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Design of a wideband random phase gradient metasurface by using line-shaped element

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Based on phase randomization theory, a method for manufacturing metasurface with diffuse scatter performance is proposed. By using the line-shaped elements with random rotate angles and random distributing positions, the metasurface can achieve good diffusion scatter performance with polarization independent characteristic. This paper studies the effects of the length of line-shaped elements on the metasurface response frequency and the radar cross section (RCS) reduction bandwidth. The simulated result shows that the wideband properties of metasurface benefit from two different length line-shaped elements. The proposed metasurface can reduce the RCS significantly for both normal and oblique incident waves. The line-shaped element is suitable for all sizes of detected objects and it can be directly sprayed on the detected object surface. To demonstrate the effectiveness of the proposed method, the metasurface prototype is fabricated and measured. Experimental results show that the fabricated metasurface can effectively reduce RCS, and it has great application prospects in stealth technology.

Keywords: Diffuse scatter characteristics; polarization independent; radar cross section reduction.

1. Introduction

Metamaterial is a kind of sub-wavelength artificial composite structure with unusual electromagnetic properties, such as negative refraction,[1,2] perfect transmission.[3] An important application of metamaterial is as a stealth structure that reduces the radar cross section (RCS) of the objects being detected. Metasurface is a two-dimensional planar form of metamaterial, which is arranged by periodic or nonperiodic of sub-wavelength unit structure.[4–6] The artificial structures distributed on the surface of metasurface will form phase gradients, which control the propagation of electromagnetic waves.

In 2011, Prof. Capasso of Harvard University proposed the generalized Snell's law based on the phase mutation of the tangential field on both sides of the phase gradient elements.[7] In 2014, Prof. Tiejun Cui of Southeast University proposed the concept of coded metamaterials.[8] They propose a new mechanism for reducing RCS by redirecting EM energies to all directions through a special coding. The "0" element corresponds to the reflection phase of 0°, and the "1" element corresponds to the reflection phase of 180°. The best RCS reduction can be achieved through optimizing the coding sequences of "0" and "1" lattices.[9,10] Two-bit coded metamaterials in Refs. 11–13 and three-bit coded metamaterial in Ref. 14 are further proposed to improve the RCS reduction of the detected objects. In 2016, Prof. Yongjiu Zhao proposed a phase gradient metasurface. This phase gradient metasurface unit element consists of a symmetric split ring and a cutting line. The cell opening angle and the rotation angle can, respectively control the phase and amplitude of the cross-polarized reflection. In 2018, Maochang Feng of Air Force Engineering University proposed an N-shaped phase gradient metasurface.[15] Based on Pancharatnam-Berry phase in Refs. 16 and 17, rotating metal pattern can change the reflection phase of electromagnetic wave.[18] The metasurface fabricated by using cut-wires is also studied in Refs. 19 and 20 for terahertz application. However, the structures of the metasurface elements designed above are complex. Thus, these metasurfaces cannot be directly sprayed on the surface of the objects need to be detected. The unit layout of metasurface needs redesign when the size of the objects being detected is changed.

In this paper, a wideband polarization independent metasurface is proposed for RCS reduction application. The line-shaped element is adopted as the metal pattern of metasurface. Because the line-shaped element is simple in structure, so the designed metasurface can be directly coated on the surface of objects. When the line-shaped elements are randomly distributed and arbitrarily rotated at the surface, a large number of phase gradients are produced. Good diffuse scatter performance will be obtained. In addition, wideband characteristic can be obtained by setting line-shaped elements

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with two lengths. The polarization independent characteristic of the metasurface benefits from the random rotate angle and arbitrary randomized position of the elements. Both simulation and measurement results show that the proposed metasurface can significantly reduce the RCS for both normal and oblique incidences. The RCS reduction bandwidth better than 10 dB are approximately 8.4 GHz for normal incident waves. Under the condition of oblique incidences, the RCS reduction bandwidth varies slightly, but the RCS reduction trend is basically the same.

2. Unit and Metasurface Design

2.1. *Unit Design*

The unit structure is shown in Fig. 1, which is a metal plate, a substrate layer, and a metal patch from the bottom layer to the top layer. Geometric parameters of the unit are $\boldsymbol{w} = 0.4$ mm, $\boldsymbol{l} = 5.0$ mm, $\boldsymbol{p} = 6.0$ mm. The metal pattern of the upper patch is a rectangle. Because the structure of the rectangular metal patch is simple, it can be replaced by using metal cut-wires in the actual production.

In this paper, the metasurface is produced by using line-shaped elements with random rotate angle and randomized position to obtain diffuse scatter characteristic. For the produced metasurface, its elements are nonperiodic arranged on the top surface of substrate with arbitrary rotate angles. Thus, various kinds of different phase gradients are induced. Then, the electromagnetic wave will be uniformly scattered to the vacuum.

2.2. *Metasurface design*

Based on the unusual diffuse reflection theory, a metasurface model is produced. A design procedure is given to guide the metasurface design. Firstly, two random functions are setup. One function is used to make sure the position of each element and another function is used to product a stochastic rotate angle for each element in the range from 0° to 180°. Then, the parameters are setup and a metasurface model is obtained. The produced metasurface is shown in Fig. 2. The total size of this metasurface model is 150 mm × 150 mm × 2.5 mm.

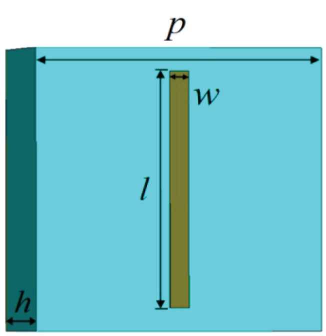

Fig. 1. The design unit structure of the proposed metasurface.

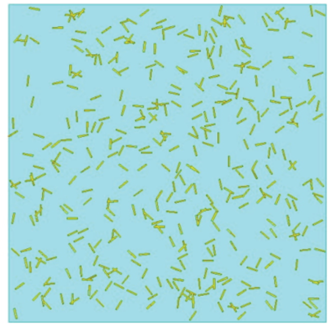

Fig. 2. The produced metasurface by using random distributing line-shaped elements.

Because the position and rotate angle of each element are stochastically produced, part of the elements will be overlapped. Then, the new phase gradient will be induced, which is beneficial for improving the diffuse scatter capacity of the metasurface. In addition, the work frequency and bandwidth are determined by the parameters of the metasurface, such as the number of the elements, length, and the width. Thus, the work frequency band can be easily controlled by adjusting the number, length, and width of the elements.

3. Performance of the Metasurface

In this section, the performance of the produced metasurface is discussed. The effect of the length of line-shaped element on the metasurface response frequency and the RCS reduction bandwidth are also discussed.

3.1. *Normal incidence*

The simulated RCS characteristic of the metasurface irradiated by the X- and Y-polarization planar waves is shown in Fig. 3. The RCS characteristic of a metal plate with the same sizes is also given in Fig. 3 as a reference. As shown in Fig. 3, the RCS reduction of the metasurface is better than 10dB ranging from 11.9 GHz to 14.3 GHz for X-polarization planar wave. It is also observed that the metasurface can reduce the RCS of 10dB in the similar frequency band ranging from 12.2 GHz to 14.6 GHz for Y-polarization planar wave. The trend of RCS reduction for the produced metasurface is basically similar in X- and Y-polarization directions. Then, the polarization independent characteristics of the metasurface can be confirmed according to simulated result. This phenomenon is mainly induced by using the random distributing elements. Due to the random position and rotate angle, various kinds of phase grads are brought into the produced metasurface. And the random phase gradients are obtained. The incident wave is scattered in many directions and the diffuse scatter characteristic is achieved.

In order to further demonstrate the scatter characteristic of the metasurface, the simulated scatter performance of the

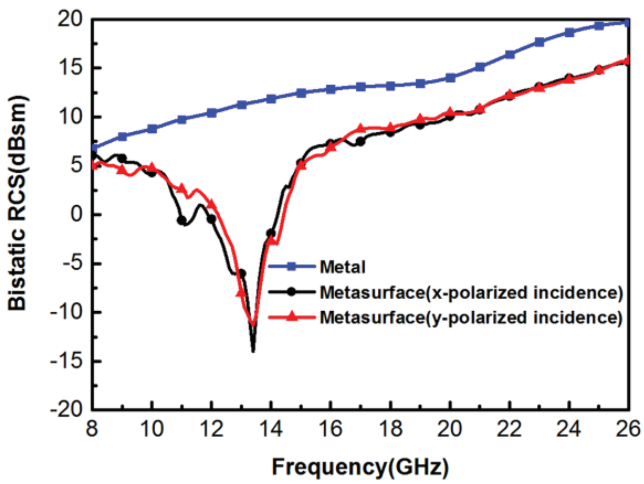

Fig. 3. The simulated RCS results of the metasurface irradiated by X- and Y-polarization planar waves.

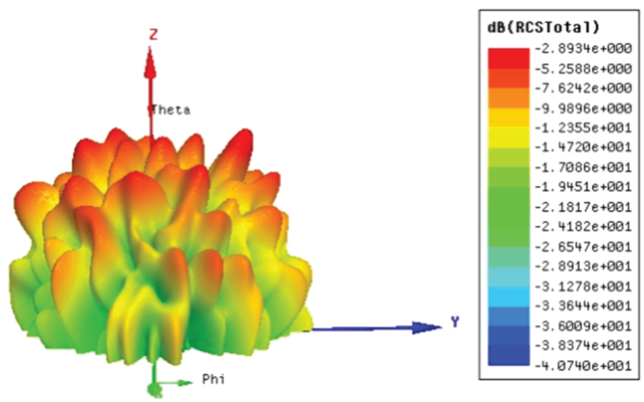

Fig. 4. The simulated scatter performance of the metasurface irradiated by X-polarization planar wave at 13.4 GHz.

metasurface irradiated by X-polarization wave is depicted in Fig. 4. The reference frequency point is selected at 13.4 GHz. It is noticed that the electromagnetic wave is scattered to the vacuum in multi-direction. There is no obvious scatter beam in the observed space. It means that good diffuse scatter characteristic is achieved by using the proposed metasurface.

3.2. *Oblique incidence*

Because the metasurface has polarization independent characteristic, the RCS reduction characteristic within different incident angles is only considered at X-polarization direction. The simulated RCS reduction performance with different incident angles is given in Fig. 5. As shown in Fig. 5, the metasurface model exhibits good RCS reduction performance along with the incident angle increases. That means the metasurface model has a good wide-angle characteristic.

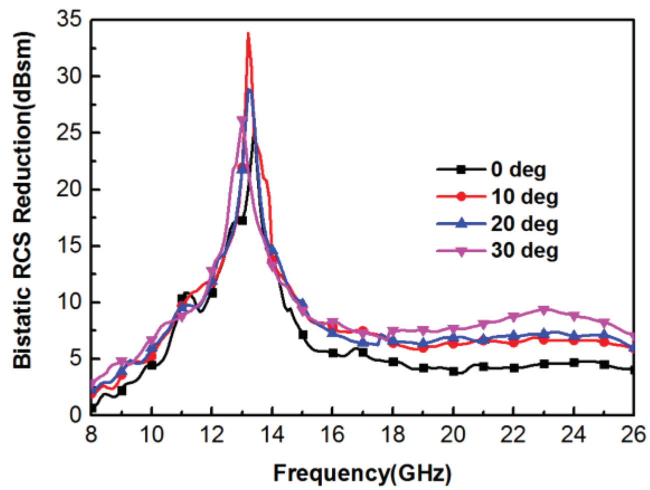

Fig. 5. The simulated RCS reduction capacity of the metasurface irradiated by X-polarization wave within different angles of incidence.

3.3. *Effect of element length*

The length of the element is an important parameter which is mainly determining the working frequency band. The RCS reduction capacity of the metasurface with different lengths is simulated and the result is given in Fig. 6. In order to analyze expediently, the width of the element is fixed to 0.6 mm while the length is changed from 3 mm to 8 mm with a step of 1 mm. As shown in Fig. 6, it is observed that the resonance frequency is closely related to the length of element for the metasurface. As the length increases, the RCS reduction peak moves to lower frequency band. By adjusting the length of the element, we can easily control the working frequency band. However, it is observed that the RCS reduction bandwidth is narrow, which is restricted in the actual application.

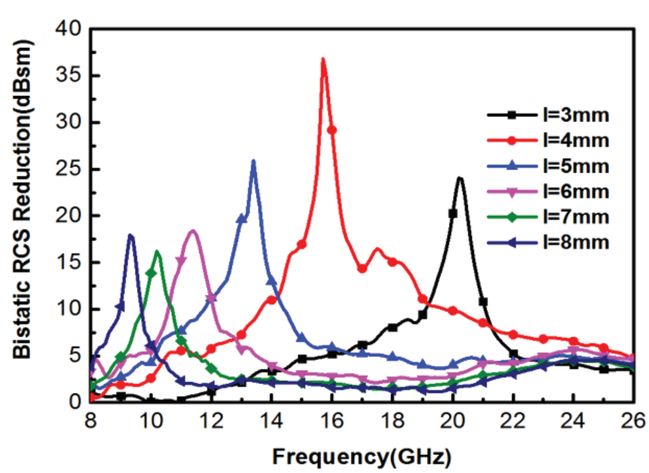

Fig. 6. The simulated RCS reduction capacity of the metasurface for different element lengths.

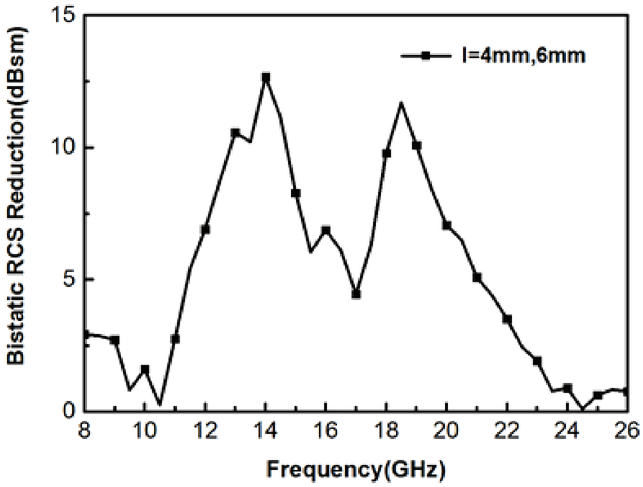

Fig. 7. The simulated RCS reduction capacity of the metasurface with two lengths line-shaped elements.

In order to increase the RCS reduction bandwidth, the line-shaped elements with two lengths is adopted. The simulated RCS reduction result is given in Fig. 7. There are 300 elements with length of 4 mm and 300 elements with length of 6 mm. According to the simulation result, the simulated RCS reduction bandwidth, better than 10 dB, is approximately 9.5 GHz. The bandwidth of the RCS reduction is effectively expanded by using line-shaped elements with two lengths.

4. Experimental Results and Discussion

In this section, to demonstrate the effectiveness of the proposed method, the metasurface prototypes are fabricated and measured.

4.1 *Fabrication of the metasurface*

According to the simulated results, the fabricated process is given as the follow steps. Firstly, a metal plate with the size of 150 mm × 150 mm is selected as the ground plane. And then the epoxy, whose relative permittivity is 2.7 and relative permeability is 1.0, is selected as the substrate of the metasurface. Secondly, the substrate with the thickness of 2.5 mm is covered in the metal plate. Finally, the line-shaped elements are randomly and well-proportioned distributing on the top surface of the substrate. There are 300 metal wires with length of 4 mm and 300 metal wires with length of 6 mm. The metal cut-wire with diameter of 0.3 mm is selected as the material of the line-shaped elements. When the epoxy is solidified, a fabricated sample is obtained. The photograph of the fabricated metasurface with two lengths cut-wires is shown in Fig. 8.

4.2. *Measured results and discussion*

In order to demonstrate the diffuse scatter performance of the proposed metasurface, the RCS reduction performance

Fig. 8. The fabricated metasurface sample by using the random distributing elements with two lengths.

of the samples irradiated by X- and Y-polarization incident waves is first measured in the axial direction of sample. The measured results of the fabricated sample are depicted in Fig. 9. As shown in Fig. 9, it can be seen that the RCS reduction in X-polarization is in decent agreement with the RCS reduction in Y-polarization. Two RCS reduction peaks are observed due to the two lengths of the elements. It means that the RCS reduction bandwidth can be extended by using different lengths. Extending the RCS reduction bandwidth by using different lengths is experimentally confirmed. It also can be seen that polarization independent characteristics are experimentally confirmed through the measured result of the fabricated sample. It means that the fabricated metasurface can significantly reduce the RCS for both normal and oblique incidences.

According to the measured result, the RCS reduction bandwidth is better than 10 dB are approximately 8.4 GHz ranging from 12.2 GHz to 20.6 GHz for X-polarization and approximately 13.1 GHz ranging from 12.6 GHz to 25.7 GHz

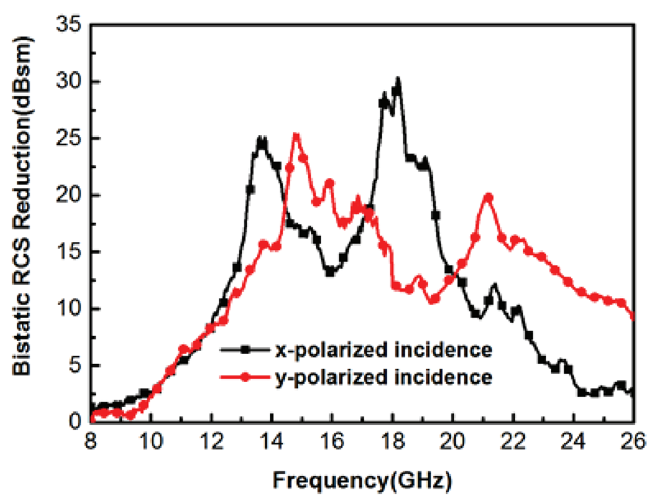

Fig. 9. The measured RCS reduction performance of the fabricated sample which is irradiated by X- and Y-polarization incident waves in axial direction.

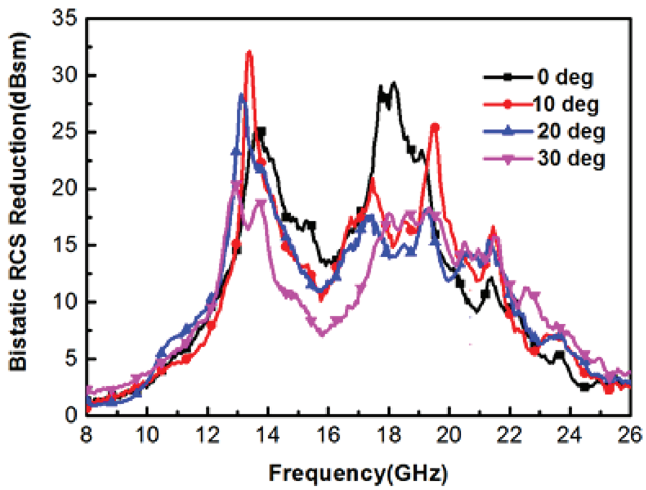

Fig. 10. The measured RCS reduction performance of the fabricated sample within different incident angles.

for Y-polarization. In addition, it is observed that the RCS reduction bandwidth in Y-polarization is wider than the bandwidth in X-polarization. This is mainly because the elements distributed in Y-polarization direction is more than that of elements in X-polarization direction. The more phase grads are induced. Then, the reflectivity of the fabricated metasurface is anisotropic. The RCS reduction abilities in X- and Y-directions are different. Anyway, the fabricated sample still reveals well performance in the operating band. Stable RCS reduction capacity and the polarization independence characteristics still can be achieved.

According to the above discussion, the fabricated sample illustrates wideband RCS reduction performance. This means that the fabricated metasurface by using the method in Sec. 4.1 can provide a good diffuse scatter capacity in the axial direction. Keeping random distributing of elements on the top layer of substrate, stable polarization independent characteristics can be obtained. The effectiveness of the proposed method for manufacturing a metasurface with good diffuse scatter performance is verified by the measured results in the axial direction.

In order to further verify the effectiveness of the proposed method for manufacturing a metasurface, diffuse scatter performance of the sample is also validated in multi-direction by using the measured RCS reduction performance. The measured RCS reduction performance along with the incident angles increases are plotted in Fig. 10. As shown in Fig. 10, good RCS reduction characteristic with different incident angles is observed. As incident angle increases (i.e., the incident angle = 0°, 10°, 20°, 30°), the fabricated sample demonstrates a similar working frequency band and RCS reduction capacity. Stable RCS reduction bandwidth in different angles is achieved. It means that good diffuse scatter capacity of the fabricated metasurface is experimentally confirmed according to the measured results. In addition, the RCS reduction in the large angle (i.e., the angle = 30°) has a little deterioration compared with that in the small angles. This is because the elements of the sample display a shorter length. Thus, the corresponding bandwidth of RCS reduction moves to high frequency band. Then, the RCS reduction capacity between the two peaks is weak. Anyway, the fabricated sample still displays a good RCS reduction performance with the incident angle of 30°.

Through the above discussion, we can conclude that the metasurface by using random distributing surface can realize a good diffuse scatter performance with wide bandwidth. Stable RCS reduction capacity and polarization independence can be achieved. Wideband diffuse scatter characteristic and polarization independence characteristics of incident waves make it promising for conformal surface retreat application.

5. Conclusion

Based on the diffuse scatter theory, a random phase distributing metasurface is proposed in this paper. By giving the element random distributing position with an arbitrary rotate angle, various kinds of phase gradients are produced and the incident waves can be scattered to arbitrary direction. Good diffuse scatter performance can be achieved. Owing to the fact that the working frequency was closely related to the lengths of the elements, wideband performance is obtained by setting line-shaped elements with two lengths. To demonstrate the effectiveness of the proposed method, one metasurface prototype is fabricated and measured. The simulated and measured results both demonstrate that good diffuse scatter characteristic and RCS reduction capacity can be obtained. Furthermore, the proposed metasurface has the advantage of easy fabrication compared with other approaches for conformal application.

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Yakuan Zhang contribute equally to this paper.

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