Dual-Band Diffusive Metasurface-Based Reflector With Low Out-of-Band Backscattering

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This work was supported in part by the National Natural Science Foundation of China (NSFC) under Grant 61871036 and in part by the Open Project of the State Key Laboratory of Millimeter Waves under Grant K202018.

\textbf{ABSTRACT} This article describes a dual-band diffusive metasurface-based reflector, with a specular reflection band together with two sidebands which exhibit low radar cross-section (RCS). A rhombus-shaped patch-ring type of polarizer with dual-band characteristics is chosen as the fundamental unit cell. The polarizer and its mirror structure have opposite phases in the polarization-rotating bands, while their phase is the same in the reflection band, which is juxtaposed in-between the middle of the two polarization-rotating bands. The designed metasurface is constructed, based on the phase cancellation theory, by arranging arrays of these two unit cells in a two-dimensional pattern. The measured results show that the realized metasurface-based reflector achieves a high-efficiency specular window from 26.2 to 38.8 GHz together with two low-RCS sidebands from 18.18 to 24.6 GHz and 40.61 to 56.4 GHz. The proposed diffusive metasurface can be potentially used as a reflector for reflector antennas, which provides a highly efficient in-band radiation together with low backscattering out-of-band.

\textbf{INDEX TERMS} Metasurface, polarizer, radar cross-section.

\section{I. INTRODUCTION}
Antenna with reflecting ground can achieve broadband and high-gain characteristics, which attracts great interests \cite{1}. Although the reflector provides broadband and high-gain characteristics to the antenna, it also exhibits a relatively larger radar cross-section (RCS). To enhance the security and stealth performance of the platform on which the antenna is installed, it is highly desirable to diminish the antenna’s RCS without compromising its performance as a radiator \cite{2}, and this prompts us to investigate the design of a reflecting surface, which offers both high reflectivity in the center-band and RCS-reduction in the sidebands, to realize a wideband reflector antenna with low-RCS sidebands.

Recently, a new concept of absorptive frequency selective reflectors (AFSRs) using resistor-embedded frequency selective surface was reported, in which the designed superstrate lossy layers absorb the impinging waves outside the operating frequency of antennas \cite{3}–\cite{8}. Comparing to the traditional absorbers, the AFSR introduces a reflection window in a wide absorption band, exhibiting absorption-reflection-absorption response \cite{9}–\cite{12}. The AFSR can be designed as a reflector in the radiation band of an antenna, while it acts as an absorber in the two sidebands. An AFSR has been designed by printing a reflective patch on a lossy layer, to introduce a reflection window within the absorption band \cite{13}. Yet another approach has been employed to realize a three-dimensional AFSR \cite{14} by using a series circuit to deactivate the absorber in the desired band. However, the performance of AFSRs relies heavily on the reliability of resistors that limits the performance of the AFSR, because lots of welded resistors generate unpredictable parasitic parameters that have adverse effects on the absorption performance of the AFSR. More importantly, the resistor-based AFSR may not be impracticable at higher frequencies.
The chessboard and checkerboard metasurfaces, comprising of arrays of subwavelength unit-cell resonators with no resistors, have been intensively exploited to realize the RCS reduction based on the scattering cancellation concept [15]–[20]. More recently, diffusive metasurfaces with low RCS at the diffraction lobes were proposed in [21]–[23]. Their scattered energy is redistributed from the normal toward other directions by properly arranging the subwavelength structures.

Nevertheless, almost all of the aforementioned metasurfaces are with wideband RCS-reduction performance, but short of frequency-selective characteristic. A reflective type 1-bit coding metasurface was reported, and it works as a metallic mirror at the center frequency while diffusing the scattering wave at two sidebands [24]. However, its reflective frequency band is relatively narrow, because the phase difference of 0° is theoretically achieved at only one point by crossing the linear phase dispersion for the ‘1’ element and a sharp phase change of 360° for the ‘0’ element.

In this article, a wideband metasurface with a diffusion-reflection-diffusion response based on the dual-band polarizer is proposed for the wideband reduction of the antenna’s RCS. A rhombus-shaped patch-ring structure and its mirror with opposite phase response at the two polarization-rotating (PR) bands and the same phase response at the center reflection band are chosen as the basic unit cells. Then, a dual-band diffusive metasurface is designed by arranging the polarizer element with ‘0’ response and its mirror element with ‘π’ response in a two-dimensional sequence. Consequently, two RCS-reduction bands of the scattered fields located below and above the wide reflection band (27.6-38.2 GHz) are realized. Simulated and measured results are in good agreement, and it proves that the proposed diffusive metasurface as a reflector is an attractive candidate for wideband antenna’s RCS reduction, especially at higher frequencies.

II. DESIGN OF DUAL-BAND POLARIZER

A metallic rhombus-shaped patch-ring structure is proposed herein to achieve a dual-band polarizer. Fig. 1 depicts the schematic diagrams of the proposed dual-band polarizer unit cell. The proposed polarizer consists of a metallic rhombus-shaped patch-ring structure printed on the top side of a Rogers 4350 substrate with a dielectric constant ($\varepsilon_r$) of 3.66, loss tangent (tan $\delta$) of 0.002 and the substrate thickness is 0.8mm. A perfect electric conductor (PEC) ground layer is printed on the backside of the substrate to eliminate the transmitted wave. The geometric parameters of the proposed dual-band polarizer are set as $l_1 = 1.8$ mm, $l_2 = 0.95$ mm, $l_3 = 1$ mm, $l_4 = 0.4$ mm, $w = 0.2$ mm. The periodicity between unit cells is $P = 2.8$ mm.

The commercial software, CST Microwave Studio, is used to simulate the performance of the proposed polarizer. Simulated results of the co- and cross-polarized reflection coefficients for the polarizer illuminated by x- and y-polarized normally incident waves are shown in Fig. 2. Here, $r_{xx}$ ($r_{yy}$) and $r_{yx}$ ($r_{xy}$) represent the co- and cross-polarized reflection coefficients under x-polarized (y-polarized) incidence, respectively. It can be seen that the reflected waves consist of three parts, co-polarized reflected wave in the reflection band from 26 to 40 GHz and cross-polarized reflected wave in the lower and upper PR bands from 17.7 to 23.8 GHz and from 41.3 to 55.4 GHz, respectively. The curves of co-polarized reflection coefficients show two resonant peaks at 18.62 and 22.75 GHz in the lower PR band and three resonant peaks at 42.18, 48.76, and 54.75 GHz in the upper PR band are generated, where the x-polarized (y-polarized) incident wave is effectively converted to the y-polarized (x-polarized) reflected wave, as shown in Fig. 2(a).

The efficiency of the polarization conversion can be quantitatively evaluated based on the polarization conversion ratio.
(PCR), which is defined as [25]

\[
\text{PCR} = \left| r_{xx} \right|^2 / \left( \left| r_{xx} \right|^2 + \left| r_{xy} \right|^2 \right) \quad \text{or} \quad \left| r_{xy} \right|^2 / \left( \left| r_{xy} \right|^2 + \left| r_{yx} \right|^2 \right).
\]  

(1)

Fig. 2(b) shows that the PCR levels are higher than 90% for both the lower and upper PR bands, while approximately 0 at the co-polarized reflection band for the proposed dual-band polarizer. According to (1), the peaks of PCR are realized as co-polarized reflection coefficients are nearly 0, which means that the locations of the PCR peaks are consistent with those of zeros of co-polarized reflection coefficients shown in Fig. 2.

In Figs. 3(a) and 3(b), the x-polarized incident wave would disintegrate into two orthogonal components, \( \vec{E}_{iu} \) and \( \vec{E}_{iv} \). The u- and v-axes are realized by using a 45° clockwise rotation of x- and y-axes, and the two components \( \vec{E}_{iu} \) and \( \vec{E}_{iv} \) have identical magnitudes and phases. Hence, the incident EM wave can be expressed as

\[
\vec{E}_i = \vec{E}_{iu} + \vec{E}_{iv} = |E_0| (\hat{e}_u + \hat{e}_v),
\]  

(2)

where \( |E_0| \) is the magnitude of two perpendicular components, and \( \hat{e}_u \) and \( \hat{e}_v \) are unit vectors in u- and v-axes, respectively.

The wave with \( \vec{E}_i \) is incident upon the polarizer and the reflected wave \( \vec{E}_r \) is obtained with PR characteristic. Then the reflected wave \( \vec{E}_r \) can be presented as the sum of the perpendicular components \( \vec{E}_{ru} \) and parallel component \( \vec{E}_{rv} \), that is,

\[
\vec{E}_r = \vec{E}_{ru} + \vec{E}_{rv} = r(\vec{E}_{iu} + \vec{E}_{iv}) = |E_0| \left( \hat{e}_u \left| r_u \right| e^{j\varphi_u} + \hat{e}_v \left| r_v \right| e^{j\varphi_v} \right),
\]  

(3)

where \( \left| r_u \right| \) and \( \left| r_v \right| \) are their corresponding reflection magnitudes, while \( \varphi_u \) and \( \varphi_v \) are their corresponding shifted phases. It should be mentioned that both two reflection magnitudes are unity (\( \left| r_u \right| = \left| r_v \right| = 1 \)) due to the PEC ground plane at the bottom layer.

Because of the anisotropy of the proposed polarizer, values of two reflection phases \( \varphi_u \) and \( \varphi_v \) are discrepant, which leads to a nonzero phase difference (\( \Delta \varphi = \varphi_u - \varphi_v \)). According to (2) and (3), the cross-polarized reflected wave arises because the phase difference \( \Delta \varphi \) ranges from 150° to 210° [19]. Therefore, the synthetic field for \( \vec{E}_{ru} \) and \( \vec{E}_{rv} \) will be along the y-axis and a 90° polarization rotation is obtained, as shown in Fig. 3(a). In addition, the co-polarized reflected wave is achieved when the value of PCR lower than 10% with the phase difference \( \Delta \varphi \) varies between -30° and +30°, as shown in Fig. 3(b).

Fig. 4 displays the reflection phase \( \varphi_u \) and \( \varphi_v \) together with their phase difference \( \Delta \varphi \) obtained by using an EM simulator HFSS. It is observed that \( \Delta \varphi \) is rough 0° in the reflection band, while the phase difference is approximately 180° from 17.7 to 23.8 GHz and from 41.3 to 55.4 GHz, implying the ability of PR in both the lower and upper PR bands.

Moreover, we notice that the dimensions of the rhombus-shaped structure have a great influence on phases \( \varphi_u \) and \( \varphi_v \). For simplicity and without the loss of generality, the influence of the parameters of the outer rhombus-shaped ring on the lower PR band is detailed here. Fig. 5 plots the dependence of the phases \( \varphi_u \) and \( \varphi_v \) on the long diagonal \( l_1 \) and short diagonal \( l_2 \), respectively. It is seen that the long diagonal \( l_1 \) has a greater impact on phase \( \varphi_u \) at higher frequencies and phase \( \varphi_v \) at lower frequencies. The short axis \( l_2 \) mainly affects the phase \( \varphi_u \) at higher frequencies and has little effect on phase \( \varphi_v \). Thus, the position of the lower PR band is determined by phases \( \varphi_u \) and \( \varphi_v \) together with phase difference \( \Delta \varphi \) through modifying the size of the outer rhombus-shaped ring. In addition, the effects of parameters \( l_3 \) and \( l_4 \) on phases \( \varphi_u \) and \( \varphi_v \) in the upper PR band are similar to those of parameters \( l_1 \) and \( l_2 \) in the lower band. That is to say, the position of the upper PR band is determined by the size of the inner rhombus-shaped patch.

To better explain the mechanism of the proposed polarizer, we turn to Fig. 6, which plots the induced currents on the rhombus-shaped resonant structure, as well as on the metallic floor. The induced currents, that are focused on the outer rhombus-shaped resonant structure, as well as on the metallic floor. The induced currents, that are focused on the outer rhombus-shaped resonant structure, as well as on the metallic floor. The induced currents, that are focused on the outer rhombus-shaped resonant structure, as well as on the metallic floor. The induced currents, that are focused on the outer rhombus-shaped resonant structure, as well as on the metallic floor. The induced currents, that are focused on the outer rhombus-shaped resonant structure, as well as on the metallic floor. The induced currents, that are focused on the outer rhombus-shaped resonant structure, as well as on the metallic floor.
patch, as displayed in Figs. 6(c)-6(d). Therefore, the resonant frequencies of 42.2 GHz and 48.7 GHz is produced by the combined actions of magnetic and electric dipole resonances. In addition, a high-order magnetic resonance mode is exited at 54.8 GHz, which is mainly associated with the outer structure, as shown in Fig. 6(e).

In summary, the location of the lower PR band is controlled by the size of the outer ring, while the upper band is attributed to the size of the inner patch as well as to the coupling effect between these structures. This type of independent controllability of the locations of the reflection band and two PR bands is well-suited for adjusting the reflection bandwidth, which helps to make the structure flexible.

III. DIFFUSION-REFLECTION-DIFFUSION METASURFACE-BASED REFLECTOR

An intuitively straightforward approach to reduce the structural RCS is to adjust the phase difference between the reflected fields of two elements to be 180° within the RCSR band [26]. To reach this goal, the proposed polarizer (‘Code0’) is simply rotated by 90° to obtain its antiphase counterpart (‘Code1’). Besides, the EM wave can be reflected when two structures are in-phase at the reflection band. Under this guidance, the proposed metasurface-based reflector with diffusion-reflection-diffusion characteristic is designed to achieve high reflectivity in the reflection band and diffusion in two broad sidebands with low RCS levels.

Fig. 7 depicts the phase difference between ‘Code0’ and ‘Code1’ for the co- and cross-polarized waves. It is seen that the phase difference of the co-polarized reflected waves is 0° while that of the cross-polarized waves is approximately 180°. In other words, the phase difference of 180° is obtained for both the lower and upper PR bands while that of 0° is achieved at the reflection band for the proposed rhombus-shaped patch-ring structure. As a great advantage, the frequency-selective in-phase at the reflection band and out-of-phase at the two PR bands can be realized through a geometric 90° rotational operation of a single element instead of constructing two different anti-phase elements.

To approximately satisfy the unit cell boundary condition used in the simulation, the ‘0’ element defined as square block includes 9 × 9 ‘Code0’ unit cells with a 0° phase response, while the ‘1’ element defined as square block includes 9 × 9 ‘Code1’ unit cells with a π-phase response. Taking the fabrication cost and structural dimensions into account, we design a metasurface which contains 11 × 11 equal-sized square blocks, with each block occupying by a sub-array of ‘0’ or ‘1’ elements; however, their distributions can be arbitrary.

According to the scattering pattern of the metasurface, block element pattern (EP) can be expressed as

\[
\text{EP} = \cos \theta. \tag{4}
\]

Then the scattering pattern (SP) can be calculated as [17]

\[
\text{SP}(\theta, \phi) = \text{EP} \cdot \text{AF} = \cos \theta \cdot \sum_{n=1, m=1}^{11, 11} e^{-j\left(\frac{2\pi}{\lambda} \sin \theta (\cos \phi mP + \sin \phi nP) + \psi_{nm}\right)}, \tag{5}
\]

where \(\theta\) and \(\phi\) are the elevation and azimuth angles of an arbitrary direction, respectively; \((m, n)\) defines the position of the element; and \(\psi_{nm}\) (0 or π) represents its scattering phase. To manipulate the scattering pattern as much as possible, the peak value of the scattering field can be expressed as the fitness function

\[
\text{fitness} = \max (\text{SP}(\theta, \phi)). \tag{6}
\]

To make the fitness function minimum at the direction of normal incidence for both two RCS-reduction (RCSR) bands, the ergodic algorithm is employed in MATLAB. The best sequence of the diffusive metasurface formed by 11 × 11 elements is obtained. As a comparison, a chessboard metasurface with the same dimension is also designed and simulated.

The element distributions of a chessboard metasurface and a diffusive metasurface are calculated by MATLAB through (5) and (6), as shown in Fig. 8(a) and Fig. 8(b), respectively. Their RCSR curves compared to an equal-sized PEC plane are given in Fig. 8(c). Fluctuation can be observed between two metasurfaces, while a stable reflection window is observed in the co-polarized reflection band. It is clear that the RCS (RCSR) of diffusive metasurface in the lower and upper bands are higher than those of the chessboard metasurface. The designed diffusive metasurface has achieved a 10-dB RCSR from 18.18 to 24.6 GHz for the lower
FIGURE 6. Simulated Surface current distributions on the rhombus-shaped layer and metallic floor at five resonance frequencies. (a) 18.6, (b) 22.8, (c) 42.2, (d) 48.7, and (e) 54.8 GHz.

FIGURE 7. The phase difference between the proposed polarizer ('Code0') and its mirror ('Code1') for the (a) co-polarized and (b) cross-polarized reflection phases.

FIGURE 8. The element distributions of (a) chessboard metasurface and (b) diffusive metasurface and (c) their simulated RCS reduction.

RCSR band and from 40.61 to 56.4 GHz for the upper RCSR band. In addition, the RCSR of approximately 0 dB has been realized from 26.2 to 38.8 GHz, in which the metasurface functions as a high reflectivity band.

Fig. 9 displays the scattering patterns of the proposed two metasurfaces in \((\theta, \varphi)-plane\) at three representative frequencies, viz., 19.5 GHz (lower RCSR band), 32 GHz (reflection band), and 50 GHz (higher RCSR band), respectively. It is seen that the reflected fields of the chessboard metasurface are reflected back as a single main lobe at 32 GHz in the reflection band, while those are divided into four symmetrical patterns at four planes \(\varphi = 45^\circ, 135^\circ, 225^\circ, 315^\circ\) at elevations of two \(\theta = 2^\circ\) and \(10^\circ\) for the lower and upper RCSR bands, respectively, as shown in Figs. 9(a)-9(c).

Furthermore, the scattering field is comprised of low-level lobes in a multiplicity of directions and the RCSR levels are higher than 10 dB for both 19.5 and 50 GHz, while an extremely strong reflection in the \(+z\)-direction is dominated at 32 GHz in the reflection band, as shown in Figs. 9(d)-9(f). This is because the diffusive metasurface is designed to redirect the incident EM energy into other directions, which achieves low energy levels in other directions based on the energy conservation principle. The peak values of the scattering fields are decreased by 9.31 and 11.7 dB than those of the chessboard metasurface for the lower and upper RCSR bands, respectively. Besides, the RCS levels in two diffusion bands will be lower with increasing the PCR of the proposed
FIGURE 9. Chessboard metasurface simulation scattering patterns in ($\theta$, $\phi$)-plane at (a) 19.5, (b) 32 and (c) 50 GHz; diffusive metasurface simulation scattering patterns in ($\theta$, $\phi$)-plane at (d) 19.5, (e) 32, and (f) 50 GHz.

FIGURE 10. Measurement setup for the designed chessboard metasurface and diffusive metasurface at (a) lower testing band (15-40 GHz) and (b) higher testing band (40-60 GHz).

polarizer, which can be inferred from (1) and (4). In addition, although some fluctuations exist in the PCR, a 10-dB RCSR can be still realized as the PCR is larger than 90% [20].

IV. FABRICATION AND MEASUREMENT

To validate our design, two metasurfaces with the same size of 277.2 mm $\times$ 277.2 mm $\times$ 0.8 mm were fabricated using PCB process and measured in an anechoic chamber, as shown in Fig. 10. Two measurement setups, as shown in Figs. 10(a) and (b), respectively, are utilized to cover the broad band ranging from 15 to 60 GHz. In Fig. 10(a), the measurement setup consists of two pairs of horn antennas, operating from 12 to 18 GHz and 18 to 40 GHz, respectively.

Two horn antennas are positioned on the same side of the designed surface in the far-field region and connected to a vector network analyzer [28]. Fig. 10(b) shows that two horn antennas operating from 39.6 to 60 GHz are utilized in the measurement setup to measure the higher RCSR band. Because of the limitation of our test system, measured results under $5^\circ$ of the incident angle are utilized to substitute those under the normal incident wave and a gating window in the time-domain is used to eliminate the mutual coupling between two horn antennas [29].

FIGURE 11. Simulated and measured results for RCS reduction of the proposed chessboard metasurface and diffusive metasurface.

Fig. 11 compares the measured results of the RCSR performance of the chessboard and diffusive metasurfaces based on the use of an equal-sized PEC ground with simulated ones, and the agreement is found to be good. Measured results indicate that a diffusion-reflection-diffusion characteristic of the designed metasurface. It is seen that measured RCSR performances are better than 10 dB at two sidebands ranging...
A diffusion-reflection-diffusion metasurface-based reflector combining the specular reflection band and diffusion scattering bands based on a dual-band polarizer has been proposed in this article. The operating principle and the physical mechanism of the proposed polarizer have been analyzed in detail. The proposed polarizer and its mirror can achieve in-phase reflection at the reflection band and out-of-phase response at the two PR sidebands for a normal incidence. A diffusive metasurface, whose structural thickness is relatively small, is easy to fabricate; hence, it has the potential to be used as the main-reflector of reflector antenna systems.

V. CONCLUSION

A diffusion-reflection-diffusion metasurface-based reflector combining the specular reflection band and diffusion scattering bands based on a dual-band polarizer has been proposed in this article. The operating principle and the physical mechanism of the proposed polarizer have been analyzed in detail. The proposed polarizer and its mirror can achieve in-phase response at the reflection band and out-of-phase response at the two PR sidebands for a normal incidence. A diffusive metasurface based on a dual-band polarizer and phase cancellation theory is then designed, fabricated. The experimental results are consistent with simulated ones, which demonstrate that the designed diffusive metasurface can scatter the incident wave into other directions with low RCS levels while behaving as a high-efficiency reflector in the selected reflection band.

REFERENCES

[1] D. Xie, X. Liu, H. Guo, X. Yang, C. Liu, and L. Zhu, “A wideband absorber with a multiresonant gridded-square FSS for antenna RCS reduction,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 629–632, 2017.
[2] E. F. Knott, J. F. Shaeffer, and M. T. Tuley, Radar Cross Section: Its Prediction Measurement and Reduction, 2nd ed. Norwood, MA, USA: Artech House, 1993.
[3] Y. Shang, Z. Shen, and S. Xiao, “On the design of single-layer circuit analog absorber using Double-Square-Loop array,” IEEE Trans. Antennas Propag., vol. 61, no. 12, pp. 6022–6029, Dec. 2013.
[4] X. Q. Lin, P. Mei, P. C. Zhang, Z. Z. D. Chen, and Y. Fan, “Development of a resistor-loaded ultrawideband absorber with antenna reciprocity,” IEEE Trans. Antennas Propag., vol. 64, no. 11, pp. 4910–4913, Nov. 2016.
[5] Q. Chen, D. Sang, M. Guo, and Y. Fu, “Miniaturized frequency-selective rasorber with a wide transmission band using circular spiral resonator,” IEEE Trans. Antennas Propag., vol. 67, no. 2, pp. 1045–1052, Feb. 2019.
[6] L. Wu, S. Zhong, J. Huang, and T. Liu, “Broadband frequency-selective rasorber with varactor-tunable interabsorption band transmission window,” IEEE Trans. Antennas Propag., vol. 67, no. 9, pp. 6039–6050, Sep. 2019.
[7] T. Guo, M. Guo, X. Jia, Q. Chen, and Y. Fu, “An absorptive frequency selective reflector with wide reflection band,” IEEE Access, vol. 8, pp. 124217–124222, Feb. 2020.
[8] B. Zhang, C. Jin, and Z. Shen, “Low-profile broadband absorber based on multimode resistor-embedded metallic strips,” IEEE Trans. Microw. Theory Techn., vol. 68, no. 3, pp. 835–843, Mar. 2020.
[9] P. Mei, S. Zhang, Y. Cai, X. Q. Lin, and G. F. Pedersen, “A reflectarray antenna designed with gain filtering and low RCS properties,” IEEE Trans. Antennas Propag., vol. 67, no. 8, pp. 5362–5371, Aug. 2019.
[10] H. Huang and Z. Shen, “Low-RCS reflectarray with phase controllable absorptive frequency-selective reflector,” IEEE Trans. Antennas Propag., vol. 67, no. 1, pp. 190–198, Jan. 2019.
[11] P. Mei, X. Q. Lin, J. W. Yu, A. Boukarkar, P. C. Zhang, and Z. Q. Yang, “Development of a low radar cross section antenna with band-notched absorber,” IEEE Trans. Antennas Propag., vol. 66, no. 2, pp. 582–589, Feb. 2018.
[12] H. Huang, Z. Shen, and A. A. Omar, “3-D absorptive frequency selective reflector for antenna radar cross section reduction,” IEEE Trans. Antennas Propag., vol. 65, no. 11, pp. 5908–5917, Nov. 2017.
[13] Y. Han, L. Zhu, Y. Chang, and B. Li, “Dual-polarized bandpass and band-notched frequency-selective absorbers under multimode resonance,” IEEE Trans. Antennas Propag., vol. 66, no. 12, pp. 7449–7454, Dec. 2018.
[14] A. A. Omar, Z. Shen, and H. Huang, “Absorptive frequency-selective reflection and transmission structures,” IEEE Trans. Antennas Propag., vol. 65, no. 11, pp. 6173–6187, Nov. 2017.
[15] Z.-H. Deng, F.-W. Wang, Y.-H. Ren, K. Li, and B.-J. Gao, “A novel wideband low-RCS reflector by hexagon polarization rotation surfaces,” IEEE Access, vol. 7, pp. 131527–131533, 2019.
[16] Z. Liu, S. Liu, J. Bornemann, X. Zhao, X. Kong, Z. Huang, B. Bian, and D. Wang, “A low-RCS, high-GBP Faby–Perot antenna with embedded chessboard polarization conversion metasurface,” IEEE Access, vol. 8, pp. 80183–80194, 2020.
[17] K. Liu, W. G. Guo, W. He, and G. Liu, “A novel broadband bi-functional metasurface for vortex generation and simultaneous RCS reduction,” IEEE Access, vol. 6, pp. 63999–64007, 2018.
[18] J. Su, Y. Cui, Z. Li, Y. Yang, Y. Che, and H. Yin, “Metasurface base on uneven layered fractal elements for ultra-wideband RCS reduction,” AIP Adv., vol. 8, no. 3, Mar. 2018, Art. no. 035027.
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