Thin Multispectral Camouflage Absorber Based on Metasurfaces with Wide Infrared Radiative Cooling Window

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Herein, a hierarchical metamaterial (HMM) is reported to achieve multispectral camouflage for thermal infrared detectors and radar. The HMM consists of a frequency-selective emitter (FSE) integrated with a microwave absorber (MA). The FSE layer has an average absorptivity of 0.18, 0.85, and 0.18 in the wavelength of 3–5, 5–8, and 8–14 μm, respectively, in the case of the normal incidence. The absorptivity of MA maintains more than 91% (87%) in the broadband of 8–12 GHz (the entire X-band) up to incident angles of ±40° for TM (TE) polarization. Overall, the average surface emissivity of HMM is 0.25, 0.86, and 0.26 in the infrared broadband of 3–5, 5–8, and 8–14 μm, respectively. The FSE considers infrared camouflage and infrared radiative cooling. The performance of HMM in microwave range remains unchanged, compared to MA structure without FSE layer. From the point of view of thickness, the HMM structure is only 2.34 mm. These excellent performances indicate that the herein described proposed HMM has promising applications in multispectral camouflage fields.

1. Introduction

Many efforts have been dedicated to developing multispectral compatible camouflage techniques, which is a challenge and trend in electromagnetic wave control, such as the stealth of the helicopter engine intake and exhaust system and the surface ship chimney part.[1–3] With regard to the active working mode of microwave detectors, the radar camouflage materials possess high absorptivity and low reflectivity.[6–8] On the contrary, to evade the detection of infrared detectors, the infrared camouflage materials equipped with low infrared emissivity, which means low absorptivity and high reflectivity, are demanded IR stealth according to Kirchhoff’s law.[9–12] Another important point is that the infrared with 5–8 μm wavelength cannot pass the atmosphere. Therefore, the frequency-selective emitters (FSEs) with high emissivity in the 5–8 μm and low emissivity in 3–5 and 8–14 μm can be infrared camouflage while maintaining thermal balance.[13,14]

Recently, the research of radar-infrared bi-stealth mainly focused on two directions: powder materials and metamaterials. Powder materials targeting absorbing microwaves usually have an infrared emissivity over 0.5.[15–19] It was hard to reconcile high absorption in the microwave band with the low emittance in the infrared band, considering just one kind of powder material. Metamaterials have been widely studied due to their outstanding capacities in manipulating electromagnetic waves, such as imaging, color filter, plasmonic structure color, surface-enhanced Raman scattering, sensing, light absorption switches, energy harvest, and thermal emitters.[20–27] Several metamaterial-based structures have been proposed to realize radar-infrared compatible camouflage.[18,19,28–35] The kernel idea to achieve the compatible camouflage is to cover a broadband microwave absorber (MA) with an infrared shielding and microwave transparent layer. Many designs have on top all-metallic surfaces with patterns to reduce thermal infrared emission at the whole band of 3–14 μm.[29–36] It has been reported that a design achieves low thermal infrared emission at 3–5 and 8–14 μm, but high thermal...
infrared emission (≈0.5) at 5–8 μm, recently.\[^{28}\] We can find that the average emittance is not large enough 5–8 μm. That is to say, the infrared radiative cooling window is narrow. We are eager to get a wide cooling window covering the waveband of 5–8 μm. And their bottom MA part is similar to spacer-medium-spacer type, and the space materials are with low dielectric constant, such as F4B, FR-4, polyethylene terephthalate, and polyvinyl chloride. The thickness is in the range of 2.4–33 mm.\[^{28–31,33–35}\]

This indicates potential in the two directions of widening the infrared radiative cooling band (taking into account the infrared camouflage concurrently) and decreasing the thickness of the MA. We can achieve these goals by using specially designed metasurfaces.

In this paper, we present a strategy to achieve compatible camouflage for thermal infrared detectors and radar by using a hierarchical metamaterial (HMM) consisting of an FSE integrated with an MA. We chose FR-4 as the spacer and Cu pattern to achieve high absorptance in the microwave regime. The simulated results indicate that the bottom absorber can realize broadband absorption at X-band (8–12 GHz) with attenuation efficiency exceeding 91%, 87% up to incident angles of ±40° for TM (linearly polarized wave with the magnetic field component along the y axis) and TE (linearly polarized wave with electric field component along the y axis) polarizations, respectively. Meanwhile, we design a metal-dielectric-metal (MDM) structure to reach the goal of infrared camouflage with a cooling window. The top FSE can contribute to both low surface emissivity (0.18, 0.18) in the infrared atmospheric window (3–5 and 8–14 μm) and high emissivity (85%) in the infrared non-atmospheric window (5–8 μm). On the whole, the surface emissivity of HMM is 0.25, 0.26, and 0.86 in the infrared atmospheric window and infrared non-atmospheric window, respectively. The absorption is over 91% in X-band, and the thickness is only 2.34 mm, which is the result of our thin multispectral camouflage absorber with wide infrared radiative cooling window.

2. Design and Results

2.1. Hierarchical Metamaterial

A schematic of our proposed HMM is depicted in Figure 1. The HMM is piled up with the MA layer and the infrared FSE layer. The MA layer includes copper (Cu) patterns embedded in FR-4 spacer, and copper (Cu) ground plane. The FSE layer is composed of periodically arranged MDM metasurfaces. The supercell of the metasurface is a rudder-shaped nickel pattern consisting of a ring and four rods symmetrically nested on it. Incident microwaves of 8–12 GHz (the entire X-band) transmit the FSE layer and are absorbed by the MA layer. The energy of the absorbed microwave is transformed into heat and terminally emitted through the FSE layer as infrared radiation in the band of 5–8 μm. The infrared radiation of 5–8 μm will be dissipated in the atmosphere, cannot be detected by IR detectors, and helps to keep the thermal balance of the whole structure. As a result, the HMM structure can achieve the goal of multispectral camouflage of microwave and infrared.

The total performance is presented in Figure 2. We can discover that the average emissivity of 3–5, 5–8, and 8–14 μm...
is 0.25, 0.86, and 0.26, respectively, which realizes the infrared camouflage and infrared radiation refrigeration concurrently. In addition, the average absorptivity of microwave of X-band (8–12 GHz) attains 95.46%, which can avoid the detection of imaging radar and fire control radar effectively.

### 2.2. Microwave Absorber

As shown in Figure 3, under the metallic (Au) patch array (thickness $t_1 = 150$ nm), one FR-4 layer (thickness is $t_2 = 1.99$ nm) is employed as the spacer to support the patch array, in which one Cu disk with notches (thicknesses are $t_3 = 0.37$ mm, $d_4 = 0.4$ mm) embedded, and the copper ground (thickness is $t_3 = 0.2$ mm) operates as a reflective mirror. The arrangement period and width of the Au patches are $p_1 = 1.05$ mm and $w_1 = 1$ mm, respectively. The Au patches on the uppermost layer of the MA occupy a large portion of the top surface area. We will discuss the contribution of the high duty ratio to the overall performance of our HMM later. The period of the FR-4 spacer and Cu ground plane is $p_2 = 6.3$ mm. As for the design of the Cu disk (radius is $r_1 = 2.9$ mm) in the FR-4 layer, four parts are cut off from the Cu disk following the figured dimensions (distances are $d_2 = 0.49$ mm, $d_3 = 0.56$ mm, and $d_4 = 1.12$ mm), which is depicted in Figure 3b. It is revealed clearly that the Cu pattern is symmetrical along the diagonal direction of MA.

We used the finite integration technique (FIT) (which is a consistent formulation for the discrete representation of Maxwell’s equations on spatial grids) to analyze the absorption performance of the MA, as shown in Figure 3c. In the FIT numerical simulations, the boundary conditions in the $x$, $y$, and $z$ directions are set to unit-cell, unit-cell, and open. The mesh type is tetrahedral. Absorption ($A$) is calculated by $A = 1 - R - T$, where $R$ and $T$ stand for reflectivity and transmissivity. Further, transmissivity is zero due to the thickness of the bottom metal layer being much larger than its skin depth of X-band, which implies that $A = 1 - R$. The constitutive parameters of the unit cell of MA are retrieved from simulated reflection ($S_{11}$) and the transmission ($S_{21}$) data through the transfer-matrix method. Then, the absorption is expressed as $A = 1 - |S_{11}|^2$. The MA exhibits a wideband absorption and has an average absorption of 95.46% between 8 and 12 GHz in the case of the normal incidence. The X band (8–12 GHz) is significant to imaging or fire control radar. In the absorption spectrum, we can find four relatively independent absorption peaks, located at 8.066, 9.392, 11.466, and 13.183 GHz, denoted as peaks I, II, III, and IV, and their absorptivity are 97.87%, 99.71%, 99.74%, and 99.82%. The corresponding reflectivity are $-16.72, -25.38, -25.92,$ and $-27.40$ dB. To increase the average absorption, we optimize the structure parameters (the thickness and shape of the embedded metal and the duty cycle of the Au patch) to make the four peaks closer.

To analyze the mechanism of the four peaks, we observed the X–Y plane electromagnetic field distribution (Figure 4). Insets (a–h) of Figure 4 show the electromagnetic field distribution of the different frequencies (8.066, 9.392, 11.466, and 13.183 GHz), corresponding to peaks I, II, III, and IV. We can see that at each absorption peak, the electric field appears as a concentrated distribution in different regions. The electric field at peak I is mainly concentrated on the edges of the two sectors on the disk. The electric field at peak II is mainly concentrated on the edges of the two antennae on the disk. The electric field at peak III is mainly concentrated on the lateral antennae and the edge of the lower left sector, and the electric field at peak IV is mainly concentrated on the two antennae and the upper right sector. Due to the notched disk resonator’s complex shape, the incident electromagnetic wave excites four dipole resonances on the notched disk. Different regions represent different effective sizes, corresponding to localized surface plasmon resonances (LSPRs) of different wavelengths. The magnetic field distribution represented by Figure 4e–h also reflects the characteristics of by-wavelength localization at different positions. To sum up, the combination of four LSPRs with similar wavelengths obtains broadband absorption covering the X-band. It is worth mentioning that the operating wavelength range of the MA we designed is broader than that reported in some previous reports.\[37,38\]

We explored the influence of the incident angle on the performance of the absorber, as shown in Figure 5. The absorption performance showed high tolerance in response to the increase of the incident angle. For the TM waves (Figure 5a), as the incident angle increases, absorption peak I keeps unity absorption; absorption peaks II and III blueshift a lot, but keep unity absorption; absorption peak IV blueshifts a little and decreases. When the incident angle is increased to 40°, the average absorption covering the band of 8–12 GHz reaches 90.69%. When it

![Figure 3](image-url)  
**Figure 3.** a) The schematic of MA. b) The specially designed Cu is embedded in the FR-4 layer. c) The absorption spectrum of MA.
comes to the TE waves (Figure 5b), the change of absorption peaks concerning frequency keeps the similarity with that of TM waves. The difference is that absorption peaks I, II, III, and IV have a little decay. When the incident angle is increased to 40°, the average absorption within the 8–12 GHz reaches 87.12%.

2.3. Infrared Frequency-Selective Emitter

The proposed three-layer MDM FSE is given in Figure 6. The material of the top metal pattern is nickel, and the permittivity of nickel is expressed by the Drude model.

\[
\varepsilon_{\text{m}}(\omega) = 1 - \frac{\omega_p^2}{(\omega^2 + i\omega\omega_c)}
\]  

where \(\omega\) is the frequency of incident light, \(\omega_p\) is the plasma frequency of metal, \(\omega_c\) is the collision frequency of metal. Here, \(\omega_p = 0.78 \times 10^{16}\text{rad s}^{-1}\), and collision frequency is \(\omega_c = 0.13 \times 10^{15}\text{rad s}^{-1}\).\(^{[39]}\) The top rudder-shaped pattern of the FSE is a nickel ring and four nickel rods symmetrically nested on it. The middle dielectric layer is the alumina (Al2O3) layer. We choose Al2O3 as the dielectric of the FSE when taking the low emissivity covering the band of 3–14 μm into account. The bottom layer is a thin continuous Au layer provided by Au patches of the MA. The next thing to consider is how to improve the emissivity at 5–8 μm.

We analyzed the performance of FES based on the finite difference time domain (FDTD) method (which solves Maxwell’s equations on a mesh and computes \(E\) and \(H\) at grid points spaced \(\Delta x, \Delta y\), and \(\Delta z\) apart, with \(E\) and \(H\) interlaced in all three spatial dimensions) and optimized its parameters by numerical parameter sweep. The inner and outer radius (\(r\)) of the upper Ni ring patterns are \(r_{\text{in}} = 0.51\ \mu\text{m}\) and \(r_{\text{out}} = 0.57\ \mu\text{m}\), respectively. The length and width of the upper Ni rod are \(l_1 = 0.55\ \mu\text{m}\) and
$w_2 = 0.05 \mu m$, respectively. The thickness of the upper Ni pattern is $t_6 = 0.06 \mu m$. The distance $d_5 = 0.27 \mu m$, which determines the Ni rod’s relative position to the Ni ring. The thickness of the planar $\text{Al}_2\text{O}_3$ layer is $t_6 = 1.00 \mu m$. The thickness of the planar Au layer is $t_7 = 0.15 \mu m$, which is considerably larger than the skin thickness of electromagnetic waves in the infrared, and prevents any incident light from transmitting through the multilayer structure. The repeat period ($p$) of the unit cell is $p_1 = 2.1 \mu m$. Hence, 226 576 (equals to 476 $\times$ 476) FSE-unitcell can be arranged on each Au patch of the MA. The uppermost thousandth thickness of the Au patch is used as the ground plane of the FSE.

In the FDTD numerical simulations, the periodical boundary conditions are adopted in the x and y directions, and the perfectly matching layers are employed in the z direction. Absorption (A) is usually calculated by the formula $A = 1 - R$, where $R$ represents reflection. The absorption spectrum under normal incidence is given in Figure 6c, which shows that the structure has an average absorptivity of 85% in the wavelength interval between 5 and 8 $\mu m$. Two absorption peaks (5.90 and 7.50 $\mu m$) arise in a separated location in the absorption spectrum. The average absorptivity over the atmospheric windows (3–5 and 8–14 $\mu m$) is 0.18 and 0.18, respectively. According to Kirchhoff’s law ($\varepsilon = \alpha = 1 - R$), the emissivity is equal to the absorptivity when the body reaches thermal balance. It means that the design has ultrahigh emissivity over the bandwidth (5–8 $\mu m$) and low emissivity over the bandwidths (3–5 and 8–14 $\mu m$).

To understand the resonance origin of the FSE, we analyze the electromagnetic field distribution at absorption peaks, which are given in Figure 7. Under the TM waves (as shown in Figure 7a–d, there exist different electromagnetic field distribution phenomena. At 5.90 $\mu m$, the electric field and the magnetic field are mainly distributed in the edge of the upper Ni ring and both ends of the upper Ni rod, where the propagating surface plasmon resonance (PSPR) dominates. The following equations determine the PSPR wavelengths.$^{[40]}$

$$k = k_0 \sin \theta \pm i2\pi/L$$

$$k_{\text{PSP}} = k_0 \sqrt{[\varepsilon_m \varepsilon_d / (\varepsilon_m + \varepsilon_d)]}$$

Equation (2) is the Bragg coupling condition, where $k_0 = \omega/c$ is the free-space wavevector, $\theta$ is the incident angle, $i$ is an integer representing the grating order, and $L$ is the grating period. Equation (3) indicates the wavevector of propagating surface plasmons (PSPs), where $\varepsilon_m$ and $\varepsilon_d$ are the dielectric constants of the top metal and the middle dielectric layer. For the MDM absorber, PSPs are excited by top metal structure and propagating at the interface. When $k = k_{\text{PSP}}$, the incident wave couples to PSPs. At 7.50 $\mu m$, the magnetic field is mainly distributed in the $\text{Al}_2\text{O}_3$ layer, which is excited by localized surface plasmons (LSPs). For LSPRs in upper nano-ring structures, an empirical formula can express the resonance frequency or wavelength.

$$\lambda/n = c//\left(\sqrt{\varepsilon_{\text{eff}}} \right) = \lambda//\sqrt{\varepsilon_{\text{eff}}}$$

where $r = (R_1 + R_2)/2$ is the average radius of the upper Ni ring, $c$ is the speed of light in free space, $\varepsilon_{\text{eff}}$ is the effective dielectric constant of the dielectric layer, and it is sensitive to thickness and the period of the structure. A sequence of high absorption is

![Figure 6](image_url)

Figure 6. a) The schematic of our proposed FSE. b) The top view of our proposed FSE. c) The emissivity/absorptivity curve of FSE (the average emissivity of 5–8 $\mu m$ is 0.85).

![Figure 7](image_url)

Figure 7. a,b) Electric field distribution of 5.90 and 7.50 $\mu m$, dominated by the rudder-shaped Ni pattern under TM waves. c,d) Magnetic field distribution of 5.90 and 7.50 $\mu m$, dominated by the rudder-shaped Ni pattern under TM waves.
caused by PSPs, LSPs, and their coupling, which produces strong absorption phenomena at non-atmospheric broadband (5–8 μm).

Next, the spectrum of absorptions with oblique incidences for both TM-polarized (ϕ = 0°) and TE-polarized (ϕ = 90°) waves is shown in Figure 8a,b, respectively. In the scale of incident angles (0–40°), we can see that the proposed absorber shows almost angle-independent absorption for both the TM and TE modes due to its small-sized resonators, and the absorption spectrum is almost unchanged. We calculated the average absorptivity of 3–5, 5–8, and 8–14 μm wavelength band when the incident angle of TM (TE) wave reaches 40°. They are 0.25 (0.25), 0.65 (0.66), and 0.47 (0.32), respectively. Therefore, the FSE maintains the characteristics of wavelength-selective emission at large angles. For 11 μm wavelength, the structure takes on different behaviors for TM-polarized and TE-polarized waves. Specifically, in the case of TM-polarized waves, an obvious absorption peak plays a role in CO₂ laser camouflage.[10,41,42] Regarding the TE-polarized wave, there exist no absorption peaks at 11 μm. In a word, our emitter can achieve excellent wide-angle and high-absorptivity performance.

We check the influence of the FSE layer on the MA layer under the microwave wave. The transmittance of the rudder-shaped Ni pattern and Al₂O₃ layer is 1 in the microwave range. We can see that there is no difference with or without the FSE layer for the microwave. After covering the FSE layer on the MA layer, the whole emittance changes marginally. The infrared emissivity value of the HMM is calculated by an empirical formula,[30]

\[ ε = ε_f S_f + ε_d S_d \]  

where ε is the emissivity of the HMM, ε_f is the emissivity of FSE, ε_d is the emissivity of the medium FR-4, and the value there is about 0.955 when the waveband is 3–14 μm. S_f and S_d are the area percentages of the FSE and medium FR-4 in a gap, respectively.[30] Here, \[ S_f = \frac{w_f}{p_f^2} \] and \[ S_d = 1 - \frac{w_f}{p_f^2} \]. To improve the total performance of the FSE, the duty ratio of Au patches is expected to be as large as possible, as mentioned before [Chapter 2.2]. According to Figure 3a, \[ S_f = 0.907, S_d = 0.093 \], and the calculated infrared emissivity values of HMM are 0.25, 0.86, and 0.26 in 3–5, 5–8, and 8–14 μm, respectively.

3. Conclusion

In summary, we propose an HMM design for multispectral camouflage of microwave and infrared waves, which realizes the emission of absorbed energy of MA through FSE. Through the HMM, we regulate that the absorption of the microwave (X-band, 2.5–3.75 cm) promotes up to 97.2%. In addition, with a special design, we dramatically improve the selective emission through 5–8 μm (average emission is 85%) and reduce the emission through 3–5 and 8–14 μm. As a result, we create a meta-surface with an infrared radiative cooling window. Based on the electromagnetic field distribution, we determined that absorption enhancement is driven principally by PSPR and LSPR. In our future studies, we will focus on broadening the absorption band of microwaves and reducing the emissivity at the atmospheric windows of the HMM with the infrared radiative cooling capacity maintained. Moreover, the design principles of HMM can provide methods for simultaneous control of electromagnetic waves for military applications and radiative cooling devices.

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Conflict of Interest

The authors declare no conflict of interest.
Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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hierarchical metamaterials, infrared radiative cooling, infrared waves, microwaves, multispectral camouflage

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