Abstract—The mid-infrared absorber is an important device for effective capture of high by atmospheric infrared transparent window, and has been a research hotspot in military, medical, biological and other fields. In this paper, a kind of ultra-thin mid-infrared ultra-broadband absorber with background insensitive is realized by stacking four metal/dielectric films (Si/Ag/Si₃N₄/SiO₂) on silver substrate and periodically arranged cross-anchor metal pattern in a method of finite-difference time domain. The results show that the absorption rate is more than 90% and the relative absorption bandwidth is 95.5% in the wavelength ranging from 9.1 µm to 24.1 µm. The average absorptivity is 92% in the range of background refractive index (n = 1~1.8). A proof of the device’s insensitivity to background refractive index. At a large incidence angle (θ ≤ 50°), the lowest absorption rate is up to 80%. The thickness of the optimized device is only 1.7 µm. The research results have important application value in infrared remote sensing, pollution monitoring, disease diagnosis and other fields.

Index Terms—Background insensitive, ultra-broadband, metamaterial perfect absorber, mid-infrared.

I. INTRODUCTION

METAMATERIAL are an artificial composite structure or composite material having extraordinary physical properties that natural materials do not have. This material has very broad application prospects in imaging, sensing, absorber and other fields [1] because of its ultra-thin size, high absorption efficiency, and highly controllable working range. Absorbers designed for traditional materials are larger and thicker, while metamaterial absorbers (MA) with a thickness of only a quarter wavelength or less are more suitable for micro-integrated optoelectronic systems [2]. In addition, due to the strong frequency select characteristics of metamaterial absorbers, the MA play an important role in the fields that traditional absorbers cannot achieve. In 2008, Landy et al. [3] developed a near-perfect absorber and presented the notion of metamaterial perfect absorber (MPA) for the first time, the research of MPA has been sparked since then. According to the absorption bandwidth, the absorber can be split into broadband and narrowband absorption. Broadband absorption can be used in solar cells [4] and stealth vests [5]. Narrow band absorption can be used for sensing [6] and photoelectric detection [7]. However, the narrow working bandwidth due to the resonance characteristics of its sub-wavelength structure, which suggests the limitation of its future application. With the improvement of micro-nano processing technology in recent years, researchers have experimented various structures and materials to broaden the absorption band in the process of realizing perfect absorption. One is to enhance the resonance properties by designing metamaterial structures to achieve ultra-wideband, such as all dielectric array structure [8], stacking structure [9], coupling metal resonator structures of various sizes [10], conical structure [11] and three-dimensional spiral structure [12]. The other is to introduce the properties of emerging 2D materials, such as black phosphorus [13], graphene [14], molybdenum sulfide [15] and so on.

Most MPAs currently are designed to operate in visible [16], [17], infrared [18], [19], terahertz [20], [21], and microwave light [22], but with a less attention on absorbers in mid-infrared (2.5~30 µm). The mid-infrared light is located in the molecular fingerprint spectral region, covering multiple transmission windows of the earth atmosphere. The mid-infrared absorber is an important device for the effective capture of high-temperature targets for the atmospheric infrared transparent window, which is widely used in thermal imaging [23], infrared temperature measurement [24], and infrared camouflage [25]. In 2020, Yu Zhou et al. [26] designed a four-layer absorber with Ti/Ge/Si₃N₄/Ti structure, which had an average absorption of 94.5% in the range of 8 µm to 14 µm, and the absorber had an average absorption of more than 90% for plane waves in TE or TM modes with 40° incidence angle. In 2020, Song Yue et al. [27] proposed a multilayer absorber with sawtooth and pyramid shapes. Its working bandwidth extends from ultraviolet (UV) to long wave infrared (LWIR) through the effective hyperbolic metamaterial model and the excitation of various slow light modes, and it maintains an average absorption rate of more than 90% under the incident light of TM and EMT modes. In 2021, Shuaizhao Wang et al. [28] designed a dual-band wide-range tunable terahertz...
absorber based on graphene and bulk Dirac semimetal (BDS),
which absorption can almost achieve 100% at 3.97 THz and 7.94
THz. Moreover, that absorber can keep the similar absorption
when the background refractive index n changes in the range of
1~1.4.

The above studies have their own characteristics in different
structures and material designs. They all focus on bandwidth,
absorbing efficiency and structure, and seldom focus on the
performance and efficiency of absorbers in complex situation.
The reason for a mid-infrared MPA that is insensitive to the
background refractive index is to be proposed in this paper.
That MPA has an average absorption of 95.5% in the range of 9.1 µm
to 24.2 µm and has polarization-independent characteristics.
The average absorption is up to 93% when the incident angle
up to 50°. The lowest absorption is greater than 92% when the
background refractive index n = 1~1.8, the thickness dimension
of the device was limited to 1.7 µm, which is less than an order
of magnitude and smaller than the wavelength of incident light.
This ultra-broadband and ultra-thin MPA can solve the application
problems in complex military and medicine scenarios, and
has substantial research significance for thermal imaging and
night vision.

II. MODEL DESIGN AND THEORETICAL ANALYSIS

The schematic diagram of the planned MPA is depicted in
Fig. 1(a). The bottom metal substrate is silver, and the dielectric
layers SiO₂ and Si₃N₄ are applied to the surface of metal
substrate. The cross-anchor pattern is arranged on the layer
Si₃N₄ surface at regular intervals, and the material is silver. To
avoid oxidation and corrosion of the cross-anchor, the top layer is
covered with a Si dielectric layer. In this paper, the time domain
finite difference software FDTD Solutions was used to simulate
the structural dimensions and optical response of the device. To
ensure correct periodic simulation, the simulation is set up with
periodic boundary conditions in the x and y directions and per-
fectedly matched layer conditions (PML) in the z direction to avoid
unphysical scattering on the boundary, we set the background
refractive index of the entire simulation space to 1.33 to simulate
the ideal state of the aqueous solution environment. The light
source is positioned directly above the device, and the simulated
plane wave is incident vertically (in the negative z direction)
on its surface, the polarization direction is x direction. The
wavelength scan mode was employed to investigate the trend
of absorption spectra as the incident wavelength changed. In
Fig. 1(b), the outer diameter of the semicircular ring is d, the
center distance of the semicircular ring is L, the line width is
w, the optimized unit structure period is P, and h₁, h₂, h₃ are
the thicknesses of the layer Si, layer Si₃N₄, and layer SiO₂,
respectively, h₄ is the thickness of the metal substrate, and t is the
cross-anchor height in Fig. 1(c). The optimized MPA structure
parameters are shown in Table I.

Although we have only conducted a simulation study of the
absorber, the feasibility of experimental manufacturing and the
preparation process need to be taken into account. First, the
silver substrate is deposited by thermal evaporation technology
[29], then the underlying SiO₂ can be deposited on the silver
substrate by low pressure chemical vapor deposition (LPCVD)
[30]. A plasma-enhanced chemical vapor deposition system
(PECVD) sputtered 270 nm thickness Si₃N₄ [31], followed by
photoresist spin coating, lithography patterning, then develop-
ment, deposition of cross-anchor by electron beam evaporation,
the photoresist is dissolved by a lift-off process to form the metal
pattern [32]. Finally, deposition of 250 nm Si is sputtered using
the PECVD process [33], [34].

The two most essential indications of broadband absorbers
are absorption rate and absorption bandwidth, and the rel-
ative absorption bandwidth (ABW) is defined as $ABW =
\frac{2 \times (\lambda_{\text{max}} - \lambda_{\text{min}})}{(\lambda_{\text{max}} + \lambda_{\text{min}})}$, where $\lambda_{\text{max}}$ and $\lambda_{\text{min}}$ are
the maximum and minimum wavelengths of the absorption
band with an absorption rate greater than 90%. Absorption
$A(\omega) = 1 - R(\omega) - T(\omega) = 1 - |S_{11}|^2 - |S_{21}|^2$, where $R(\omega)$ is
reflectance, $T(\omega)$ is transmittance, $S_{11}$ and $S_{21}$ denote the
scattering parameters relevant to reflection and transmission
coefficients, separately, which has the following relationship
with MPA [35]:

$$
\begin{align*}
S_{11} &= \frac{i}{2} \left( \frac{1}{z} - z \right) \sin(nkd) \\
S_{21} &= \frac{1}{\cos(nkd) - \frac{1}{2} \left( \frac{1}{z} + \frac{1}{z^*} \right) \sin(nkd)}
\end{align*}
$$

(1)

Where n is the refractive index and k is the free space wave
vectors, d represents the thickness of the dielectric slab, z is
the wave impedance [36] of the dielectric slab. In general,
the equivalent impedance of MPA may be made equal to the
free space impedance by modifying structural characteristics.
According to the S-parameter retrieval methods [35], the value
of the equivalent impedance can be determined by measuring
the phase and amplitude of the electromagnetic waves transmitted
and reflected from the device, as follow:

$$
Z = \pm \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}}
$$

(2)
According to the impedance matching principle [37], when the equivalent impedance of device matches the free space impedance (\(\text{Re}[Z] = 1, \text{Im}[Z] = 0\)), the reflection is completely suppressed, resulting in the absorption rate reaching its maximum. A sufficiently thick metal substrate will prevent incoming light from penetrating, the equation above may be simplified to:

\[
Z = 1 + S_{11}/1 - S_{11}
\]

The refractive index of silicon is set to 3.42. Optical constant of silicon dioxide is derived from the parametric mode of Palik, and the optical constants of silicon nitride in MIR were adopted from the experimental data of Kevin Luke et al. [38] Relative permittivity of silver characterized through Drude mode:

\[
\varepsilon(\omega) = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}
\]

Here \(\omega\) is the angular frequency of incident light, \(\omega_p = 1.39 \times 10^{16}\text{rad/s}\) is plasma frequency, \(\gamma = 2.7 \times 10^{13}\text{rad/s}\) is metal loss factor, the metal dielectric constant at infinity frequency is \(\varepsilon_{\infty}\), which is 3.4 at high frequency.

The red and black curves represent the absorption and reflectance of MPA in Fig. 2(a), respectively. The absorption bandwidth of MPA is 15 \(\mu\text{m}\) (9.1 \(\mu\text{m}\)–24.1 \(\mu\text{m}\)), and the relative absorption bandwidth is roughly 90.4%, with an average absorption of up to 95%. Fig. 2(b) plots a curve of the equivalent impedance versus wavelength for the MPA, demonstrating that the real and imaginary components of the equivalent impedance corresponding to the five peaks of \(\lambda_1\) (9.5 \(\mu\text{m}\)), \(\lambda_2\) (10.8 \(\mu\text{m}\)), \(\lambda_3\) (14.1 \(\mu\text{m}\)), \(\lambda_4\) (18.9 \(\mu\text{m}\)), \(\lambda_5\) (22.7 \(\mu\text{m}\)) are near to 1 and 0. The impedance matching is excellent and matches to the five equivalent impedance, while the black dashed line is the imaginary component of equivalent impedance.

**III. RESULTS AND DISCUSSION**

Fig. 3(a)–(c) shown the structure without cross-anchor, di-electric layers SiO\(_2\) and Si\(_3\)N\(_4\) and our structure, separately. The absorption spectra of the above three structures are shown in Fig. 3(d). The absorption spectra without cross-anchored structure are shown by the red curves in Fig. 3(d), and the development of absorption peaks at 9.5 \(\mu\text{m}\), 11.7 \(\mu\text{m}\), and 22 \(\mu\text{m}\) is due to material absorption loss. In order to avoid the effect of absorption by lossy materials, we used a lossless medium with a refractive index of 2.5 in place of the dielectric layers SiO\(_2\) and Si\(_3\)N\(_4\). In this situation, the absorption peaks at 14.1 \(\mu\text{m}\) and 18.9 \(\mu\text{m}\) are mainly from plasmon resonance on the surface of cross-anchor. The black curve is the absorption spectrum of the combination of the red curve and the blue curve. The superposition of the material absorption loss in the red curve and the resonance absorption in the blue curve ultimately generate an ultra-broadband absorption. The electromagnetic field distribution at 9.5 \(\mu\text{m}\) and 10.8 \(\mu\text{m}\) is shown in Fig. 3(e), (f). As can be observed, the electromagnetic field strength of the cross-anchor surface is low, and its coupling capacity to the incident light field is minimal; thus, the absorption impact at this time is largely due to material absorption loss. In Fig. 4(a), we comparing the absorption spectra of cross-like, quartefoil, and cross-anchor structures. The cross-like and quartefoil structures show a nearly identical trend of change between the range of 9.1 \(\mu\text{m}\) to 13 \(\mu\text{m}\). Fig. 4(b) shows the comparison of the absorption spectra when the cross-anchor materials are gold (yellow), germanium (blue), titanium (red), and tungsten (gray). And it can be concluded that the appearance of the two absorption peaks is not related to the metal structure and materials in combination with Fig. 3(a).

Fig. 5(a1) (a2) (a3) demonstrates a surface current vector distribution of the cross-anchor. It can be seen that the cross

![Image](https://example.com/figure2.png)

**Fig. 2.** (a) Absorption and reflection spectra of MPA. (b) The equivalent impedance curves of MPA. The black solid line is the real component of equivalent impedance, while the black dashed line is the imaginary component of equivalent impedance.

![Image](https://example.com/figure3.png)

**Fig. 3.** (a) Absorption spectra of MPA without cross-anchor (red). (b) Absorption spectra of MPA with layers SiO\(_2\) and Si\(_3\)N\(_4\). (c) The combined structure of both (black). (d) Absorption spectra under different materials and structures. (e–f) The electric field intensity distributions of the cross-anchor surface.

![Image](https://example.com/figure4.png)

**Fig. 4.** (a) Comparison of absorption spectra of different metal structures. (b) Comparison of absorption spectra of different metal materials.
produces a current parallel to the direction of incident polarization, while the current flow direction of the metal substrate surface shown in Fig. 5(b1) (b2) (b3) is perpendicular to the direction of incident polarization, and the top and bottom metal structure surface currents are not parallel to each other, which means that no electrical resonance or magnetic resonance mode has been formed in the structure. To better understand the MPA absorption characteristics shown in the absorption spectrogram, we further investigated the electromagnetic field distribution on the cross-anchor surface at the locations of the three absorption peaks, and Fig. 5 shows the $x$-$y$ plane normalized electromagnetic field strength ($|E|$) ($|H|$). By observing Fig. 5(c1) (c2) (c3), we can see that the electric field is greatly enhanced at 14.1 $\mu$m, 18.9 $\mu$m and 22.7 $\mu$m. The electric field enhancement at 14.1 $\mu$m is localized at both ends of the cross-anchored semicircle, which is the localized surface plasmon resonance (LSPR). The electric field enhancement at 18.9 $\mu$m and 22.7 $\mu$m occurs in the polarization direction of the cross-anchored semicircle, which is a typical electric dipole resonance. As shown in Fig. 5(d1) (d2) (d3), the charge within the cross-anchor will travel towards the ends under the operation of an external electromagnetic field to create a current, which creating a greater magnetic field. The incident light field energy is coupled into the electric and induced magnetic fields at both ends and eventually dissipated due to the ohmic thermal effect to achieve the effect of electromagnetic absorption.

Next, we explore the absorption characteristics of MPA by changing the structural dimensions of the cross-anchor, the cell period. The absorption spectra of different heights $t$ are given in Fig. 6(a). The average absorption gradually increases when the height of the cross-anchor increases from 20 nm to 40 nm, and shows a decreasing trend when the height increases further. The absorption spectra for different line widths $w$ are shown in Fig. 6(b), the absorption of MPA reaches a maximum at $w = 30$ nm and then gradually decreases. Obviously, changing the structural parameters of the cross-anchor has a large impact on the intensity of the surface plasmon resonance, and optimization leads in the absorption rate reaching its maximum at $w = 30$ nm, $t = 40$ nm. The effect of the half-circular circle center distance $L$ on the absorption spectra is seen in Fig. 6(c). A huge amount of charge accumulates at the cross-anchor ends, generating an electric dipole resonance, and the increased dipole moment causes the 18.9 $\mu$m and 22.7 $\mu$m absorption peaks to redshift. Fig. 6(d) depicts the absorption spectra of several periods of the cell structure. The absorption peaks at 18.9 $\mu$m and 22.7 $\mu$m are blueshift when $P$ increases from 1400 nm to 1800 nm. For parallel polarized light, the dipole oscillators between the units are mutually reinforcing when the period is much smaller than the incident light wavelength, which causing the resonance frequency to shift to high frequency [39].

Fig. 7(a) shows the complex refractive index data for diesel soot, water, and ice ($H_2O$). The solid line represents the real part of the refractive index and the dashed line represents the imaginary part of the refractive index. Fig. 7(b) shows the absorption spectra of MPA with background environments of diesel soot, water, and ice ($H_2O$), respectively. Fig. 7(c), (d) illustrates the equivalent impedance of the device in different background environments. It is found that the curve conforms to the absorption trend and the impedance
match is excellent, indicating that MPA still has outstanding absorption performance under the complex environments. The dispersion plot of the background refractive index \( n \) versus the absorption shown in Fig. 8(a). The refractive index range of 1 to 1.8 essentially covers the refractive index range of gases and liquids, and absorption performance improves as refractive index increases. From Fig. 8(b) that absorption is basically unchanged when \( \theta \) in the range of 0° to 90°, the polarization-independent property of this MPA is attributable to the rotational symmetry of the cross-anchor. As shown in Fig. 8(c), the absorption rate falls around 13 \( \mu \)m and 16 \( \mu \)m as \( \varphi \) increases from 0° to 50°, while the absorption maintains a high effect in the rest of the band.

**IV. Conclusion**

To summarize, the MPA suggested in this study, in contrast, is made up of four thin films and a metallic structure of periodically arranged cross-anchor with an average absorption of up to 95.5% performance in the range of 9.1 \( \mu \)m to 24.1 \( \mu \)m and polarization-independent. Our device overcomes the thickness limit of traditional 1/4 wavelength and has a thickness one order of magnitude smaller than the incident wavelength. The property of the lowest absorption is greater than 92% when the background refractive index \( n = 1 \sim 1.8 \) will lead to the widespread use of this MPA for molecular detection, invisibility cloaks, infrared camouflage.

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