Design of Switchable Frequency-Selective Rasorber With A-R-A-T or A-T-A-R Operating Modes

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Abstract—This letter presents a switchable frequency-selective rasorber (SFSR) with two operating modes. Switching from transmission to reflection can be achieved by appropriately adding feeders and PIN diodes based on cascaded two-dimensional lossy and lossless frequency-selective surface screens. The proposed SFSR can realize out-of-band absorption. Analysis of the equivalent circuit model can be useful for achieving a switchable rasorber. As the state of the PIN diodes changes, the working state of the SFSR can be switched from low-frequency reflection and high-frequency transmission to low-frequency transmission and high-frequency reflection, respectively. In the final-revision simulation of the working band of the SFSR, in the ON state, reflection and transmission peaks of −0.55 dB at 4.06 GHz and −0.52 dB at 5.97 GHz, respectively, are achieved; in the OFF state, the transmission and reflection peaks of −0.31 dB at 4.04 GHz and −0.26 dB at 6.01 GHz, respectively, are obtained. A prototype sample is developed and validated. The results are in good agreement with those of the final-revision simulations. The proposed design can be used in intelligent antijamming communication.

Index Terms—Frequency-selective rasorbers (FSRs), reflection, switchable, transmission.

I. INTRODUCTION

FREQUENCY-SELECTIVE rasorbers (FSRs) can be designed as radomes with low insertion within the absorption band, which can reduce the radar cross-section (RCS) in a radar antenna system. According to the location of the transmission response in the absorption band, FSRs can be classified into three categories: transmission below the absorption band (T-A) [1], [2], transmission between two absorption bands (A-T-A) [3], [4], [5], [6], [7], [8], [9], and transmission above the absorption band (A-T) [10], [11].

With the development of dual-band antenna systems [12], single-passband FSRs are unsuitable for multiband radar antenna systems. In recent years, dual-band FSRs have attracted considerable attention [13], [14], [15], [16], [17]. It is well known that lumped components, including inductance and capacitance (LC), can be utilized to realize series resonance or parallel resonance [13]. In addition, the parallel resonances of the metal structure are used to generate two transmission bands [14], [15], [16]. In [17], these two methods have been combined to generate dual transmission bands via the capacitance and metal gap.

Although the dual-band FSRs described above can be designed as passive radomes, they are not suitable for multifunctional systems. Generally, PIN diodes are chosen as switches in the FSR [18], [19], [20]. The design of a switchable frequency-selective rasorber (SFSR) with A-R-A-T or A-T-A-R operating mode was proposed in this letter to realize a reconfigurable wave-transmission window and strong reflection band in the wide −10 dB reflection band of the SFSR. The novelty of this work can be summarized as follows: first, switching diodes are applied to control the transmission window and reflection band of the rasorber. In this case, the proposed switchable structure can be operated in two operating modes based on the engineering requirements. Second, unlike the previously designed typically lossy layers in switchable FSRs, the proposed design has two wave-transmitting windows corresponding to different operating principles. Finally, fewer lumped elements are required in one unit, which simplifies the complexity of the SFSR. The manufactured prototype was tested and validated through simulations. The designed SFSR satisfies the engineering requirements of an intelligent antijamming system [21], [22]. A reconfigurable wave-transmission window and a strong reflection band in the wide −10 dB reflection band of the SFSR are achieved. The proposed design can realize intelligent antijamming communication and shield high-power electromagnetic interference attacks.

II. DESIGN OF THE SFSR

A schematic of the transmission/reflection responses of the SFSR is shown in Fig. 1. When the PIN diodes are in the OFF state, low-frequency transmission at approximately 4 GHz and high-frequency reflection around 5.6 GHz were acquired in the A-T-A-R mode. In contrast, low-frequency reflection and high-frequency transmission were acquired in the A-R-A-T mode when the PIN diodes are in the ON state.

A dual-band lossy layer was designed based on the resonance principle [14], [15], [16]. The SFSR is composed of a dual-band lossy layer and a switchable FSS separated by an air gap with a thickness of \( h = 15 \text{ mm} \), as shown in Fig. 2. Copper (0.035 mm) of the top and bottom layers was printed on the F4BM substrate ( \( \varepsilon_r = 2.2, \tan \delta = 0.001, \text{thickness} = 0.5 \text{ mm} \)). The lossy layer was constructed using four resistors...
(R = 300 Ω) to realize the absorption bands, as shown in Fig. 2(b). The diodes were welded to the metal crevices of the FSS. In Fig. 2(c), the diodes SMP1320-079LF (ideal simplified equivalent parameters: \( L_{\text{chip}} = 0.7 \) nH, \( C_{\text{off}} = 0.23 \) pF, \( R_s = 0.75 \) Ω [23]) produced by Skyworks were selected as the switch. The four black circles shown in Fig. 2(c) and (d) are vias that connect the bottom feedline to the supply voltage of the diodes. By supplying different voltages to the positive and negative poles of the diodes, the resonant frequency of the switchable FSS is transformed from one band to another. The dimensions are as follows: \( P = 32 \) mm, \( w = 1 \) mm, \( w_1 = 0.33 \) mm, \( w_2 = 0.5 \) mm, \( a = 8 \) mm, \( a_1 = 3.83 \) mm, \( a_2 = 5.83 \) mm, \( a_3 = 4.83 \) mm, \( a_4 = 3 \) mm, \( l_1 = 4 \) mm, \( l_2 = 6.3 \) mm, \( l_3 = 5.4 \) mm, \( l_4 = 4.3 \) mm, \( l_5 = 7 \) mm, \( l_6 = 4 \) mm, \( l_7 = 0.7 \) mm, \( x = 10.5 \) mm, \( b = 5.8 \) mm, \( dv = 0.4 \) mm, \( le = 0.8 \) mm, \( gap = 0.5 \) mm. The simulations of a linearly polarized normal incidence propagating toward the -z direction are presented in Fig. 3. Indeed, owing to the structural symmetry, the simulated results for the TE and TM polarizations are nearly identical in the ON and OFF states. Here, only the TE polarization results are provided and discussed. The simulations are illustrated in Fig. 3(a) when a forward bias is applied to the diodes. The reflection and transmission peaks found in the ON state are \(-0.73 \) dB at 4.03 GHz and \(-0.41 \) dB at 5.63 GHz. With a \(-10 \) dB reduction, the absorption bands are 2.79 to 3.46 GHz and 4.47 to 5.01 GHz. The simulations are shown in Fig. 3(b) when a reverse bias is applied to the diodes. The transmission and reflection bands have peaks of \(-0.33 \) dB at 4.03 GHz and \(-0.39 \) dB at 5.64 GHz, respectively. The absorption bands range from 2.58 to 3.52 GHz and 4.56 to 5.19 GHz with \(-10 \) dB reduction.

The dimensions \( l_4 \) of the lossy layer were investigated, which resulted in a shift in the upper transmission frequency, as illustrated in Fig. 4. As the value of \( l_4 \) increased, the upper transmission shift to a lower frequency. Fig. 5 depicts the simulations under different oblique incidence angles. In TE polarization, (a) the TM polarization. In ON state: (c) TE polarization and (d) TM polarization.
both states of the diodes, the SFSR remains almost constant under the premise that the incident angle is less than 30°. In TM polarization, the SFSR are stable when the incident angle is less than 10° in OFF state and 5° in ON state.

### III. Design and Analysis of Equivalent Circuit

An equivalent circuit model (ECM) was established to explain the design better. LC parallel resonances and LC series resonance with resistance are extensively utilized to realize a lossy layer of the SFSR. In ECM, parallel and series resonances with resistance produce transmission bands and absorption, respectively. Resultantly, two parallel resonances were used to provide dual transmission bands. Fig. 6 depicts the final ECM concept. In the ON state, the simplified diode models are equivalent to $L_{\text{chip}}$ and $R_s$ in series, whereas in the OFF state is equivalent to $L_{\text{chip}}$ and $C_{\text{off}}$ in series.

The parasitic elements of the purchased diode are unclear. Therefore, the values of $L_{\text{chip}}$, $R_s$, and $C_{\text{off}}$ that cause changes in the results are investigated in the ECM, as shown in Fig. 7. Within a certain range, when the diode in the OFF state and $L_{\text{chip}}$ are fixed as a constant, variable $C_{\text{off}}$ is the most crucial element affecting the low transmission band, whereas variable $L_{\text{chip}}$ has minimal effect when $C_{\text{off}}$ is constant, as depicted in Fig. 7(a) and (b). Similarly, in the ON state, the variable $L_{\text{chip}}$ modifies the upper transmission band, and the variable $R_s$ primarily causes high-frequency insertion loss, as illustrated in Fig. 7(c) and (d).

### IV. Fabrication and Experimental Verification

The performance of the SFSR was validated by manufacturing a prototype with dimensions of 340 × 340 mm, including 10 × 10 unit cells, as shown in Fig. 8. The prototypes of the lossy and switchable layers are depicted in Fig. 8(a) and (b), respectively. The gap between the lossy and switchable layers was secured using nine plastic screws. The lumped resistors were soldered between the metal gaps of the lossy layer. The SMP1320-079LF diodes were soldered onto the switchable FSS. A dc source was employed to control the states of the PIN diodes to operate them properly. The prototype was measured using two pairs of lens antennas (2–4 and 4–8 GHz), as shown in Fig. 8(c). The configuration and measurement of the lens antenna system are described in detail in [24], [25]. From the analysis of the ECM in Section III, frequency shift caused by diode will damage the final results. Thus, the switchable FSS is primarily manufactured and measured to ensure transmission response in various diode states. Fig. 9 shows the simulations and measurements. Unpredictable parasitic parameters cause discrepancies between simulations and
TABLE I
COMPARISON WITH OTHER STRUCTURES

| Ref | S/T | Number of the switchable band | Operating bandwidth | Frequency Response | Max. RT(dB) | Polarization insensitive | Thickness (d/λ) | Number of lumped elements | Oblique incident angles (°) |
|-----|-----|-------------------------------|---------------------|-------------------|-------------|-------------------------|----------------|---------------------------|---------------------------|
| [13] | No | 0 | 123% | A-T-A-T-A | -1.2/-0.82 | Yes | 0.077λ | 12 | 40 |
| [14] | No | 0 | 122.2% | A-T-A-T-A | -0.15/-0.31 | Yes | 0.091λ | 4 | N.A. |
| [15] | No | 0 | 117.8% | A-T-A-T-A | -0.25/-0.1 | Yes | 0.076λ | 4 | 40 |
| [16] | No | 0 | 87.6% | A-T-A-T | -0.39/-0.64 | Yes | 0.117λ | 4 | 30 |
| [17] | No | 0 | 100% | A-T-A-T | -0.33/-0.92 | No | 0.099λ | 3 | 20 |
| [18] | Yes | 1 | ON:120% | A-T/R | ON: -0.34 | OFF: N.A. | Yes | 0.158λ | 8 | 40 |
| [19] | Yes | 1 | ON:92.6% | A-T/A-A | ON: N.A. | OFF: -0.45 | Yes | 0.081λ | 12 | 45 |
| [20] | Yes | 2 | ON:62.2% | A-T/R-A | ON: N.A. | OFF: -0.62 | Yes | 0.168λ | 16 | 30 |
| This letter | Yes | 2 | ON:70.6% | ON: A-R-A-T | -0.55/-0.52 | OFF:80% | OFF: A-T-A-R | -0.31/-0.26 | Yes | 0.153λ | 8 | TE:30/30(ON/OFF) |
| | | | | | | | | | | TM:5/10(ON/OFF) |

S/T: switchable or tunable; A: absorption; T: transmission; R: reflection; RT: simulated reflection or transmission coefficient; d is the lowest frequency; Number of lumped elements excludes the lumped elements of feed line.

Fig. 9. Measurements and simulations of the switchable FSS with (a) diodes ON and (b) diodes OFF.

Fig. 10. Measured and simulated results of the SFSR with (a) diodes ON and (b) diodes OFF.

measurements. The measured transmission band of the switchable FSS is at 5.96 GHz in ON state, existing deviation, as shown in Fig. 9(a). The measured transmission band in the OFF state is almost identical to that in the simulation at 4.04 GHz, as shown in Fig. 9(b). However, because the dielectric substrate is just 0.5 mm thick, the bent substrate cannot maintain the switchable FSS parallel to the calibration surface. Consequently, the measured bands outside the transmission band were worse than the corresponding bands in the simulations.

Compared with the simulation, the measured passband of the switchable FSS shifted in the ON state and changed slightly in the OFF state. Revising the simulation model is necessary, and there are two steps: matching the simulation of the switchable FSS with measured results \((x = 9.75 \text{ mm in ON state}, x = 10.5 \text{ mm in OFF state})\). Subsequently, the two passbands of the lossy layer were revised following the revised switchable FSS \((d_4 = 3 \text{ mm})\). The final-revision segmented simulations of the SFSR are shown in Fig. 10. When the PIN diodes are in the ON state, the reflection and transmission peaks of the operating band are at 4.06 GHz \((-0.55 \text{ dB})\) and 5.97 GHz \((-0.52 \text{ dB})\), respectively. The absorption bands are from 2.87 to 3.38 GHz and 4.56 to 5.3 GHz with a \(-10 \text{ dB}\) reduction. In experiment, when 1.3 V forward bias voltage was applied to the diodes, 0.98 A forward bias current was obtained and the calculated total power is 1.274 W. In OFF state, 10 V reverse bias voltage was applied on the diodes. The simulated and measured findings were compared and found to be in high agreement, as shown in Fig. 10. The measured absorption bands in the ON state are 2.53–3.53 GHz and 4.67–5.36 GHz. The reflection and transmission bands have peaks of \(-0.75 \text{ dB at 4.1 GHz} and \(-1.29 \text{ dB at 5.95 GHz}\), respectively. The observed absorption bands in the OFF state are at 2.43–3.62 GHz and 4.65–5.43 GHz. The reflection and transmission bands have peaks of \(-1.15 \text{ dB at 4.09 GHz} and \(-0.46 \text{ dB at 6.11 GHz}\), respectively.

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V. CONCLUSION

In this letter, an SFSR including the A-R-A-T or A-T-A-R mode was proposed. Metal resonances were employed to realize the two transmission bands of the lossy layer. The effect of the parameters of the diodes on the transmission response in ECM was investigated. A prototype was fabricated. A distinct production approach was used to minimize the frequency deviation caused by unknown causes. A prototype of the proposed SFSR was developed and tested. The measurement results and the revised simulation results were in high agreement.
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