of the top titanium of the structure is relatively thinner, the refined mesh should be added in the $z$-direction.
3. Results and Discussion

Fig. 1(b) shows the absorber’s absorption spectrum for TM mode and TE mode. The absorptivity is over 90%, from 8.8 to 12.5 μm for TM polarization, and the average absorption is 96.5%. There are absorption peaks at 9.43 μm and 11.65 μm, and the corresponding peak absorptivity is 98.8% and 98.9%, respectively. Caused by the ellipse does not satisfy the 90° rotational symmetry, the absorption is decreased for TE mode. However, the absorptivity is also over 90%, from 8.8 to 11.4 μm, and the average absorption is 90.3%. There are absorption peaks at 9.13 μm and 11.1 μm, and the corresponding peak absorptivity is 91.7% and 91.5%, respectively.

The theory of surface plasmons can explain the absorption mechanism of the proposed electromagnetic metamaterial absorber. Based on the propagation mode of Surface Plasmon (SP) of electromagnetic metamaterials, Surface Plasmon Resonance (SPR) is generally divided into two types [14,16]. One type is Propagating Surface Plasmons Resonance (PSPR), the excited evanescent wave propagating along the interlayer surface between the conductor and the dielectric layer. The other type is the collective resonance of electrons on the surface of metal particles excited by incident light's electric field. This resonance mainly exists around the surface metal pattern called Localized Surface Plasmons Resonance (LSPR). By designing structures and optimizing structural parameters, the PSPR and LSPR can be excited together to achieve a wide-spectrum absorption effect.

To further understand the physical absorption mechanism of the proposed single-ellipse metasurface absorber, the electric and magnetic field distributions at the resonant wavelengths of 9.43 μm and 11.65 μm are given in Fig. 2 for the TM polarization. As we can see from Fig. 2, the electric field's distribution is similar, and the distribution of the magnetic field has two modes. As shown from Fig. 2(a),2(b),2(e),2(f), the enhancement of the electric field is mainly restricted near the top titanium layer, which represents the resonance of the surface plasmon of the metamaterial absorber. Comparing the magnetic field distribution from Fig. 3(c),3(d),3(g),3(h), we can see that the first magnetic field distribution mode is at 9.43 μm, the distribution presents several layers, and there is almost no influence between different layers, which means PSPR dominates it. The second magnetic field distribution mode is at 11.65 μm. It can be observed that the magnetic field excited by the top metal affects the lower layers, which means that LSPR is dominant. With the coupling of these two surface plasmon resonance modes, the metamaterial absorber's absorption in 8.8-12.5 μm is enhanced. Similar to TM polarization, TE polarization's absorption is also caused by the coupling of PSPR and LSPR.
Based on the previous single-ellipse absorber mechanism analysis, we try to broaden the absorption band further. By adjusting the period, position, and pattern parameters with the fixed thickness of each layer as shown before, the four-ellipse absorber is proposed as shown in Fig. 3, and the specific parameters of the unit are shown in Table 1:

| Ellipse 1 | Ellipse 2 | Ellipse 3 | Ellipse 4 | Center position of ellipse ± c | Period p |
|----------|----------|----------|----------|-------------------------------|---------|
| a₁       | b₁       | a₂       | b₂       | a₃                           | b₃       | a₄       | b₄       | ± 0.65 | 2.8     |
| 0.6      | 0.25     | 0.25     | 0.5      | 0.4                          | 0.6      | 0.6      | 0.25     |         |         |

The proposed four-ellipse absorber's absorption curves for TM polarization and TE polarization are shown in Fig. 3(c). We can see the absorber has spectral absorption over 80% in the range of 8 to 15 μm, with an average absorption of up to 89.5% for TM polarization. There are three peaks \( \lambda_1, \lambda_2 \) and \( \lambda_3 \) at 9.48 μm, 11.36 μm and 13.72 μm, and the corresponding peak absorption is 97.4%, 90.3%, and 89.1%. For TE polarization, the absorber has an average absorption rate of 84.8% in the 8 to 15 μm. There are two absorption peaks at 10.02 μm and 14.68 μm, and the peak absorption rates are 99.1% and 90%, respectively. Since the first peak is close to the peak of human radiation, it will help infrared detection of the human being.
Figure 3. (a) Schematic diagram of the proposed cell of four-ellipse periodic structure. (b) Top view of the four-ellipse cell. (c) Absorption spectrum of four-ellipse absorber for TM polarization and TE polarization.

Since the differences between the four-ellipse and single-ellipse structures are only surface patterns and periods, its electromagnetic field distribution is similar to that of single-ellipse. The magnetic field distributions of the four-ellipse at the peak wavelengths of $\lambda_1$, $\lambda_2$, and $\lambda_3$ are plotted in Fig. 4, and they can reveal absorption intensity more clearly. The coupling effect between PSPR and LSPR is still the main reason for the formation of broad-spectrum absorption, and the excitation of the two plasmon resonances is no longer limited by wavelength. For example, when $\lambda_1 = 9.48 \mu m$, ellipse two can excite a stronger LSPR, promoting the appearance of the first absorption peak, as shown in Fig. 4(a) and Fig. 4(c). It can be seen from Fig. 7 that ellipse two is dominated by LSPR, while PSPR dominates the surface plasmon resonances of other ellipses excited at different wavelengths.

Subsequently, we further investigate the effects of different geometrical parameters on the absorption of the proposed four-ellipse metasurface absorber. First, we discuss the effects of changing the thickness of the top metal titanium pattern for TM polarization. As displayed in Fig. 5(a), increasing $h_1$ induces the absorption curve blue-shift, and decreasing $h_1$ collapses the coupling of
LSPR and PSPR. They all harm the high absorptivity, which puts forward requirements for accuracy in actual manufacturing. When the dielectric layer's total thickness is kept constant ($h_2 + h_3 = 0.6 \, \mu m$), we can conclude from Fig. 5(b) that decreasing thickness of germanium cause curve blue-shift, but the effect is relatively little. As shown in Fig. 5(c), when the doped silicon's carrier concentration is between $10^{15} \, cm^{-3}$ and $10^{18} \, cm^{-3}$, several curves are almost overlapped. When it increases to $10^{19} \, cm^{-3}$, the absorption curve shows a blue-shift. When it increases to $10^{20} \, cm^{-3}$, since the nature of doped silicon has changed from semiconductor to metal at this time, the absorption curve has changed dramatically. Fig. 5(d) shows that when we increase the absorber's $p$, the absorption spectra' width will decrease accordingly. It causes the peak absorption to increase but average absorption decreases.

![Figure 5](image)

Figure 5. Absorption as a function of parameters variations. (a) Absorption as a function of thickness of top Ti $h_1$. (b) Absorption as a function of thickness of dielectric layer $h_2$ & $h_3$ (c) Absorption as a function of doping level $N$ for doped silicon. (d) Absorption as a function of period $p$

The above discussion only considers the absorption at normal incident light, and it is necessary to figure out the effect of the incident angle on the absorption. For this purpose, we further investigate the optical absorption of the proposed four-ellipse absorber with different incident angles to explore the absorption dependence at oblique incidence for both the TM and TE polarizations. It can be seen from Fig. 6 that the proposed four-ellipse structure can ensure the insensitive polarization performance with the incident angle from 0° to 70° for TM polarization due to the thin top layer. When the incidence is from 30° to 60°, the absorption in the whole target band is over 90%. The plane wave of TE polarization is different from that of TM polarization due to the asymmetry of patterns. However, it can be observed that there is always high absorption near the peak wavelength of human radiation at 9.4 μm for TE polarization, and the average absorption is 85% can be maintained from 8 to 15 μm.
Figure 6. Absorption spectra of the four-ellipse absorber as a function of wavelength and incident angle for (a) TM polarization and (b) TE polarization

4. Conclusion

This paper first designs and analyzes a periodic broadband absorber with a single-ellipse on the top layer, which can achieve high absorption of over 90% in the range of 8.8 to 12.5 μm and the average absorptivity is 96.5%. There are absorption peaks at 9.43 μm and 11.65 μm, and the corresponding peak absorptivity is 98.8% and 98.9%, respectively. Next, by analyzing the longitudinal electromagnetic field, the absorber's broad spectrum and high absorptivity mechanism are analyzed; it is pointed out that the mutual coupling of the propagating surface plasmon resonance and the localized surface plasmon resonance is the cause of the high absorptivity. To further broaden the absorption spectra, optimization with the four-ellipse pattern on the top layer is also proposed. The four-ellipse absorber can achieve a full absorptivity of more than 80% in the range of 8 to 15 μm, and the average absorption can reach 89.5% for TM polarization. The absorption does not change significantly as the incident angle changes from 0° to 70°, and the average absorption has been maintained at 90%. The effect is better when the incidence is from 30° to 60°, and the high absorptivity of over 90% in the entire target band can be achieved. As the incident angle is changed from 0° to 30°, the absorber's absorption does not change significantly, the average absorptivity is over 80%, and there is a high absorption band near the peak wavelength of human radiation at 9.4 μm. The analysis and design method proposed in this paper can also be used for reference in many other fields, such as the design and analysis of other uncooled infrared devices, solar energy utilization, and broadband absorbers.

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