Design of frequency selective rasorber with high in-band transmission and wideband absorption properties

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Abstract A low-frequency transmissive frequency selective rasorber (FSR) with high in-band transmission and wideband absorption characteristics is proposed and experimentally demonstrated. It comprises the top resistive sheet and the bottom bandpass FSS. For resistive sheet, the tiny strip-type parallel LC resonator composed of square spiral inductor and its two-sided capacitors is inserted between the resistor-loaded crosses to achieve lower insertion loss (IL) by cutting off the lossy path. The bandpass FSS with high selectivity consists of Jerusalem cross slot array and capacitive metallic patches. An IL of 0.3 dB is obtained at 3.55 GHz, and the 10-dB-absorption band is 5.4–13.2 GHz.

Keywords: frequency selective rasorber, high in-band transmission, wideband absorption, insertion loss

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Frequency selective surface (FSS) is a kind of periodic structure composed of the metallic patches or aperture elements of arbitrary geometries [1, 2, 3]. In the past, due to its frequency selective properties, FSSs have been widely used to construct hybrid radomes [4, 5], spatial filters [6, 7, 8], and absorbers [9, 10, 11]. For the conventional FSS-based radomes, the out of band incoming electromagnetic (EM) waves would be reflected towards an unthreatening direction to reduce the radar cross section (RCS) of the antenna system. However, it can only achieve monotonic RCS reduction, whereas, for the bistatic or passive radar, this method is useless. To solve this problem, the frequency selective rasorber (FSR) with both transmissive/absorptive properties was proposed. In [12], the concept of FSR was introduced in detail, and meanwhile, an FSR with wideband absorbing properties has been designed by using high-impedance surfaces. Unlike the FSS-based radomes, FSR would absorb the out of band incoming EM waves rather than reflect them.

In general, a two-dimensional FSR is usually composed of a resistive sheet and a bandpass FSS. It performs as a bandpass filter at antenna’s operating band, while acts as an absorber to the out of band incoming EM waves. The insertion loss (IL) of pass-band and the fractional bandwidth (FBW) of the 10-dB-absorption band (with the reflection coefficient less than $-10$ dB) are two criteria for evaluating FSR. In recent years, various FSRs have been widely investigated, such as the FSRs with high-frequency pass-band proposed in [13, 14, 15, 16], and the FSRs with two-sided absorption bands reported in [17, 18, 19, 20, 21, 22, 23, 24, 25, 26]. Besides, to meet the stealth requirements of low-frequency antenna systems, several FSRs with low-frequency pass-band were also presented in [27, 28, 29, 30, 31]. In [27], the magnetic material is utilized to design the FSR, whose 10-dB-absorption band is 5.8–8.4 GHz, corresponding to the FBW of 37%. In [28], the resistor-loaded square loop patches and the meandering square slot array were used to synthesize the FSR. Its FBW of the 10-dB-absorption band is 52%, and the in-band IL is less than 0.8 dB. In [29], a 3-D FSR with high selectivity was constructed by using multiple resonators. Its FBW of the 10-dB-absorption band is 64% and the in-band IL is less than 2.4 dB. Moreover, the resistor-loaded double-square loops and the convoluted slots were also applied for constructing the FSR, whose FBW is 100% and the in-band IL is less than 1 dB [30]. In [31], a miniaturized FSR is designed by using the resistor-loaded incurve square loop. Its IL of pass-band at 0.92 GHz is less than 0.5 dB and the FBW reaches 100%. For the above-mentioned FSRs with low-frequency transmission behavior, the minimum in-band IL is 0.5 dB, and the maximum FBW is 100%. Unfortunately, none of them can achieve a lower in-band IL on the premise of ensuring a wide absorption band.

In this letter, another low-frequency transmissive FSR, which has a lower in-band IL and, at the same time, a wide absorption band, is designed. The lower IL of 0.3 dB is realized at 3.55 GHz by introduced the compact parallel LC (CPLC) resonator into the resistive sheet. In addition, due to the small physical dimensions of the CPLC resonator, which is only 3.4 mm x 3.8 mm, FSR’s periodicity is finally miniaturized to only 8 mm. As a result, the grating lobe problems is improved remarkably. On the other hand, by using the highly selective bandpass FSS constructed by loading capacitive metallic patches below the Jerusalem cross slot array, FSR’s absorption performance is improved effectively. Its FBW of the 10-dB-absorption band reaches 84% and 88%, respectively, under TE and TM polarization.

2. Equivalent circuit analysis

In general, FSR should be transparent to the radio frequencies within operating band. However, when the in-band signals pass through the lossy layer, the IL always exists...
due to the lossy elements. Fortunately, by loading parallel LC resonator into the resistive sheet, low IL can be realized. To introduce its working principle qualitatively, a simplified FSR structure together with its equivalent circuit model (ECM) is illustrated in Fig. 1(a) and (b), respectively. In the ECM, \(Z_0\) is the characteristic impedance of free space, \(Z_{in}\) is the input impedance, and \(Z_R\) and \(Z_P\) denote the complex impedances of resistive sheet and bandpass FSS, respectively, which can be represented as \(Z_R = R + jX_R\) and \(Z_P = jX_P\).

Before derivation, it should be emphasized that only the pass-band of FSR is considered, that is, the bandpass FSS is always in resonance and \(Z_P\) is infinite. As a result, the ABCD matrix of this FSR can be simplified as

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \begin{bmatrix}
1 & 0 \\
1/Z_R & 1
\end{bmatrix} \begin{bmatrix}
\cos \theta & jZ_0 \sin \theta \\
j \sin \theta/Z_0 & \cos \theta
\end{bmatrix}
\]

(1)

Where \(\theta = \beta h = 2\pi f \lambda/c\), \(c\) stands for the speed of light, and \(h\) is the thickness of the air spacer. Then, its transmission coefficient (S21) can be calculated with

\[
[S21] = \frac{2Z_0}{AZ_0 + B + CZ_0 + DZ_0} = \frac{2}{(2 + Z_0/Z_R) \cos \theta + j(2 + Z_0/Z_R) \sin \theta}
\]

(2)

It is observed that the \([S21]\) or the transmissivity of pass-band is proportional to \(Z_R\). In other words, the in-band IL is inversely proportional to \(Z_R\). When \(Z_R\) is infinite, the transmissivity will become 100% and the in-band IL will be zero. For \(Z_R\), its real part \(R\) is determined by the resistance value of the lumped resistor on the resistive sheet, so it is impossible to achieve an infinite impedance just by adjusting \(R\). Hence, the only way to realize the infinite impedance is by adjusting \(Z_R\)’s imaginary part, which is jointly determined by its equivalent inductance and capacitance. Therefore, the parallel LC resonator with infinite impedance at resonance is considered to be introduced into the resistive sheet. Noting that it should have the same resonant frequency as the bandpass FSS. The improved ECM is presented in Fig. 1(c). From an equivalent circuit point of view, when the parallel LC resonator \((L_r + C_r)\) resonates within the pass-band, its branch circuit is in an open state. Under this situation, no current will flow through the lumped resistors and hence, low ohmic loss can be realized.

3. FSR design and performance

Based on the above impedance analysis, a low-frequency transmissive FSR with lower in-band IL and wideband absorption characteristics is designed. Its three-dimensional configuration and the corresponding ECM are shown in Fig. 2(a) and (b), respectively. It is synthesized by placing a resistive sheet on top of a bandpass FSS separated by a 5.5-mm-thick air spacer. The thickness, loss tangent, and relative permittivity of the dielectric substrates used in this FSR design are 0.508 mm, 0.0037, and 3.48, respectively.

3.1 Resistive sheet design

The resistive sheet is utilized to absorb the out of band incoming EM waves with the bandpass FSS as a ground plane. Meanwhile, it should also provide a transparent window with low IL to transmit the in-band signals. To meet above requirements, the resistive sheet is designed to be composed of the resistor-loaded cross and the strip-type CPLC resonator \((L_{c2} + C_{c2})\), as shown in Fig. 2(c) and (d). Resistors are loaded on the arms of the cross to constitute the lossy path for realizing desired absorption performance at certain frequency band. For the CPLC resonator, its inductor \(L_{c2}\) comprises two identical 2-turn square spiral inductors (SSIs) in series connection. Their outermost turns are connected to two crosses, respectively, and the innermost turns are connected together through two metallic via holes and an underpass strip. Its equivalent inductance value is proportional to metallic strips’ total length (number of turns), while inversely proportional to strip’s width. On the other hand, on both side of SSI, two capacitors realized by the parallel metallic strips are in parallel to construct CPLC resonator’s capacitor \(C_{c2}\). Its equivalent capacitance value is positively related to parallel strips’ length \(w_3\) and negatively related to their gaps \(w_6\). As for the resistor-loaded cross, it can be equivalent to a series RL circuit \((R + L_{c3})\). In cooperation with the capacitor
$C_{12}$, a series $LC$ resonator ($L_1$ and $C_{12}$) characterized by a stop-band is realized. It should be noted that, in order to circumvent the grating lobe problem and meanwhile, make the CPLC resonator resonates at low frequency band, the width of these metallic strips used in CPLC resonator are optimized to be 0.1 mm. Finally, the dimensions of the CPLC resonator are miniaturized to $3.4 \times 3.8 \text{mm}$, and FSR’s periodicity is reduced to only 8 mm, $0.35\lambda_{HF}$ at the higher frequency of the absorption band (13.2 GHz).

The reflection/transmission coefficients of this resistive sheet under different incident angles and polarizations are obtained by using ANSYS HFSS simulation tool, as depicted in Fig. 3. It is seen that the transparent window achieved by the CPLC resonator is located around 3.55 GHz, and is independent of the angle and polarization of incoming EM waves. Noting that there are two spurious resonances occur in the stop-band at the oblique incidence of $45^\circ$ under TE polarization. This is because the high-order harmonic resonance will shift towards the lower frequency at oblique incidence.

![Fig. 3. Reflection (S11)/transmission (S21) coefficients of the resistive sheet under different incident angles (a) TE polarization. (b) TM polarization.](image)

3.2 Bandpass FSS design

The bandpass FSS is designed to transmit the in-band signals within desired operating band and performs as a ground plane at the absorption band. In general, the bandpass FSS with high selectivity, characterized by a broader stop-band and faster roll-off, contributes to improving FSR’s absorption performance and shortening the transition band between transmission and absorption bands. For this purpose, by loading capacitive metallic patches below the Jerusalem cross aperture array separated by a thin dielectric substrate, a highly selective bandpass FSS is achieved. Its unit cell structures of upper and lower periodic surfaces are shown in Fig. 2(e) and (f), respectively. Under the radiation of incoming EM waves, the Jerusalem cross aperture array behaves as a parallel $LC$ resonator ($L_{p1}$ and $C_{p1}$) characterized by a pass-band. The capacitive metallic patch is equivalent to a capacitor ($C_{p2}$) that plays an important role in dominating the selectivity of bandpass FSS. For the metallic patch, its equivalent capacitance value is proportional to its dimensions. The specific ECM of this bandpass FSS is shown in the dashed frame to the right of Fig. 2(b).

![Fig. 4. Reflection (S11)/transmission (S21) coefficients of the bandpass FSS under different incident angles (a) TE polarization. (b) TM polarization.](image)

3.3 FSR’s performance

The resistance $R$ of the lumped resistor and the thickness $h$ of the air spacer are two key parameters in affecting FSR’s absorption performance. In general, $R$ is determined by trial and error. As for $h$, it is usually set as a quarter of wavelength corresponding to the center frequency of the absorption band (around 9.5 GHz in this letter). Considering the effects of the thin dielectric substrate below the resistive sheet, $h$ is finally optimized to be 5.5 mm. Then, the resistance $R$ is optimized to be 100 $\Omega$. The simulated reflection/transmission coefficients of the proposed FSR
under different incident angles are depicted in Fig. 5. It is seen that under both polarizations, the stable pass-band at 3.55 GHz with IL less than 0.3 dB is realized. Under TE polarization, the 10-dB-absorption band ranges from 5.4 to 13.2 GHz and shows good angular stability within 30°. At an oblique incidence of 45°, two spurious resonances occur around 12 GHz. As explained in section 3.1, they are caused by the top resistive sheet. On the other hand, under TM polarization, the 10-dB-absorption band is slightly wider, spanning from 5.3 to 13.7 GHz. Similarly, the absorption performance is stable within 30° and starts to deteriorate after that. Nevertheless, in the case of oblique incidence at 45°, the absorptivity can still maintain more than 70% in the frequency range of 6.5–14 GHz.

4. Experimental verification

As described above, a low-frequency transmissive FSR is synthesized and simulated. To further demonstrate its validity, a planar FSR prototype containing 25 × 25 unit cells with the size of 220 mm × 220 mm is fabricated using the standard printed circuit board technology, as shown in Fig. 6(a). The structural parameters of the prototype are the same as the designed ones aforementioned. The resistive sheet is printed on the surface of a 0.508-mm-thick Rogers 4350B substrate with εr = 3.48 and tan δ = 0.0037. In each unit cell, four chip resistors of 100 Ω with 0402 package are soldered on the cross, which can be seen in the enlarged view of the unit cell of resistive sheet. Similarly, the two layers of periodic surfaces of the bandpass FSS are printed on both sides of another 0.508-mm-thick Rogers 4350B substrate, respectively. Then, the resistive sheet and the bandpass FSS are bonded together using several handmade 5.5-mm-thick foam blocks (εr ≈ 1). The total thickness of the prototype is 6.516 mm.

The prototype is measured in a microwave anechoic chamber using the free-space measurement setup composed of a network analyzer (Agilent N5221A), a transmitting antenna, and a receiving antenna. The testing frequencies range from 2 GHz to 13.5 GHz, which almost contains all the desired frequency band. The measured reflection/transmission coefficients of the fabricated FSR, together with the simulated ones, are shown in Fig. 7.

It is seen that the measured frequency responses of the FSR prototype agree well with the simulated ones except...
for a small frequency-shift occurring at pass-band. This can be attributed to the misalignment between the unit cells in different layers and the manufacturing tolerance. Furthermore, it can be noted that the high-frequency absorption band in experimental results is slightly narrower than that in simulation results. This is mainly caused by the deviation between the actual thickness $h$ of the air spacer and the desired ones. Fortunately, the FBW attenuation is small. Under TE and TM polarizations, the measured 10-dB-absorption band is 5.5–13.4 GHz and 5.6–13.5 GHz, respectively, corresponding to the FBW of 84% and 83%. Meanwhile, it should be noted that the magnitude fluctuations of the measured curves can be attributed to the coupling and interaction between two horn antennas as well as the diffraction of EM waves. Ignoring the above factors, the overall trend of the testing curves is consistent with the simulated ones, which can demonstrate the validity of the proposed FSR. A comparison between the proposed FSR and others in the literature is implemented, as tabulated in Table I.

As observed, the proposed FSR has the advantages of better transmission properties, fewer lumped resistors, and smaller periodicity. Although in terms of the absorption bandwidth, the proposed FSR cannot catch up with the FSRs in [30, 31], yet its FBW of the 10-dB-absorption band still reaches 84%.

5. Conclusion

In this letter, a low-frequency transmissive FSR with high in-band transmission and wideband absorption properties is designed and experimentally validated. By introducing the space-saving CPLC resonator into the resistive sheet, the IL of pass-band as well as the grating lobe problem is improved effectively. By loading the capacitive metallic patches into the bandpass FSS, an ideal resonant curve with a wide stop-band and faster roll-off is realized. As a result, FSR’s out of band absorption performance is improved effectively. The proposed FSR has the potential to be used in the applications of RCS reduction and EM shielding.

Table I. Performance comparison.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Transmission band (GHz)/ IL (dB)</th>
<th>10-dB- absorption band (GHz)/FBW</th>
<th>Thickness ($\lambda$)</th>
<th>Number of lumped resistors</th>
<th>Periodicity (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[12]</td>
<td>4.6/0.3</td>
<td>10–18/57%</td>
<td>0.08</td>
<td>N.A.</td>
<td>11</td>
</tr>
<tr>
<td>[27]</td>
<td>2.24/N.A.</td>
<td>5.8–8.4/37%</td>
<td>N.A.</td>
<td>N.A.</td>
<td>18</td>
</tr>
<tr>
<td>[28]</td>
<td>6.0/0.8</td>
<td>10.6–18/52%</td>
<td>N.A.</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>[29]</td>
<td>4.15/2.4</td>
<td>4.8–9.3/64%</td>
<td>0.27</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>[30]</td>
<td>1/1</td>
<td>3–9/100%</td>
<td>0.03</td>
<td>8</td>
<td>36</td>
</tr>
<tr>
<td>[31]</td>
<td>0.92/0.5</td>
<td>3–9/100%</td>
<td>0.03</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>This work</td>
<td>3.55/0.3</td>
<td>5.4–13.2/84%</td>
<td>0.08</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>

$\lambda$ is free space wavelength at the center frequency of transmission band; $^2$Number of lumped resistors required in a unit cell.

References

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