Design of Dual-Polarized Frequency Selective Rasorber With Two Independent Transmission Windows Using Multi-Resonators

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ABSTRACT In this paper, a dual-polarized frequency selective rasorber (FSR) with two independent transmission windows and three absorption bands is designed and characterized. The proposed FSR is composed of the resistive sheet and the bandpass frequency selective surface (FSS), which are separated by the air spacer. At the top resistive sheet, two concentric modified square loops with different lengths are inserted into the square loop with four lumped-resistor-loaded legs, which provides two independent transmission windows. The bottom bandpass FSS, consisting of the combination of the square slot and the four-leg arrow shaped slot, is adopted to realize the same transmission bands as the upper resistive sheet. Performance of the proposed FSR is investigated via its equivalent circuit model and full-wave simulations. The simulated results exhibit dual-band frequency response, which has two independent transmission windows within three absorption bands. The two pass-bands operate at 8.5GHz and 13GHz with insertion loss of 0.31dB and 0.48dB, respectively. And the three absorption bands are in the range of 4.1GHz-7.5GHz, 9.1GHz-12.3GHz, and 14GHz-19.7GHz, respectively. Also, the band with reflection coefficient lower than -10dB covers from 4.2 GHz to 19.6GHz and the fractional bandwidth is up to 129.4%. Furthermore, prototype of the FSR is fabricated and measured. Good agreements between the measured and the simulated results can be observed.

INDEX TERMS Frequency selective rasorber, dual-band, dual-polarized.

I. INTRODUCTION

Frequency selective surface (FSS) is a periodic structure composed of identical constituting elements, which exhibits frequency filtering response [1], [2]. Due to its frequency filtering property, FSS has been widely applied in the field of microwave to construct hybrid radome, antenna reflector, EM shelter, and so on. When the FSS is applied to construct hybrid radome, the EM waves within the pass-band of FSS can pass through the radome with low loss and the out-of-band EM waves will be reflected [3]–[5]. Considering the out-of-band EM waves are only reflected rather than absorbed, the reflected EM waves can also be detected by the bistatic radar system. Hence, the FSS loaded hybrid radome is only suitable for monostatic RCS reduction.

For the purpose of RCS reduction, various techniques including low-observation shape design [6], wave absorption with radar absorbing material [7], and phase cancellation with metasurface [8]–[10], have been proposed. For example, a concave/convex-chessboard random parabolic-phased metasurface is designed for broadband RCS reduction in [9]. However, in order to reduce the RCS of radome, especially the bistatic RCS, it is desired that the radome exhibits good transparency of the in-band EM waves and high absorption of the out-of-band EM waves. Hence, these aforementioned techniques can not be directly applied for radomes.

Motivated by this requirement, frequency selective rasorber (FSR) has been investigated and proposed by researchers. Actually, FSR is a two-layer structure, which is composed of the top lossy resistive sheet and the bottom bandpass FSS [11]–[13]. By cascading the two periodic arrays, FSR exhibits good in-band transparency and out-of-band...
absorption characteristics. Hence, FSR has been applied as spatial filter to reduce the radar cross section (RCS) of antennas and radomes.

Generally, FSR can be sorted into three types with respect to the relative locations of the pass-band and the absorption band: 1) the pass-band below the absorption band [14]–[16], 2) the pass-band above the absorption band [13], [17], [18], and 3) the pass-band among the absorption band [19]–[25]. However, most of these FSRs have only one transmission band, which limits their applications in the multiband communication system.

To meet the requirements of interference reduction in multiband communication system, dual-band or multiband FSRs have been investigated in [26]–[30]. As discussed in [26], the two transmission bands can be achieved by forming two impedance poles of the resistive sheet. Then, dual-band FSR with low insertion loss is designed in [27]. A dual-band FSR based on folded loops is proposed in [28]. FSR with three transmission bands and three absorption bands is designed and proposed in [29]. When the dual-band FSR is applied in the multiband communication system, the transmission windows of the FSR should be consistent with the enclosed antenna system. Hence, it is desired that resonant frequencies of the two transmission windows can be independently adjusted by changing corresponding structural parameters, respectively. Related discussions on the independent controllability of the pass-bands are not provided in these aforementioned FSRs. Motivated by this requirement, a dual-polarized FSR with two independently controlled pass-bands is investigated and proposed in [30]. However, the absorption band above the transmission band at higher frequency band is not achieved in [30].

In this paper, a dual-polarized FSR with two independent transmission windows within three absorption bands is proposed. By inserting two concentric modified square loops into the square loop with four lumped-resistor-loaded legs, two impedance poles are formed by the multi-resonators in the resistive sheet. The proposed FSR can realize two independent pass-bands at 8.5GHz and 13GHz with insertion loss of 0.31dB and 0.48dB, respectively; three absorption bands in the range of 4.1GHz-7.5GHz, 9.1GHz-12.3GHz, and 14GHz-19.7GHz, respectively. Also, fractional bandwidth of the low reflection band (|S11| < -10dB) is up to 129.4% (4.2GHz-19.6GHz), which is larger than these aforementioned researches.

II. DESIGN AND ANALYSIS OF THE FSR
A. STRUCTURE AND EQUIVALENT CIRCUIT ANALYSIS

Fig.1 shows the geometrical structure of the FSR, which is composed of the upper resistive sheet, the bottom band-pass FSS, and the air spacer. Both the resistive sheet and the FSS are supported by Rogers 4350B substrate, which has a relative permittivity of 3.45 and a loss tangent of 0.004. The thicknesses of the two substrates and the air spacer are \(h_1 = 0.25\text{mm}, h_2 = 0.5\text{mm},\) and \(H = 5\text{mm},\) respectively. Unit cell of the upper resistive sheet is the combination of three concentric resonators. All the three resonators are the modified square loops, in which resonator 1 and resonator 2 are the square loops with four legs on each side, and resonator 3 is the convoluted square loop. And four lumped resistors of 130Ω are loaded on the legs of resonator 1 for the purpose of EM wave absorption. As for the bottom band-pass FSS, it is composed of the combination of the rotated square loop slot and the four-leg arrow shaped slot.

Actually, performance of the FSR can be predicted via its equivalent circuit model (ECM) shown in Fig.2. As for the top resistive sheet, resonator 2 and resonator 3 can be equaled to two series LC resonators \((L_2 - C_2)\) and \((L_3 - C_3)\). For resonator 1, its lumped-resistor-loaded legs can be modeled by the series RLC resonator \((R - L_1 - C_1)\) and its square loop part is modeled by an inductor \((L_S)\). Noting that \(L_S\) is parallel with series LC resonators \(L_2 - C_2\) and \(L_3 - C_3\), two pass-bands will be formed by the \(Z_P\) part. Assuming that the two series LC resonators are independent from each other, resonate frequencies of the two pass-bands can be adjusted by changing values of \(L_2 - C_2\) and \(L_3 - C_3\) individually. Transmission coefficient \(|S_{21}|\) of the resistive sheet can be calculated by

\[
|S_{21}| = \frac{2}{|Z_0 + Z_R/Z_P|} \quad (1)
\]

where \(Z_R = Z_p + Z_g\) is the impedance of the resistive sheet and \(Z_0 = 377\Omega\) is the wave impedance of free space. At resonant frequencies of the two pass-bands, \(Z_P\) is infinite, which ensures good transparency (\(|S_{21}| = 1\)).

As for the bottom FSS, the combination of slots provides two independent resonant paths, which form two independent pass-bands. Hence, it can be modeled by the series of two parallel LC resonators \((L_{p1} - C_{p1})\) and \((L_{p2} - C_{p2})\). When the resonant frequencies of the two pass-bands are the same with those of the top resistive sheet, the FSR exhibits good transparency for the in-band EM waves, which ensures the
communication requirements of the enclosed antenna system. Meanwhile, for the out-of-band EM waves, the bottom band-pass FSS behaves like a metal plate. Then, the FSR can be regarded as a circuit analog absorber for the out-of-band EM waves. Hence, high absorption for the out-of-band EM waves can be achieved by properly designing the top resistive sheet (changing the imaginary and real part of $Z_R$), which meets the requirement of interference reduction of multiband communication system.

### B. SIMULATION RESULTS AND DISCUSSIONS

Based on the equivalent circuit analysis, the proposed FSR can provide two independent pass-bands with out-of-band absorption characteristic. For verification, S-parameters under normal incidence of the FSR and its constituting parts are simulated jointly and separately.

As shown in Fig. 3(a) and Fig. 3(b), both the resistive sheet and the band-pass FSS provide two pass-bands operating at 8.5GHz and 13GHz, which are constant with the ECM analysis. By cascading the two layers, the FSR exhibits two-band transmission response. As observed in Fig. 3(c), the two pass-bands occur at 8.5GHz and 13GHz with insertion losses of 0.31dB and 0.48dB, respectively. In addition, the low reflection band ($|S_{11}| < -10$dB) ranges from 4.2GHz to 19.6GHz, whose fractional bandwidth is up to 129.4%. Meanwhile, it can be seen in Fig. 3(d) that the absorption bands with absorption rates greater than 80% range from 4.1GHz to 7.5GHz, 9.1GHz to 12.3GHz, and 14GHz to 19.7GHz. Here, absorption rate is calculated by $1 - |S_{21}|^2 - |S_{11}|^2$.

Due to the symmetrical design of the unit cell, the two-band transmission response keeps stable with respect to TE and TM polarizations.

The electric field distributions of the resistive sheet and the band-pass FSS at resonant frequencies are investigated for further verification. As shown in Fig. 4(a), at the resonant frequency of the first pass-band, the electric field mainly distributes along legs of resonator 2 in the resistive sheet and four-leg arrow shaped slot in the band-pass FSS, while the electric field values are extremely weak outside the aforementioned areas. In contrast, as observed in Fig. 4(b), the electric field distributions at the second resonant frequency concentrate mainly at resonator 3 in the resistive sheet and the rotated square loop slot in the pass-band FSS. According to the electric field distributions at resonant frequencies, the two pass-bands of the FSR are formed by different areas and separated from each other. Hence, the independent resonant areas ensure the independent controllability of the two transmission windows of the FSR.

Full-wave simulations are carried out to investigate the independent controllability of the pass-bands. Based on the discussions above, resonant frequency of the first pass-band can be adjusted by changing parameters $g_4$ and $d_4$ of the FSS and resistive sheet. Meanwhile, the second resonant frequency can be changed by parameters $d_7$ and $d_{10}$.

Considering the requirement on thickness of the FSR in practical applications, structural parameter $H$ keeps unchanged ($H = 5$mm) during the simulations. Meanwhile,
on premise of the good in-band transparency and high out-of-band absorption characteristics, the maximum tuning range of structural parameters $g_4$, $d_4$, $d_7$, and $d_{10}$ is 0.1mm to 0.6mm, 1.8mm to 4.4mm, 3.2mm to 3.6mm, and 3.8mm to 4.8mm, respectively. In order to investigate the controllability of the pass-band, six cases are simulated. As observed from Fig. 5(a) and Fig. 5(b), under these aforementioned constraints, resonant frequencies of the two pass-bands can be tuned from 7 GHz to 9.7GHz and 11.6GHz to 14.6GHz by changing corresponding structural parameters.

Moreover, the $|S_{11}|$ becomes larger than $-10$dB at some frequency points when adjusting the structural parameters. This worsens the low reflection characteristic of the proposed FSR. Actually, the rise of $|S_{11}|$ can be compensated by adjusting structural parameter $H$. As indicated by Fig.5(c) and Fig.5(d), if $H$ is set to be 4.45mm, 5mm, 5.13mm, 4.05mm, 5mm, and 5.15mm for the six cases orderly, the wideband low reflection ($|S_{11}| < -10$dB) characteristic can be maintained well. In addition, for practical applications without thickness requirements, the tuning range of the two pass-bands of the FSR can be further extended by adjusting the structural parameter $H$.

Simulated results in Fig.5 prove that the two pass-bands can be independently controlled. The controllability of the two pass-bands makes it possible to optimize the FSR easily according to the practical application requirements.

In order to investigate the angular stability of the FSR, both S-parameters and absorption rates at oblique incidence are simulated. As shown in Fig.6(a) and Fig. 6(b), the two-band transmission response maintains well at oblique incidence for both TE and TM polarizations. For TE polarization, when the incident angle increases to 30°, insertion loss of the second pass-band increases to 0.72dB, which is still acceptable in practical applications. For TM polarization, the insertion loss at oblique incidence is almost unchanged. Also, at 30° incidence, the $|S_{11}|$ increases above $-10$dB at some frequencies within the low reflection band under both TE and TM polarizations. This worsens the absorbing property out of the pass-bands. However, as observed from Fig.6(c) and Fig. 6(d), the absorption rate of the three absorption bands still keeps above 80%. Moreover, bandwidth of the third absorption band narrows from 5.7GHz to 4.5GHz at 30° incidence for TE polarization. In spite of the changes in bandwidth of absorption band, the FSR exhibits good angular stability when the incident angle reaches to 30°.

III. EXPERIMENTAL VERIFICATION

For further verification, prototype of the proposed FSR has been fabricated and measured. As shown in Fig.7, the FSR prototype is composed of the resistive sheet and the bandpass FSS, which are separated by the nylon spacers. Both the resistive sheet and the bandpass FSS are fabricated on the Rogers 4350B substrate with the standard printed circuit board (PCB) technique and are composed of $27 \times 27$ unit cells. The overall size of the prototype is about 300mm\times300mm. As for the resistive sheet, lumped resistors with 0402 package and a resistance of 130Ω (ERA2AEB131X from Panasonic) are loaded on the four legs of Resonator 1.

![Figure 5. Controllability of the pass-bands. (a) and (b) With structural parameter $H$ fixed. (c) and (d) With structural parameter $H$ changed.](image-url)
FIGURE 6. The S-parameters and absorption rates at oblique incidence of the FSR. (a) and (c) S-parameters and absorption rates for TE polarization. (b) and (d) S-parameters and absorption rates for TM polarization.

S-parameters of the prototype were measured with the free-space measurement system. As shown in Fig.8, the free-space measurement system is composed of the transmitting (Tx) antenna, the receiving (Rx) antenna, the absorbing screen with a rectangular opening in the center, and the vector network analyzer (VNA, N5242A).

For the transmission coefficient measurement, the Tx and Rx antennas are placed on each side of the absorbing screen (1m × 1m in size). And the FSR prototype is fixed on the central opening of the absorbing screen. The rectangular opening has the same size with the FSR prototype. In order to determine the transmission coefficient, $S_{21}$ parameter without the FSR prototype $S_{21,\text{b}}$ is firstly measured for calibration. Then, $S_{21}$ parameter $S_{21,\text{p}}$ with the FSR prototype is measured. With the two sets of $S_{21}$ parameter, the transmission coefficient $\tau$ can be calculated by

$$\tau = 20 \log_{10} \left| \frac{S_{21,\text{p}}}{S_{21,\text{b}}} \right|.$$ 

For the reflection coefficient, the Tx and Rx antennas are placed on the same side of the absorbing screen. Different from the transmission coefficient measurement, a metal plate with the same size of the FSR prototype is adopted and placed at the opening of the absorbing screen. And the S21 parameter of the metal plate $S_{21,\text{m}}$ is firstly measured for calibration. Then, we replace the metal plate with the FSR prototype and its S21 parameter $S_{21,\text{p}}$ is measured again. The reflection coefficient of the FSR prototype $\Gamma$ can be determined by

$$\Gamma = 20 \log_{10} \left| \frac{S_{21,\text{p}}}{S_{21,\text{m}}} \right|.$$ 

Furthermore, time-domain gating technique has been adopted in the measurement of transmission coefficient and reflection coefficient to eliminate multipath interference. Details on the measurement of the transmission and the reflection coefficients can be found in [28].

Comparisons between the simulated and the measured results at normal incidence are shown in Fig.9. Due to the
TABLE 1. Comparisons with similar FSRs.

| Ref    | A^1^T^2^ Location | Transmission Band/IL^3^ | FBW^4^ (%) | Thickness @λ^5^ | Number of resistors | Angular Stability | Polarization |
|--------|-------------------|-------------------------|------------|-----------------|---------------------|------------------|--------------|
| [26]   | A-T-A-T           | 7.2GHz/2.3dB            | Mea. 95.94 | 0.205           | 2                   | 20°              | Single       |
|        | 13.05GHz/1.69dB   |                         |            |                 |                     |                  |              |
| [27]   | A-T-A-T-A         | 9.1GHz/0.43dB           | Mea. N.A.  | 0.184           | 4                   | N.A.             | Dual         |
|        | 11.21GHz/0.35dB   |                         |            |                 |                     |                  |              |
| [28]   | A-T-A-T           | 8GHz/0.39dB             | Sim. 87.64 | 0.187           | 4                   | 30°              | Dual         |
|        | 11.9GHz/0.64dB    |                         |            |                 |                     |                  |              |
| [30]   | A-T-A-T           | 6.1GHz/0.06dB           | Sim. 105.7 | 0.183           | 3                   | 30°              | Dual         |
|        | 10.1GHz/0.2dB     |                         |            |                 |                     |                  |              |
|        | 8.5GHz/0.31dB     | Sim. 129.4              | 0.163      | 4               | 30°                |                  | Dual         |
|        | 13GHz/0.48dB      |                         |            |                 |                     |                  |              |
|        | 8.34GHz/0.54dB    |                         |            |                 |                     |                  |              |
|        | 12.75GHz/0.87dB   |                         |            |                 |                     |                  |              |

^1^ Absorptive Band, ^2^ Transmission Band, ^3^ IL: Insertion Loss, ^4^ FBW: Fractional Bandwidth of -10dB reflection, ^5^ λ: Wavelength of the first pass-band in free space.

As observed in Fig. 9(a), the measured results exhibit dual-band frequency response, in which, the two transmission windows operate at 8.34GHz and 12.75GHz with the insertion loss of 0.54dB and 0.87dB, respectively. In the measurement frequency range, the low reflection band (|S11| < -10dB) ranges from 4GHz to 19.5GHz. The measured fractional bandwidth is about 131.9%, which is larger than the simulated result. Also, from Fig. 9(b), the measured absorption bands with absorption rate above 80% are in the range of 4GHz-7.3GHz, 9.3GHz-112.4GHz, and 13.9GHz-19.7GHz, respectively. The measured results are consistent with the simulated ones very well in the measured frequency range. Compared with the simulated results, the shift in resonant frequency and the increase in insertion loss of the pass-bands are mainly caused by the fabrication errors and the parasitic effect of lumped resistors.

IV. CONCLUSION

A dual-polarization FSR with two independent controllable transmission windows within three absorption bands has been proposed and investigated in this paper. Two independent resonant paths are obtained with the design of three concentric resonators in the resistive sheet, which ensures the independent controllability of the two transmission windows. Performance of the FSR has been investigated by full-wave simulations and experiment verifications. Both the simulated and measured results demonstrate that the FSR exhibits dual-band frequency response and has wider low reflection band than similar researches. Also, performance of the FSR remains stable at 30° incidence for both TE and TM polarizations. Hence, the proposed FSR can be applied in the multiband communication system for the purpose of interference reduction.
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