

## RESEARCH ARTICLE

# A Multifunctional Coating for Radar-Infrared Stealth-Compatible at High Temperatures

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**ABSTRACT** In order to achieve compatibility stealth for the radar stealth and infrared stealth, a multifunctional coating for achieving both radar stealth through the polarization conversion and infrared emission reduction at high temperature was skillfully designed in this paper. The multifunctional coating consists of three layers, from outside to inside, followed by the metasurface, the high-temperature resistant dielectric and the metal background. The radar stealth at microwave frequency was mainly generated from polarization conversion excitation through the unsymmetrical metasurface structure. Infrared emission reduction is attributed to the reflection of the metasurface with a high filling ration. By the simulation, radar stealth with an efficiency of 90% could be achieved in the low-frequency band of 5.2-7.8 GHz, and the infrared emission of the multifunctional coating could be as low as 0.22. Furthermore, the experimental results at different temperatures demonstrate that the theoretical design is effective. The measured co-polarization reflection in the 5-9 GHz frequency band is below -8 dB and lower as the frequency increases, indicating more than 84% polarization conversion is achieved. A low emission performance is also validated, with the mean emissivity as low as 0.25. Because of the excellent multispectral compatibility, the multifunctional coating may find applications in multispectral stealth technology.

**INDEX TERMS** High-temperature resistant, metasurface layer, emissivity, infrared emission reduction.

## I. INTRODUCTION

Controlling electromagnetic wave radiation is highly important in civil and military fields [1], [2], [3], [4], [5]. The polarization of electromagnetic waves containing linear and circular polarization components is the most fundamental object of interest for advanced electromagnetic warfare. Most researches focus on the polarization states of electromagnetic wave, because more wireless devices can produce polarized electromagnetic waves [6], [7], [8]. However, according to the Faraday effect and nematic liquid crystal, traditional

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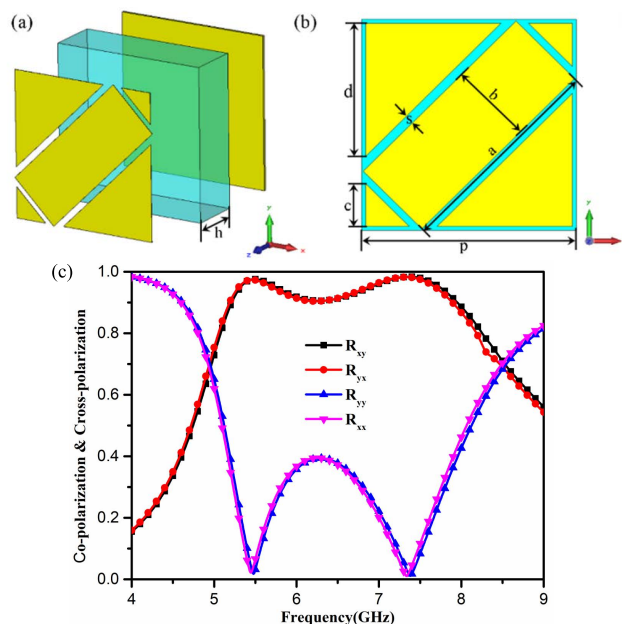
approaches to producing polarization are bulky [9], [10]. For this reason, more convenient approaches should be proposed to achieve the same result.

Additionally, with the fast development of the combined multi-band detecting technology, radar and infrared stealth compatibility has drawn much attention. To achieve infrared stealth, previous research controlled the infrared radiation intensity by reducing the body's temperature or decreasing the surface's infrared emission according to the Stefan-Boltzmann equation. According to the law of Kirchhoff, low emission equals low absorption. The interaction between electromagnetic wave and matter has reflection, absorption and transmission. Due to the presence of the metal back plate,

the transmission is zero, so low absorption means high reflection [11], [12], [13]. So high absorption and low reflection are required in radar stealth, while low absorption or thermal emissivity is demanded in infrared stealth. In material science, many efforts have been done to solve the restriction between radar and infrared stealth. Obviously, it is challenging to realize the materials with simultaneously radar stealth by the polarization conversion and infrared emission reduction because of different working principles. Besides, the infrared radiance is proportional to be four power of temperature according to the Stefan-Boltzmann equation. So the temperature factor has to be considered in the infrared detection field. Therefore, materials selection must adapt to high-temperature environments, such as super-aircraft and missile work parts. Moreover, although the wavelength of a radar wave is different from that of the infrared wave, it is possible to find a strategy with radar stealth through the polarization conversion in the microwave band and a lower emissivity in the infrared band for high-temperature applications.

Due to the unique characteristics of flexible regulation of electromagnetic waves over the sub-wavelength scale, metasurface has attracted tremendous attention from academic and industrial communities. Compared with metamaterials involving wave propagation over long distances, metasurface has structural and dimensional advantages in precisely manipulating electromagnetic wave amplitude and phase. By properly adjusting the geometry parameters of metasurface patterns, it is possible to manipulate the reflection, refraction and polarization modes of electromagnetic waves when the metasurface interacts with the electromagnetic wave, thus achieving control in both the radar and infrared bands. For example, Zhang proposed a multilayer metasurface to achieve 8-16 GHz broadband microwave absorption and controlled the infrared emissivity at 0.2 [14]. Tian designed a structure that can reduce the microwave reflection in the 8-12 GHz band, and the infrared emissivity is less than 0.3 from  $\lambda = 8$  to  $14 \mu\text{m}$  [15]. And in our previous research, a radar-IR stealth-compatible structure with microwave absorption peaks and low IR emissivity (0.32 from  $\lambda = 3$  to  $14 \mu\text{m}$ ) was reported [16]. However, a strategy with multifunctional metasurface for low-frequency radar stealth through the polarization conversion ( $<8$  GHz) and infrared emission reduction at high temperatures has not been reported yet.

This paper proposed both low-frequency radar stealth and infrared emission reduction based on multifunctional coating. Not only radar stealth at high temperature can be achieved by using the unsymmetrical metasurface structure, but also infrared emission reduction can also be mediated with a high filling ration of metallic metasurface structure. The structure design and experimental demonstration are conducted in detail. This strategy can be applied in wireless communication, EM compatibility and stealthy radome. The principle of radar stealth here is the polarization conversion by some plasmon resonances [17], [18], [19], [20], while the low infrared emission root in the high filling ration of the high reflectivity metal [21], [22], [23]. Due to the different operating

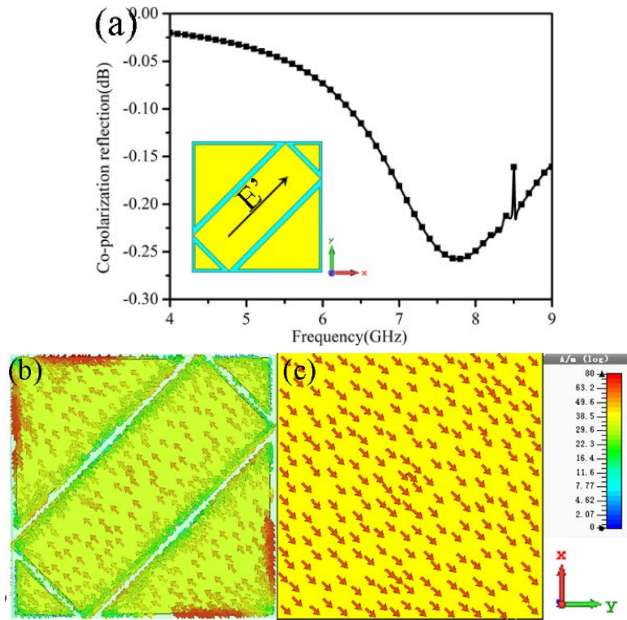


**FIGURE 1.** (a) The perspective and (b) the front view of the designed unit cell; (c) simulated results for different polarized wave.

principles at two different frequency bands, the ingeniously designed multifunctional coating can achieve multifunction in this work.

## II. STRUCTURE DESIGN AND DISCUSSION

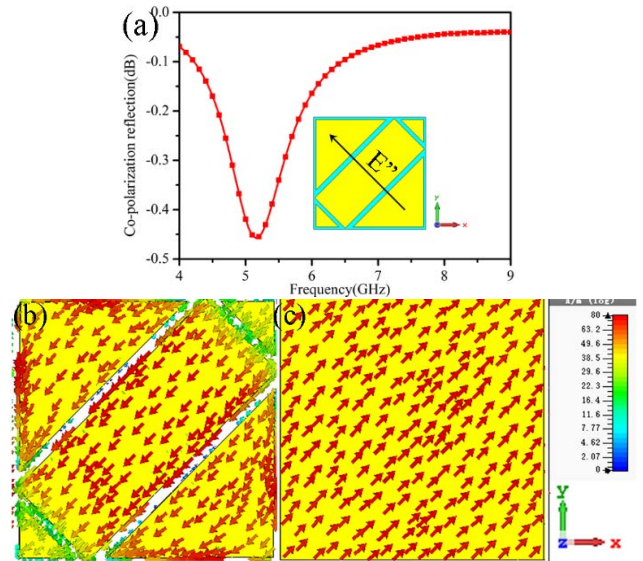
Figure 1(a) shows the designed multifunctional coating with three layers structure. From outside to inside, this coating consists of the unsymmetrical metasurface layer, high temperature resistant ceramic substrate and metal background. As shown in Figure 1(b), the unsymmetrical metasurface layer consists of periodic symmetry-broken cut wire and two tiny and two big triangular metals. Here metallic silver is selected as high-temperature resistant metal. The length and width of the symmetry-broken cut wire are  $a = 6$  mm and  $b = 2.3$  mm, respectively. The sides of the two tiny triangular metals are  $c = 1.23$  mm, and the two big triangular metals are  $d = 3.85$  mm. The gap width between the cut wire and triangular patches in the top layer is  $s = 0.25$  mm. Based on its advantageous character for processing and manufacture, the metasurface layer is conducted by screen printing to validate our work.  $\text{Al}_2\text{O}_3$  ceramic is selected as the high-temperature resistant dielectric. The permittivity of the  $\text{Al}_2\text{O}_3$  ceramic is about 8.35 in tested frequency as shown in Figure 6. The Figure 6 shows that the permittivity of  $\text{Al}_2\text{O}_3$  ceramic exhibits temperature stability. The loss tangent of  $\text{Al}_2\text{O}_3$  ceramic varies with tested frequency. The dielectric layer thickness is 2 mm, and the repetition period of the dielectric substrate is represented by  $p = 6$  mm. The designed multifunctional coating's polarization conversion performance was simulated with the commercial software CST Microwave Studio TM 2015. In the simulations, to test designed performances, the sample was performed by the free space method in a microwave anechoic chamber. Thus, the



**FIGURE 2.** Direction of the incident electric field along cut-wire: (a) eigen-mode of resonance; Surface current distributions on (b) the metasurface and (c) the metal background.

boundary conditions are set as unit cells along the x and y axes. The TE-polarized wave is fed using a port along the  $-z$  axis, so the directions of the electric field and magnetic field are along the y axis and x axis, respectively. As a result, the co-polarization reflection and cross-polarization reflection were obtained in the simulation. When incident wave is TE polarized wave, cross-polarization conversion reflection and co-polarization conversion reflection are  $R_{xy}$  and  $R_{yy}$ , while  $R_{yx}$  and  $R_{xx}$  stand for cross-polarization conversion reflection and co-polarization conversion reflection, when incident wave is TM polarized wave. Figure 1(c) shows the co-polarization reflection and cross-polarization conversion reflection versus frequency under normal incidence for different polarized wave. The cross-polarization conversion reflection larger than 90% can be obtained in the 5.2 - 7.8 GHz frequency region as shown in Figure 1(c). From Figure 1(c), we can see that two distinct cross-polarization peaks are at 5.5 GHz and 7.4 GHz, respectively.

To further investigate the mechanism of polarization conversion, the surface current distributions on the metasurface and metal background were monitored in the following section. Resonance mode belongs to electric or magnetic resonance at the resonant frequencies, which is better to monitor the surface current distribution to judge. Firstly, the electric field's direction is along the y-axis when TE polarized wave is perpendicularly incident on the metasurface. In order to determine the mode of electromagnetism resonance, the electric field direction is divided into two other directions, one is along the cut-wire direction, and another is perpendicular to the cut-wire direction. And then, surface current distributions of eigen-mode frequencies are shown in Figure 2 and Figure 3, respectively. Figure 2 shows the surface current distributions when the electric component along the cut-wire,

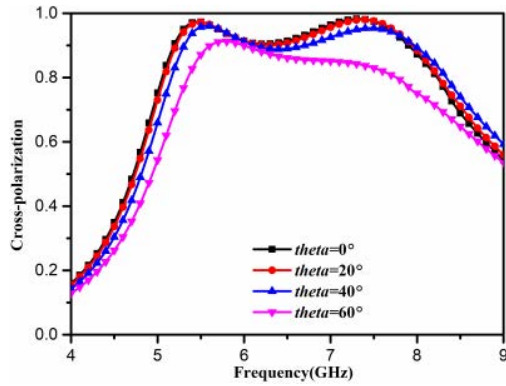


**FIGURE 3.** Direction of incident electric field perpendicular to cut-wire: (a) eigen-mode of resonance; Surface current distribution on (b) the metasurface and (c) the metal background.

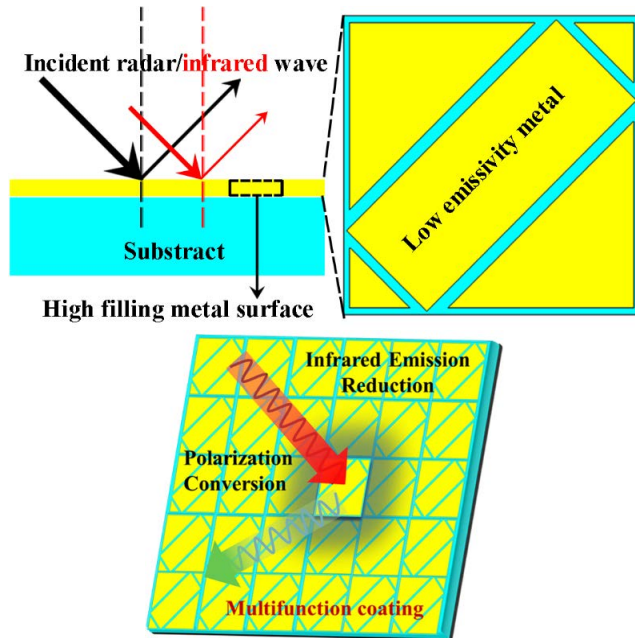
the electric component along the cut-wire direction excites the corresponding plasmon resonance eigen-mode, and the plasmon resonant frequency is 7.76 GHz. The amplitude of co-polarization reflection is about  $-0.26$  dB. The surface current distributions on the metasurface layer and the metal ground plane are shown in Figures 2(b) and 2(c), respectively. Because the surface current directions are opposite between the metasurface layer and the metal ground plane, the surface current forms a loop, this is analogous to a magnetic dipole. Hence, it verifies the type of resonance, which belongs to magnetic resonance.

Figure 3 shows that the direction of the electric component is perpendicular to the cut-wire. As shown in Figure 3(a), the electric component excite the corresponding plasmon resonance eigen-mode, the plasmon resonant frequency is 5.16 GHz. The amplitude of co-polarization reflection is about  $-0.45$  dB. Figures 3(b) and 3(c) show the direction of surface current on the metasurface layer and metal background, respectively. The surface current directions are also opposite between the metasurface layer and the metal ground plane. According to the above resonant type analysis, the surface current distributions of the two resonant frequencies have the same characteristics. Therefore, the second resonance is also a magnetic resonance, which is the same as the first resonance type.

Combined with the above resonance analyses, the resonant type at both eigen-mode frequencies belongs to magnetic resonance. Figures 2(a) and 3(a) show that magnetic resonance are generated by the couplings surface current between the symmetry-broken structure of the metasurface layer and the metal ground plane. At last, the TE-polarized incident wave is successfully converted to the TM-polarized reflected wave.



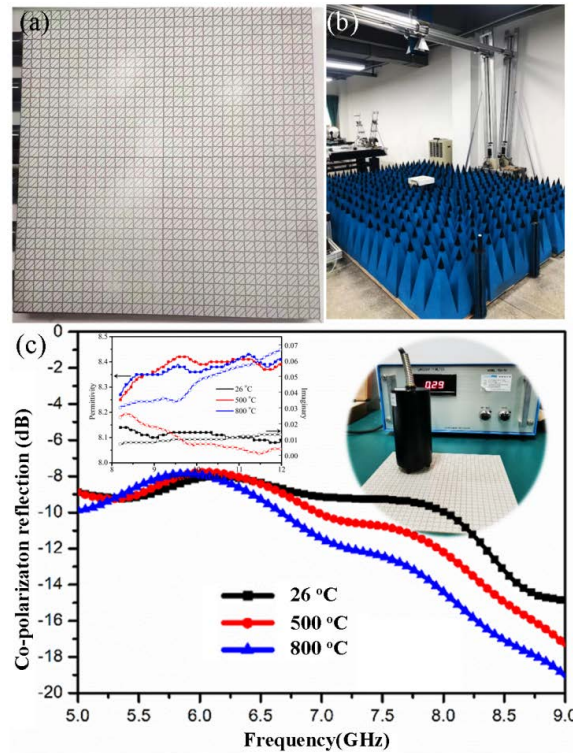
**FIGURE 4.** Simulated cross-polarization conversion spectra of the multifunctional coating with different oblique incidence angles of 0°, 20°, 40° and 60° for TE polarized wave.



**FIGURE 5.** Multifunctional coating for radar-infrared stealth-compatible.

In stealth, angular stability is a very important indicator, so the wide-angle polarization conversion performance for the multifunctional metasurface was also discussed. Figure 4 shows the simulated cross-polarization conversion spectra of the multifunctional metasurface under different oblique incident of TE polarized wave. The rate of polarization conversion and bandwidth are almost the same with oblique incident of 0°–40°, and the polarization conversion is above 80% with the incident angles of 60°. The absorption bandwidth is almost stability with the incident angles of 0°–40°, but the polarization conversion bandwidth becomes narrow when the incident angle is 60°. So the polarization transformation has a certain angle stability. The polarization conversion performance under TE polarized wave is mainly different during the relationship with different angle between the electric field and metasurface structure.

As noted, the high filling ration of the high reflectivity metal cause the low infrared emission is shown in Figure 5.



**FIGURE 6.** (a) Photographs of the fabricated prototypes; (b) microwave measurement environment; (c) the measured co-polarization reflection and infrared emissivity of the sample.

The filling ration of the metasurface is also calculated to evaluate the infrared performance. The metallic part of the metasurface has low emissivity ( $\epsilon_{Ag} = 0.1$ ), whereas the high temperature resistant dielectric layer has high emissivity ( $\epsilon_{Al_2O_3} = 0.8$ ). The filling ration ( $r$ ) is equal to  $(a * b + d^2 + c^2) / p^2$  according to the designed unit cell in the Figure 1(b). So the infrared emission could be calculated by the mix rules:  $\epsilon_{Ag} * r + \epsilon_{Al_2O_3} * (1-r)$ . Considering that  $a = 6$  mm,  $b = 2.3$  mm,  $c = 1.23$  mm, and  $d = 3.85$  mm, the final estimate is 0.22. Hence, the designed structure shows low infrared emission, having the potential of infrared stealth. The designed coating can realize multifunctional stealth with both radar stealth and infrared stealth.

### III. MEASUREMENT

To further verify the designed high-temperature resistant radar stealth and infrared emission reduction of the multifunctional coating, one prototype with a size  $180 \times 180$  mm<sup>2</sup> has been fabricated using screen printing (Figure 6(a)). Figure 6(b) gives the schematic illustration of the reflection measurement setup. The sample is irradiated by one of the two horn antennas, while the other antenna receives the reflected co-polarization wave, and therefore co-polarization reflections can be measured. The measured co-polarization reflection curve is shown at different temperatures in Figure 6(c).

As shown in Figure 6(c), the co-polarization reflection in 5~9 GHz is below -8 dB and lower with the frequency

increases, indicating more than 84% polarization conversion is achieved. Compared with simulation, measured copolarization reflection is basically accord with the simulation results when considering the error. This discrepancy is due to several reasons. One explanation is that the sample is too small for the measured frequency band, which causes a major error in the test. The second reason is the permittivity difference at 26 °C, 500 °C, and 800 °C as shown in Figure 6(c). The real part of the permittivity of Al<sub>2</sub>O<sub>3</sub> ceramics increased from 8.1 to 8.35. At the same time, the imaginary part also increased from 0.01 to 0.04. Besides, the error of sample making process is a non-negligible factor. Based on the above analysis, the measured result is in basic agreement with the full-wave simulation when taking into account those factors.

The emissivity of the multifunctional coating is difficult to obtain in the simulation. In other words, due to the significant differences between the operating wavelength of the electromagnetic waves and the size of the structure, the emissivity of the multifunctional coating is difficult to obtain by the simulation. Hence, in the present study, we only give a mean infrared emissivity, which is easy to obtain accurate measurements. Figure 6(c) shows the photograph of the infrared measurement of the multifunctional coating and the infrared emissivity. The measured infrared emissivity was performed in the infrared band of 3-14 μm using the TSS-5X IR Emissivity meter. In order to measure the veracity of the emission, several arbitrarily different regions are selected to measure. The emission rates of the several different areas are all less than 0.29, and one photograph of infrared measurement is shown in Figure 6(c). The average of these measurements is as low as 0.25. Hence, the prepared multifunctional coating provides the potential for infrared stealth. Based on the above analysis and measurement, the final test results are consistent with the previous design.

#### IV. CONCLUSION

In conclusion, a multifunctional coating for achieving both radar stealth and infrared stealth through the metasurface was skillfully designed and verified in this paper. The metasurface consists of symmetry-broken cut wire and two tiny and two big triangular metals. The symmetry-broken structure of metasurface results in radar stealth in the low-frequency band of 5.2-7.8 GHz. The high filling ration of the metasurface causes low infrared emission as low as 0.22. Simulation and measurement demonstrated that the multifunctional coating can achieve compatibility stealth for the radar stealth and infrared stealth at high temperature. Meanwhile, the experimental results at different temperatures demonstrate that the theoretical design is effective. Because of the excellent multispectral compatibility, the multifunctional coating may find applications in multispectral stealth technology.

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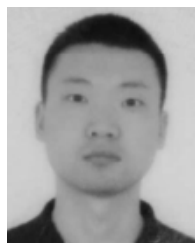
the characteristic of high temperature metamaterials and integrated manufacturing of composite structure.



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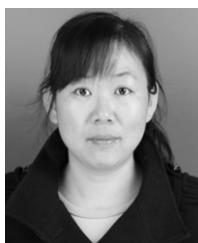
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