Single-Layered Flexible Dual Transmissive Rasorbers With Dual/Triple Absorption Bands for Conformal Applications

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ABSTRACT This article presents flexible frequency selective surface (FSS) based rasorbers exhibiting dual/triple absorption bands along with dual-band transmission. The proposed rasorbers are designed by combining the individual designs of dual-/triple-band resonant absorber and dual bandpass FSS on the two sides of a flexible substrate. At the absorption frequencies, the bandpass FSS acts as reflective metallic ground. The proposed FSS based rasorbers are flexible, single-layer structures having a thickness of 0.005λ₀ at the lowest absorption frequency and can serve as suitable candidates for the much practical conformal applications. The working of the proposed rasorbers is analyzed using an equivalent circuit model. Further, an optimum range at each absorption frequency is determined by studying the parametric effects on the proposed design. Prototypes consisting of 17 × 25 unit cells are fabricated and experimental validation is achieved. The performance of the rasorbers is also studied by bending their fabricated prototypes with 120°, 150°, and 180° degrees of curvatures.

INDEX TERMS Frequency selective surface (FSS), frequency selective rasorber (FSR), polarization-insensitive, equivalent circuit model (ECM).

I. INTRODUCTION

Frequency selective surface (FSS) is a periodic structure capable of interacting with the incident electromagnetic (EM) wave and has gained increased attention in the last decade due to its wide range of applications like spatial filters, absorbers, radomes, EM shielding, and polarization converters [1]–[6]. Among them, FSS based EM absorbers have been widely studied in the last decade due to its superior features such as thin, light and compact as compared with the conventional absorbers [7]. These FSS based absorbers have been employed in various applications such as stealth technology [8], radar cross section reduction [9], EM interference reduction [10], and radio frequency identification (RFID) [11].

Generally, in the design of FSS based absorbers, an array of metallic resonator is backed with a complete metallic plating on the other side of substrate [12]. The metallic layer on the other side of substrate ensures zero transmission across the structure, and the absorption takes place at the resonant frequency, at which the reflections are minimized. Several such resonant absorbers have been reported in the past [13], [14]. Using multiple resonant structures in a single unit cell, the absorption have been increased from single-band to multi-band [15]–[18]. Bandwidth enhancement in the FSS based absorbers has been reported in [19], in which close optimization of the resonant structures are carried, such that the absorption peaks are brought closer to realize a bandwidth-enhanced absorption. For achieving the broadband absorption, lossy elements like lumped resistors have been incorporated in the FSS design, which is based on the concept of circuit analogue absorber. The broadband absorber is generally a two-layer structure consisting of resistive and ground layers, with an appropriate distance between the two layers. Several such broadband absorbers have been reported in [20] and [21].

The FSS based absorber, however suffers from communication blockade limitation, in which the shielded system remains completely isolated due to zero transmission through the absorber. This communication limitation has...
been addressed by the introduction of FSS based rasorbers, also known as frequency selective rasorber (FSR). In the recent years, these FSR have gained much popularity over the FSS absorbers, due to its transmission characteristics in addition to absorption [22]–[27]. The FSS based rasorbers are generally obtained by integrating a bandpass FSS with the absorbers. The ground layer of the FSS based absorber is replaced by the bandpass FSS leading to an additional transmission band besides the absorption band. In the recent past, bandpass FSS as a separate application has also been extensively studied due to its potential demand in the multi-band wireless communication and radar system [28].

A FSR with a lowpass band and broadband absorption has been reported in [29], which is a two-layer design consisting of double resistive layer. Another FSR based on four-layer design is reported in [30], wherein the combination of two absorption layers and two transmission layers is utilized to achieve a transmission band within the two absorption bands. In [31], a FSR is reported which is a three-layer structure designed using double lossy layer and a lossless layer, realizing a transmission window within a broad absorption band. Also, FSR reported in [32] is a two-layer design exhibiting a transmission band in between the two absorption bands. Recently, a layer broadband rasorber is reported in [33], in which each layer is designed using a conformal substrate, achieving a passband within a wide absorption band. The rasorbers reported in [29]–[33] are multi-layered structures where the lumped resistors are incorporated in the design and are mostly suitable for wide-band absorption applications. However, in view of the practical applications, the flexibility in multi-layered absorber/rasorber design is challenging to achieve while maintaining the desired absorption/transmission performance. Recently, a graphene based flexible rasorber has been reported in [34]. However, the performance of the reported graphene based rasorber is limited due to the premature fabrication conditions of graphene.

As an attempt to address this flexibility limitation, the objective of the work in this paper is to design a single-layered flexible FSS structure, where the resonant absorption and transmission characteristics are retained by the appropriate FSS designs on the two sides of a single-layer substrate.

In this paper, FSS based rasorber designs are proposed with dual-/triple-band absorptions and dual transmission bands. A rasorber with dual-band transmission and dual-band absorption (2T2A) is obtained by combining the designs of dual resonant FSS absorber and dual bandpass FSS on the two sides of a single dielectric substrate. Further, the rasorber structure is modified by an additional resonant structure that is capable of achieving a third resonant absorption in between the two transmission bands, thus obtaining a rasorber with dual-band transmission and triple-band absorption (2T3A).

The proposed rasorbers have desirable features like ultra-thin, polarization-insensitive, single-layered, and also exhibit conformal characteristics which makes the proposed structure more suited for practical applications. An equivalent circuit model (ECM) of the proposed rasorber is studied for analyzing the working principle of rasorber. For experimental validation, an array consisting of $17 \times 25$ unit cells for both 2T2A and 2T3A rasorbers are fabricated, and the results are verified for both flat and curved structures. The main contribution achieved in this study can be encapsulated as follows.

- A single-layer polarization-insensitive rasorbers exhibiting 2T2A and 2T3A characteristics with high absorptivity (>90%), and low insertion loss (≤0.5 dB).
- An ultra-thin, flexible structure with 0.254 mm thickness which is 0.005λ₀ at the lowest absorption frequency.
- Measured results on the fabricated prototype of the proposed rasorber designs confirm that the absorption and transmission characteristics are retained up to...
180° curvature angle, making it an ideal candidate for conformal applications.

This work is presented in the following sequence. Section II presents the design and analysis of the proposed rasorbers. Section III discusses the parametric studies on the proposed rasorbers. The experimental verification and discussion is provided in Section IV, and the conclusion is summarised in Section V.

II. DESIGN AND ANALYSIS OF THE RASORBER
A general theoretical understanding of a FSS based rasorber is represented by the schematic shown in Fig. 1. The wave incident on a rasorber can be transmitted or reflected or absorbed depending upon its interaction with the structure at a particular frequency. In the transmission mode, the FSS rasorber selectively transmits the incident wave, whereas the reflections are minimized. However, the absorption mode occurs when both the transmission and reflection are minimum in a particular frequency band. This can be mathematically expressed by the following relation:

$$A = 1 - R - T$$

where A, R, and T are the absorption, reflection and transmission coefficients, respectively.

In the design for FSS based rasorber, the ground layer of the absorber is replaced by the bandpass FSS. However, the key point is that the bandpass FSS should act as a metallic reflecting surface at the absorbing frequencies, such that both the absorption and transmission characteristics are retained. Accordingly, the design approach for the FSS based rasorber involves the three-step process. In the first step, a dual bandpass FSS is studied. In the next step, the resonant absorption for various resonant structures are studied so as to appropriately locate the absorption frequencies with respect to the transmission bands of the bandpass FSS. In the last step, the absorption and bandpass FSS designs are combined on the two sides of a single substrate to realize the desired absorption and transmission characteristics. The proposed FSS based rasorber is designed on an ultra-thin flexible Teconic substrate of thickness ($t$) equal to 0.254 mm, dielectric constant ($\varepsilon_r$) of 2.2, loss tangent ($\tan\delta$) equal to 0.0009, and the thickness of copper plating equal to 0.035 mm.

A. BANDPASS FSS
The unit cell schematic of the dual bandpass FSS is depicted in Fig. 2. The unit cell consists of a cross-loop shaped slot etched at the center of the unit cell with length $l_b_1$. Also, a quarter of cross-loop shaped slot with length $l_b_2$ is etched...
at each corner of the unit cell. The center and the corner loop slots give rise to the passband at their corresponding resonating frequencies. The simulated response of bandpass FSS shows dual transmission bands at 9.7 and 13.0 GHz as illustrated in Fig. 3(a), where the transmission bands at 9.7 GHz and 13.0 GHz are due to the center loop slot and the corner loop slot, respectively. The design flow of the bandpass FSS is illustrated using Fig. 3(b) and 3(c), where the simulated response for cross slot and cross-loop slot are shown, respectively. In the case of cross slot shaped bandpass FSS, the passband is obtained at around 14.3 GHz (Fig. 3(b)). The passband is decreased from 14.3 to 9.7 GHz (Fig. 3(c)) by inserting a metallic cross of width $w_{c1}$ in between the cross shaped slot, thus modifying the slot shape from simple cross to cross-loop. The decrease in transmission frequency in the case of cross-loop shaped design can be attributed to the increased slot dimensions for cross-loop slot. Also, in the case of cross-loop shaped bandpass FSS, the transmission response has a higher selectivity and is steeper at the passband in comparison with the simple cross shaped bandpass FSS.

For rasorber design, the passband with higher selectivity is more preferred, so that bandpass FSS can be utilized as a reflective surface in the near adjacent bands. The addition of corner slots in the bandpass FSS results in an another passband at a higher frequency of 13.0 GHz. The dependence of the two passbands on its corresponding slots is further illustrated in Fig 4(a) and 4(b), where the response of the
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**FIGURE 9.** Front view of the unit cell of the proposed 2T3A rasorber. \( p = 15 \), \( r_1 = 5.0 \), \( w_1 = 0.5 \), \( l_3 = 7.0 \), \( w_3 = 0.4 \), \( r_2 = 5.9 \), \( w_2 = 0.9 \), \( g = 0.8 \) (all dimensions are in mm).

**FIGURE 10.** Perspective view of the proposed 2T3A rasorber.

bandpass FSS with respect to the varying slot lengths \( l_{h1} \) and \( l_{h2} \) are provided, respectively. The variation of center cross-loop length \( l_{h1} \) from 7.5 mm to 9.5 mm, causes the lower passband to decreases from 10.9 to 8.9 GHz, respectively and a marginal shift in the upper passband frequency. Similarly, the variation of corner cross-loop length \( l_{h2} \) from 5.3 mm to 7.3 mm, decreases the higher passband from 15.2 to 11.2 GHz, while lower passband frequency remains unaltered.

**B. FSS ABSORBER**

The FSS absorber is designed in such a way that at the absorption frequencies, the bandpass FSS analyzed in the previous subsection acts as a maximum reflective surface. The unit cell schematic of the dual-band FSS absorber as shown in Fig. 5, consists of a metallic ring resonator surrounding a metallic cross resonator printed on the front side of substrate while having a complete metallic cover on its other side. The inner and outer radii of the ring resonator are denoted by \( r_1 \) and \( r_1 + w_1 \), respectively. The length and width of the cross resonator are denoted by \( l_3 \) and \( w_3 \), respectively. The two resonators leads to the resonant absorption at two separate frequencies. The two resonant structures are selected such that its corresponding resonant frequencies are above and below the two passband frequencies obtained for the bandpass FSS in the previous subsection. The simulated reflection coefficient of the dual-band FSS absorber is shown in Fig. 6, where the resonant absorption at two frequencies are obtained. The absorption at higher frequency of 15.1 GHz corresponds to the cross resonator while the ring resonator contributes to the absorption at 6.6 GHz. The two absorption frequencies achieved are located on the two sides of the dual passband frequencies of the bandpass FSS (9.7 and 13.0 GHz) studied in the previous subsection.

**C. PROPOSED 2T2A AND 2T3A RASORBERS**

The schematic of the proposed 2T2A rasorber is shown in Fig. 7. The design of the proposed rasorber with dual-band absorption and dual-band transmission is accomplished by printing the individual designs of dual-band FSS absorber and dual bandpass FSS on the front and back sides of a 0.254 mm thick Diclad substrate, respectively. The front side of the rasorber unit cell consists of the printed metallic ring and cross resonators (Fig. 7(b)). On the backside of rasorber, centre and corner cross loop slots are etched out within the metal plated substrate (Fig. 7(c)). The proposed design of the rasorber is analyzed using CST EM Solver. The simulated transmission and reflection coefficients of the 2T2A rasorber are shown in Fig. 8. Maximum absorption of 93.62% and 92.29% are obtained at the lower absorption frequency \( f_{al} = 6.4 \text{ GHz} \) and the upper absorption frequency \( f_{au} = 14.7 \text{ GHz} \), respectively. The lower transmission frequency \( f_{dl} = 9.6 \text{ GHz} \) and the upper transmission frequency...
Figure 12. Electric field distribution of the proposed 2T3A rasorber.

Figure 13. Surface current distribution of the proposed 2T3A rasorber (a) 6.6 GHz, (b) 11.1 GHz, (c) 14.7 GHz, (d) 9.6 GHz, and (e) 13.4 GHz.

(\(f_{lu} = 13.4\) GHz) exhibits a minimum insertion loss of 0.2 dB and 0.4 dB, respectively.

Further, it can be observed from Fig. 8 that between the two transmission bands at 9.6 and 13.4 GHz, there occurs a reflective band within which the transmission dip occurs. This reflective band between the two transmission bands is utilized for achieving another absorption band. The proposed 2T2A rasorber, is modified to obtain the third absorption band in between the two transmission bands, thus leading to two transmission and three absorption (2T3A) bands. The front view of the modified unit cell for obtaining dual transmission and triple absorption bands is shown in Fig. 9, which consists of an additional split-ring resonator along with the ring and cross resonators. The split-ring has an inner and outer radii of \(r_2\) and \(r_2 + w_2\), respectively. The gap dimensions of the split-ring are denoted by \(g\). The split-ring resonator is capable of achieving a resonance at the desired frequency between the two transmission bands. The perspective view of the 2T3A rasorber is shown in Fig. 10. The simulated reflection and transmission coefficients for the 2T3A rasorber are shown in Fig. 11. A middle absorption frequency (\(f_{am}\)) in between the two transmission bands is achieved in addition to the lower and upper absorption frequencies. The three absorption frequencies in the proposed 2T3A rasorber are obtained at 6.6 GHz, 11.1 GHz and 14.7 GHz with the absorption peaks of 94.00\%, 96.81\% and 91.91\%, respectively. The transmission bands for 2T3A rasorber are at 9.6 and 13.4 GHz, with the minimum insertion loss of 0.3 dB and 0.5 dB, respectively.
The working of the proposed rasorber can be explained by the electric field/surface current distributions and the corresponding equivalent circuit model (ECM). The scalar electric field intensity (volts/meter) on the front and back sides for the proposed 2T3A rasorber at different frequencies of interest (6.6, 9.6, 11.1, 13.4 and 14.7 GHz) are shown in Fig. 12. At the absorption frequencies of 6.6, 11.1 and 14.7 GHz, the electric field is strongly concentrated on the front side of circular ring, split-ring and cross resonators, respectively. Relatively, lesser concentration of field is observed on the back side of each resonator at the absorption frequencies. The strong concentration of fields shows that there is no reflection and no transmission, leading to absorption of incident EM wave.

The absorption and transmission phenomenon can further be explained by the analysis of surface current and the associated ECM model. The surface current distributions at the absorption and transmission frequencies for the 2T3A rasorber are shown in Figure 13. An equivalent circuit model (ECM) for both 2T2A and 2T3A rasorbers are presented in Fig. 14. The metallic resonators at the front side is modelled using a series networks whereas, the slot resonators are represented by the parallel LC network. The addition of split-ring in the 2T3A rasorber is model by an additional $L_3 - C_3$ network (Fig. 14(b)).

At 6.6 GHz (lower absorption frequency), the surface currents are concentrated along the circular ring resonator (Fig. 13(a)). Due to the induced time varying current, an inductive effect gets generated along the metallic ring patch, while the inter-element spacing leads to the capacitance effect. This inductor-capacitor arrangement can be reduced to a simple series LC network ($L_1$ and $C_1$ in Fig. 14) at that particular frequency. At 11.1 GHz (middle absorption frequency) the surface currents are concentrated along the split-ring resonator on the front side of the structure Fig. 13(b). Due to the split-gap in the resonator an additional capacitor exists in the corresponding LC network. Thus, the equivalent network contributed by split ring resonator can be reduced to series LC network ($L_3$ and $C_3$ in Fig. 14) shown in the ECM. The currents at the higher absorption frequency of 14.7 GHz are concentrated along the metallic cross patch at the center of the structure thus leading to the corresponding series LC response as shown in Fig. 13(c). The equivalent network contributed by the metallic cross patch is also a series LC network ($L_2$ and $C_2$ in Fig. 14).

For the transmission frequencies at 9.6 and 13.4 GHz, it can be observed that the electric field intensity is concentrated along the edges of the center and corner cross loop slots, respectively on the back side of the structure (Fig. 13).
In contrast to the absorption frequencies, relatively less concentration of fields is observed on the metallic resonators printed on the front side of substrate. Due to the higher concentration of electric fields along the edges of the slot, the transmission occurs at the corresponding resonant frequency while the reflections are minimized.

The surface current intensity at transmission frequencies of 9.6 and 13.4 GHz are induced at the edges of the center and corner cross loop slot, respectively at the backside of the structure in accordance with the incident electric field. The inductance and capacitance effect due to the induced surface current at 9.6 and 13.4 GHz is modelled using the LC network shown in Fig. 13(d) and 13(e), respectively. The networks corresponding to 9.6 GHz and 13.4 GHz can be reduced to the parallel LC arrangement ($L_{P1}$, $L_{P2}$, $C_{P1}$, $C_{P2}$ at 9.6 GHz and $L_{P3}$, $L_{P4}$, $C_{P3}$, $C_{P4}$ at 13.4 GHz in Fig. 14).

The dielectric thickness is modelled using a transmission line of length equal to the substrate thickness $t$ and the characteristics impedance $Z_d$ given by

$$Z_d = \frac{Z_0}{\sqrt{\varepsilon_r}} \quad (1)$$

where $Z_0$ is the characteristic impedance of free space. $R_d$ models the equivalent resistance due to the dielectric loss of substrate [35]. The overall ABCD parameters of the ECM can be obtained by the cascaded matrix multiplication given as:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Y_F \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} R_d \\ 0 \end{bmatrix} \times \begin{bmatrix} \cos \beta t \\ j \sin \beta t/Z_d \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ j \varepsilon_r \sin \beta t/Z_0 & \cos \beta \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ Y_P & 1 \end{bmatrix} \quad (2)$$

where $Y_F$, $Y_P$ represents admittance of front resonant structure and dual bandpass FSS at the back side of substrate, respectively. Also, the propagation constant $\beta$ is given as $\beta = \sqrt{\mu_r \varepsilon_r}$ ($\mu_r$ and $\varepsilon_r$ are the relative permeability and permittivity of the dielectric substrate, respectively).

The S-parameters of the ECM are calculated from the ABCD parameters using the conversion formula given as follows:

$$S_{11} = \frac{A + B/Z_0 - CZ_0 - D}{A + B/Z_0 + CZ_0 + D} \quad (3)$$

$$S_{21} = \frac{2}{A + B/Z_0 + CZ_0 + D} \quad (4)$$

The absorptivity, $A(\omega)$ can be calculated from S-parameters obtained in equation (3) and (4) using the formula given below.

$$A(\omega) = 1 - |S_{11}|^2 - |S_{21}|^2 \quad (5)$$
The ECM of the proposed 2T2A and 2T3A rasorbers are analyzed using Keysight ADS simulator. The simulated transmission and reflection coefficients for the proposed rasorbers are shown in Fig. 15. The simulation response for ECM of 2T2A rasorber shown in Fig. 15(a), achieves dual resonant absorption at 6.5 and 14.8 GHz, along with dual passband at 9.5 and 13.5 GHz. The additional resonant network in the ECM of 2T3A rasorber achieves a third resonant absorption at 11.1 GHz as depicted in Fig. 15(b).

The proposed 2T2A and 2T3A rasorbers are analyzed under various polarization angles of the incident EM wave as shown in Fig. 16. For both the 2T2A and 2T3A rasorbers, the simulated transmission and reflection coefficients remains unaltered for different polarization angle, thereby verifying the polarization-independent behavior of the proposed rasorber.

The polarization characteristics of the proposed 2T3A rasorber are analyzed by studying the cross-polarized ($t_{ij}$) transmission coefficients with respect to their co-polarized ($t_{ii}$) counterpart. The co- and cross-polarization transmission response for the x-polarized or y-polarized incident wave for 2T3A rasorber is shown in Fig. 17(a). The cross-polarized transmission coefficient ($t_{xy}$ or $t_{yx}$) for the x-polarized or y-polarized incident wave is negligible as compared to the co-polarized transmission coefficient ($t_{xx}$ or $t_{yy}$), which suggests that the transmitted wave has the same polarization as that of the incident wave. Thus, the proposed transmissive rasorber structures do not affect the polarization of the incident EM wave. The polarization conversion ratio (PCR) [36] plot for the proposed 2T3A rasorber is provided in the Fig. 17(b). It can be observed that $PCR_{yy}$ is close to 1, while $PCR_{xy}$ is close to 0 at the two transmission frequencies, which further verifies that no polarization conversion takes place in the proposed rasorber structure.

The oblique incidence response of the proposed rasorbers is studied under various angle of incidence for TE polarization as shown in Fig. 18. In both 2T2A and 2T3A rasorbers, an acceptable response for the reflection and transmission coefficients are maintained up to 40° of incident angle, within which the acceptable transmission and absorption at the corresponding frequencies are maintained. Beyond 40° of incident angle, the absorption at only 14.7 GHz gets considerably degraded, even though the performance at other frequencies of interest are maintained up to 60° of incident angle, thus limiting the overall angular stability of the proposed rasorber to 40°.

**III. PARAMETRIC STUDIES ON THE PROPOSED RASORBERS**

In the proposed 2T2A rasorber, resonant absorption occurring at the two sides of the dual passband corresponds to the ring
and the cross metallic resonators printed on the front side of the substrate. The lower absorption frequency is associated with the ring resonator while the upper absorption frequency is associated with the cross resonator. A parametric analysis is carried out on the proposed 2T2A rasorber with respect to the dimensions of the ring and cross resonators, keeping the bandpass dimensions constant such that a frequency range is obtained within which the lower and upper absorption frequency can be tuned in the proposed design.

The reflection and transmission coefficients for varying values of \( r_1 \) while keeping other parameters constant, are shown in Fig. 19. The variation in the performance parameters of the 2T2A rasorber with varying \( r_1 \) shown in Fig. 19 has been arranged in Table 1. It can be observed from Table 1 that decreasing the value of \( r_1 \) from 6.9 mm to 4.3 mm increments the lower absorption frequency (\( f_{al} \)) from 4.61 GHz to 7.51 GHz while the other frequencies of interest (\( f_{tl}, f_{tu}, f_{au} \)) remains nearly the same with small variations. It can be observed that by increasing the value of \( f_{al} \) beyond 6.94 GHz the corresponding absorption reduces below 90%. Thus for retaining the absorption greater than 90% the range of lower absorption frequency \( f_{al} \) can be achieved from 4.61 to 6.94 GHz by changing the value of \( r_1 \) from 6.9 mm to 4.7 mm, respectively.

In another case the reflection and transmission coefficients corresponding to varying length of cross resonator \( l_3 \) keeping the other parameters constant, are depicted in Fig. 20. The performance parameters at each frequency of interest for varying cross resonator length \( l_3 \) are illustrated in Table 2. The upper absorption frequency (\( f_{au} \)) increases from 14.02 to 15.86 GHz by decreasing the resonator length \( l_3 \) from 7.5 mm to 6.5 mm, respectively. Also, the performance at other frequencies of interest (\( f_{tl}, f_{tu}, f_{au} \)) remains nearly the same.

### Table 1: Performance parameters of 2T2A rasorber with varying \( r_1 \).

| \( r_1 \) (mm) | \( f_{al} \) (GHz) | \( f_{tl} \) (GHz) | \( f_{tu} \) (GHz) | \( f_{au} \) (GHz) |
|-----------|----------------|----------------|----------------|----------------|
| 6.9       | 4.61 (94.64%) | 9.61 (0.32 dB) | 13.35 (0.53 dB) | 14.69 (93.10%) |
| 6.7       | 4.89 (92.27%) | 9.67 (0.28 dB) | 13.38 (0.49 dB) | 14.74 (92.89%) |
| 6.5       | 5.05 (94.05%) | 9.57 (0.30 dB) | 13.42 (0.49 dB) | 14.69 (93.33%) |
| 6.3       | 5.29 (97.70%) | 9.60 (0.32 dB) | 13.38 (0.50 dB) | 14.71 (93.60%) |
| 6.1       | 5.48 (94.75%) | 9.60 (0.30 dB) | 13.38 (0.47 dB) | 14.76 (92.44%) |
| 5.9       | 5.64 (92.40%) | 9.58 (0.33 dB) | 13.36 (0.47 dB) | 14.69 (90.84%) |
| 5.7       | 5.69 (97.32%) | 9.61 (0.28 dB) | 13.42 (0.49 dB) | 14.71 (91.36%) |
| 5.5       | 5.86 (97.11%) | 9.60 (0.31 dB) | 13.41 (0.47 dB) | 14.69 (91.00%) |
| 5.3       | 6.12 (92.84%) | 9.61 (0.27 dB) | 13.42 (0.47 dB) | 14.71 (92.71%) |
| 5.1       | 6.41 (92.57%) | 9.67 (0.28 dB) | 13.39 (0.45 dB) | 14.82 (92.56%) |
| 4.9       | 6.69 (92.13%) | 9.61 (0.29 dB) | 13.42 (0.49 dB) | 14.67 (92.70%) |
| 4.7       | 6.94 (91.61%) | 9.63 (0.30 dB) | 13.46 (0.47 dB) | 14.69 (92.74%) |
| 4.5       | 7.23 (81.45%) | 9.65 (0.30 dB) | 13.45 (0.46 dB) | 13.71 (90.56%) |
| 4.3       | 7.51 (71.67%) | 9.65 (0.36 dB) | 13.46 (0.50 dB) | 14.72 (91.92%) |

### Table 2: Performance parameters of 2T2A rasorber with varying \( l_3 \).

| \( l_3 \) (mm) | \( f_{al} \) (GHz) | \( f_{tl} \) (GHz) | \( f_{tu} \) (GHz) | \( f_{au} \) (GHz) |
|-----------|----------------|----------------|----------------|----------------|
| 7.5       | 6.45 (91.25%) | 9.56 (0.29 dB) | 13.43 (0.51 dB) | 14.02 (78.79%) |
| 7.4       | 6.45 (94.48%) | 9.56 (0.28 dB) | 13.43 (0.47 dB) | 14.13 (82.98%) |
| 7.3       | 6.42 (92.57%) | 9.54 (0.28 dB) | 13.22 (0.51 dB) | 14.25 (85.90%) |
| 7.2       | 6.41 (92.97%) | 9.60 (0.38 dB) | 13.43 (0.47 dB) | 14.46 (88.74%) |
| 7.1       | 6.42 (94.52%) | 9.58 (0.30 dB) | 13.43 (0.48 dB) | 14.51 (92.29%) |
| 7.0       | 6.43 (93.62%) | 9.63 (0.29 dB) | 13.46 (0.48 dB) | 14.76 (90.29%) |
| 6.9       | 6.37 (93.29%) | 9.75 (0.27 dB) | 13.69 (0.43 dB) | 15.07 (90.61%) |
| 6.8       | 6.57 (92.35%) | 9.77 (0.27 dB) | 13.67 (0.43 dB) | 15.24 (89.62%) |
| 6.7       | 6.62 (94.17%) | 9.75 (0.30 dB) | 13.70 (0.42 dB) | 15.45 (88.02%) |
| 6.6       | 6.64 (93.00%) | 9.79 (0.28 dB) | 13.74 (0.41 dB) | 15.69 (83.80%) |
| 6.5       | 6.57 (90.80%) | 9.79 (0.27 dB) | 13.67 (0.42 dB) | 15.86 (82.55%) |

Ab: Absorption; LL: Insertion loss; \( f_{al} \): Lower absorption frequency; \( f_{tl} \): Lower transmission frequency; \( f_{tu} \): Upper transmission frequency; \( f_{au} \): Upper absorption frequency.
However, for retaining the absorption greater than 90%, the upper absorption frequency $f_{au}$ can slide from 14.51 GHz to 15.07 GHz by the decreasing the value of $l_3$ from 7.1 mm to 6.9 mm, respectively.

In the 2T3A rasorber design, the middle absorption frequency ($f_{am}$) corresponds to the resonance frequency of the split-ring resonator. Thus a range for $f_{am}$ can be obtained by studying the parametric variation of split-ring radius $r_2$ on the corresponding absorption frequency. The reflection and transmission coefficients of the proposed 2T3A rasorber for the varying value of $r_2$ while keeping the other parameters constant, are depicted in Fig. 21. The performance at
FIGURE 24. Simulated and measured reflection and transmission coefficients of the proposed (a) 2T2A, and (b) 2T3A rasorbers.

Each frequency of interest with respect to different values of $r_2$ has been provided in Table 3. It can be observed that by varying the radius of split-ring $r_2$ from 5.6 mm to 6.6 mm, the middle absorption frequency $f_{am}$ decreases from 12.30 GHz to 9.82 GHz, respectively. However, below 10.37 GHz, the absorption reduces below 90%. As such an acceptable range of $f_{am}$ can be defined from 12.30 GHz to 10.37 GHz which corresponds to value of $r_2$ from 5.6 mm to 6.4 mm, respectively.

IV. EXPERIMENTAL VERIFICATION AND DISCUSSION

An experimental verification of the proposed 2T2A and 2T3A rasorbers are obtained by carrying out measurements on the fabricated prototype of each rasorber. An array consisting of 17 × 25 unit cells for each 2T2A and 2T3A rasorber are fabricated on a 0.254 mm thick Taconic substrate having dielectric constant ($\varepsilon_r$) of 2.2 and loss tangent (tan $\delta$) equal to 0.0009. The photograph of the fabricated prototype for both 2T2A and 2T3A rasorbers, with an overall dimensions of 265 mm × 385 mm are shown in Fig. 22. The bandpass FSS design on the back side of substrate is same for both the proposed rasorbers as shown in Fig. 22(c).

The measurement of the fabricated prototypes are carried out in an anechoic chamber using free space measurement technique. For carrying out measurements a pair of three different standard gain horn antennas connected with a Keysight PNA Network Analyzer N5224B, are sequentially used. The three different horn antennas used belongs to separate J(5.85−8.20 GHz), X(8.20−12.40 GHz) and Ku(12.40−18.0 GHz) frequency bands. The experimental setups for reflection and transmission measurements are shown in Figs. 23(a) and 23(b), respectively. A reference measurement is initially carried out in both the reflection and transmission setup, with which the measured results are then normalised for obtaining the effective reflection and transmission coefficients. In case of reflection, the reference measurement is the reflections obtained from a metallic sheet while for the other case of transmission, the direct free space path loss measurement between the two horn antennas provides the reference measurement. The comparison of simulated and measured reflection and transmission coefficients for both the 2T2A and 2T3A rasorbers are shown in Fig. 24.
agreement between the measured and simulated results for both the rasorber provides an experimental validation for the responses of the proposed rasorbers.

The performance of the proposed rasorbers has been verified experimentally under the oblique incident waves. The schematic of measurement setups for reflection and transmission coefficients for wave striking the rasorbers at oblique angles is shown in Fig. 25. The rasorber structure (DUT: Device Under Test) is placed at the center of the defined circular area. The path perpendicular to the surface is the normal incidence path (or the $0^\circ$ line). For measurement at different oblique angles of incidence, the transmitting and the receiving antennas are moved along the circular path (either clockwise or anticlockwise) making the required oblique angles with the normal incidence path.

In case of reflection measurement, as depicted in Fig. 25(a) the transmitting and receiving antennas are placed at the front side of the structure. In the normal incidence both the antennas are placed along the $0^\circ$ line, while for the oblique incidence transmitting and receiving antennas are moved in the anticlockwise (or clockwise) and clockwise (or anticlockwise) direction, respectively on the circular path making the necessary angle with the normal path. This measurement technique for the different angles is consistent with the basic theory of EM propagation i.e. angle of incidence is equal to angle of reflection.
For transmission coefficient measurement, the transmitting antenna is placed at the front side of the structure, while the receiving antenna is placed at the back side of the structure (Fig. 25(b)). For the normal incidence both the antennas are placed along the 0° line, while for the oblique incidence, the transmitting and the receiving antennas are moved along the circular path in the same direction i.e. either clockwise or anticlockwise, making the required oblique angle with the normal incidence path.

The measured reflection and transmission coefficients of the rasorber prototypes carried out under oblique incidence for TE polarization is provided in Fig. 26, and the angular stability up to 40° is experimentally verified.

In order to verify the flexible behavior of the proposed rasorber, reflection and transmission measurements for TE polarized incident wave are also carried out for the curved surface. The fabricated prototype is pasted on a cylindrical foam based structure, with the curvature given along the narrower side and the degree of curvature equal to 120°. The radius \( r \) of the cylindrical foam based structure is 126.5 mm, which is calculated using the formulae \( r = \frac{180A}{\pi D_C} \), where \( A \) is the arc length and \( D_C \) is the degree of curvature. The narrower side of structure having length of 265 mm is the arc length \( A \). The photograph of the curved structure for both 2T2A and 2T3A rasorbers are shown in Fig. 27. The reference measurement for reflection is obtained by the metal sheet pasted on the same cylindrical foam. The measured reflection and transmission coefficients of the curved structure in comparison with the measured results of the flat structure for both the 2T2A and 2T3A rasorbers are shown in Fig. 28. A close agreement between the measured results of curved and flat structures, verifies the conformal behavior of the proposed rasorbers.

The conformal behavior of the proposed structures is further studied by increasing the degree of curvature \( D_C \) to 150° and 180° for each curved structure. For obtaining the degree of curvature \( D_C \) equal to 150° and 180°, the structures are pasted on cylindrical foam having radius \( r \) equal to 101.2 mm and 84.3 mm, respectively. Fig. 29 compares the measured response of the curved 2T2A and 2T3A rasorber prototypes at various degrees of curvature \( D_C \). An acceptable response at each frequency of interest even up to 180° degree of

### TABLE 4. Performance Comparison of proposed FSS based rasorber with earlier reported multi/wide-band absorbers/rasorbers.

| Ref. | Absorption | Transmission / Min. Insertion loss | Thickness | Unit cell size | No. of layers | Lumped elements | Polarization | Conformal |
|------|------------|-------------------------------|-----------|---------------|--------------|----------------|--------------|-----------|
| [15] | Dual-band (4.6 and 24.4 GHz) | -Nil- | 0.022\(\lambda_0\) 0.076\(\lambda_0^2\) | 1 | No | Insensitive | No |
| [17] | Pentaband (9.9, 10.4, 10.9, 11.7 and 13.2 GHz) | -Nil- | 0.026\(\lambda_0\) 0.146\(\lambda_0^2\) | 1 | No | Sensitive | No |
| [18] | Triple-band (4.1, 6.6, and 9.9 GHz) | -Nil- | 0.000\(\lambda_0\) 0.038\(\lambda_0\) | 1 | No | Insensitive | Yes |
| [24] | Wide band (4.0–6.2 GHz and 8.2–12.0 GHz) | Dual-band (7.2 GHz / 2.3 dB and 13.0 GHz / 1.69 dB) | 0.107\(\lambda_0\) 0.029\(\lambda_0^2\) | 2 | Yes | Sensitive | No |
| [25] | Wide band (1.6–2.9 GHz, 3.8–4.7 GHz and 5.3–6.9 GHz) | Dual-band (3.5 GHz / 0.35 dB and 4.9 GHz / 0.1 dB) | 0.076\(\lambda_0\) 0.021\(\lambda_0^2\) | 2 | Yes | Dual | No |
| [29] | Wide band (3.8–10.8 GHz) | Low pass (< 860 MHz) / (< 1 dB) | 0.140\(\lambda_0\) 0.048\(\lambda_0^2\) | 2 | Yes | Dual | No |
| [30] | Wide band (1.5–4.6 GHz, 9.2–13.7 GHz) | 6.5 GHz / 0.67 dB | 0.171\(\lambda_0\) 0.010\(\lambda_0^2\) | 4 | Yes | Dual | No |
| [31] | Wide band (2.3–5.3 GHz and 7.8–14.6 GHz) | 6.3 GHz / 0.78 dB | 0.111\(\lambda_0\) 0.023\(\lambda_0^2\) | 3 | Yes | Dual | No |
| [32] | Wide band (2.5–4.6 GHz and 7.7–12.0 GHz) | 6.0 GHz / 0.27 dB | 0.073\(\lambda_0\) 0.010\(\lambda_0^2\) | 2 | Yes | Dual | No |
| [33] | Wide-band (2.9–5.6 GHz and 7.4–9.2 GHz) | Single-band (6.0 GHz / 0.38 dB) | 0.0639\(\lambda_0\) 0.038\(\lambda_0^2\) | 1 | Yes | Dual | No |
| [33] | Wide-band (3.1–5.0 GHz and 6.4–8.3 GHz) | Single-band (5.8 GHz / 0.45 dB) | 0.0878\(\lambda_0\) 0.042\(\lambda_0^2\) | 1 | Yes | Dual | No |
| [33] | Wide-band (3.2–6.4 GHz and 8.3–10.5 GHz) | Single-band (7.7 GHz / 0.25 dB) | 0.0987\(\lambda_0\) 0.045\(\lambda_0^2\) | 2 | Yes | Dual | Yes |
| This work | Dual-band (6.4 and 14.7 GHz) | Dual-band (9.6 GHz / 0.29 dB and 13.4 GHz / 0.48 dB) | 0.0054\(\lambda_0\) 0.101\(\lambda_0^2\) | 1 | No | Insensitive | Yes |
| This work | Triple-band (6.6, 11.1 and 14.7 GHz) | Dual-band (9.6 GHz / 0.31 dB and 13.4 GHz / 0.52 dB) | 0.0055\(\lambda_0\) 0.108\(\lambda_0^2\) | 1 | No | Insensitive | Yes |

\(\lambda_0\) = free space wavelength at the lowest frequency of interest.
curvature confirms the enhanced conformality of the proposed structures.

The comparison of the performance of the proposed ultra-thin, conformal rasorbers with the previously reported multi-band absorbers/wide-band rasorbers is presented in Table 4. The proposed rasorbers possess the superior performance of exhibiting dual transmission band along with the dual/triple absorptions as compared to the reported multi-band absorbers in [15], [17], and [18]. In comparison with the wide absorptive rasorber reported in [24], [25], [29]–[33] the proposed rasorber is an ultra-thin, conformal, single-layer structure with multiple narrow band absorptions and does not require any mounted lumped elements. Furthermore, the proposed rasorber is also a flexible structure and the measured results verifies the conformal characteristics up to 180° curvature angle.

V. CONCLUSION

In this work, polarization-insensitive flexible rasorbers with dual transmission and dual/triple absorption bands are designed on a 0.254 mm thick single layer substrate. The design for dual bandpass FSS is studied and combined with dual-band resonant absorber in such a way that at the absorption frequencies the bandpass FSS possess maximum possible reflection, thus realizing a 2T2A rasorber where the two resonant absorption \( f_{alt} = 6.4 \, \text{GHz} \) and \( f_{amu} = 14.7 \, \text{GHz} \) are located on the two sides of dual transmission bands \( f_{alt} = 9.6 \, \text{GHz} \) and \( f_{amu} = 13.4 \, \text{GHz} \). Further, the structure is modified to 2T3A rasorber in which an additional resonant absorption \( f_{amu} = 11.1 \, \text{GHz} \) is obtained in between the two transmission bands. Parametric studies are carried out on the proposed rasorbers for determining the range within which each absorption frequency can be varied in the proposed design by the judicious selection of the corresponding design parameter which controls it. Keeping other performance parameters constant the lower and upper absorption frequency in the 2T2A rasorber can be varied from 4.61 to 6.94 GHz and 14.51 to 15.07 GHz, respectively. In 2T3A rasorber, the middle absorption frequency can be tuned from 10.37 to 12.30 GHz while maintaining the other performance parameters. The working of proposed rasorbers is analysed using an ECM. The results are experimentally verified by carrying out measurements on the fabricated prototype consisting of 17 × 25 unit cell for each of the dual and triple absorptive rasorbers. Furthermore, the conformal property of the proposed rasorbers is experimentally verified by carrying out measurements on the curved prototypes with multiple curvature angles. The proposed ultra-thin flexible rasorbers with absorptions and transmissions in multiple bands, along with conformal behavior can be useful in various potential applications like radar technology and EM shielding.

REFERENCES

[1] B. Munk, Frequency Selective Surfaces: Theory and Design. New York, NY, USA: Wiley, 2000.
[2] W. S. Arceneaux, R. D. Akins, and W. B. May, “Absorptive/transmissive: Radarome,” U.S. Patent 5 400 043, May 11, 1995.
[3] B. Han, S. Li, and Z. Li, “Asymmetric transmission for dual-circularly and linearly polarized waves based on a chiral metasurface,” Opt. Exp., vol. 29, pp. 19643–19654, 2021.
[4] S. J. Li, Y. B. Li, L. Zhang, Z. J. Luo, B. W. Han, R. Q. Li, X. Y. Cao, Q. Cheng, and T. J. Cui, “Programmable controls to scattering properties of a radiation array,” Laser Photon. Rev., vol. 15, no. 2, Feb. 2021, Art. no. 2000449.
[5] S. J. Li, Y. B. Li, H. Li, Z. X. Wang, C. Zhang, Z. X. Guo, R. Q. Li, X. Y. Cao, Q. Cheng, and T. J. Cui, “A thin self-feeding Janus metasurface for manipulating incident waves and emitting radiation waves simultaneously,” Annalen Phys., vol. 532, no. 5, May 2020, Art. no. 2000020.
[6] Z. Y. Li, S. J. Li, and B. W. Han, “Quad-band transmissive metasurface with linear to dual-circular polarization conversion simultaneously,” Adv. Theory Simul., vol. 4, no. 6, 2021, Art. no. 2100017.
[7] T. K. Wu, Frequency Selective Surfaces and Grid Arrays. New York, NY, USA: Wiley, 1995.
[8] W. F. Bahret, “The beginnings of stealth technology,” IEEE Trans. Aerosp. Electron. Syst., vol. 29, no. 4, pp. 1377–1385, Oct. 1993.
[9] 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.
[10] W. Yin, H. Zhang, T. Zhong, and X. Min, “A novel compact dual-band frequency selective surface for GSM shielding by utilizing a 2.5-dimensional structure,” IEEE Trans. Electromagn. Compat., vol. 60, no. 6, pp. 2057–2060, Dec. 2018.
[11] F. Costa, S. Genovesi, and A. Monorchio, “A chipless RFID based on multiflorentant high-impedance surfaces,” IEEE Trans. Microw. Theory Techn., vol. 61, no. 1, pp. 146–153, Jan. 2013.
[12] R. Anwar, L. Mao, and H. Ning, “Frequency selective surfaces: A review,” Appl. Sci., vol. 8, no. 9, p. 1689, Sep. 2018.

[13] N. I. Landy, S. S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, “A perfect metamaterial absorber,” Phys. Rev. Lett., vol. 100, pp. 207–402, Jan. 2008.

[14] H. Li, L. H. Yuan, B. Zhou, X. P. Shen, Q. Cheng, and T. J. Cui, “Ultrathin multiband gigahertz metamaterial absorbers,” J. Appl. Phys., vol. 110, no. 1, 2011, Art. no. 014909.

[15] J. Wang, R. Yang, J. Tian, X. Chen, and W. Zhang, “A dual-band absorber with wide-angle and polarization insensitivity,” IEEE Antennas Wireless Propag. Lett., vol. 17, no. 7, pp. 1242–1246, Jul. 2018.

[16] P. Mei, S. Zhang, X. Q. Lin, and G. F. Pedersen, “A triple-band absorber with wide absorption bandwidths using an impedance matching theory,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 3, pp. 521–525, Mar. 2019.

[17] P. Jain, A. K. Singh, J. K. Pandey, S. Garg, S. Bansal, M. Agarwal, S. Kumar, N. Sardana, N. Gupta, and A. K. Singh, “Ultra-thin metamaterial perfect absorbers for single-dual/multi-band microwave applications,” IET Microw., Antennas Propag., vol. 14, no. 5, pp. 390–396, Apr. 2020.

[18] A. K. Singh, M. P. Abegaonkar, and S. K. Koul, “Dual- and triple-band polarization insensitive ultrathin conformal metamaterial absorbers with wide angular stability,” IEEE Trans. Electromagn. Comput., vol. 61, no. 3, pp. 878–886, Jun. 2019.

[19] J. Lee and S. Lim, “Bandwidth-enhanced and polarization-insensitive metamaterial absorber using double resonance,” IET Electron. Lett., vol. 47, no. 1, pp. 8–9, 2011.

[20] S. Li, J. Gao, X. Cao, W. Li, Z. Zhang, and D. Zhang, “Wideband, thin, and polarization-insensitive perfect absorber based the double octagonal rings metamaterials and lumped resistances,” J. Appl. Phys., vol. 116, no. 4, 2014, Art. no. 043710.

[21] D. Lim and S. Lim, “Ultrawideband electromagnetic absorber using sandwiched broadband meta-surfaces,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 9, pp. 1887–1891, Sep. 2019.

[22] F. Costa and A. Monorchio, “A frequency selective radome with wideband absorbing properties,” IEEE Trans. Antennas Propag., vol. 60, no. 6, pp. 2740–2747, Jun. 2012.

[23] M. Qu, S. Sun, L. Deng, and S. Li, “Design of a frequency-selective absorber based on notch structure,” IEEE Access, vol. 7, pp. 3704–3711, 2019.

[24] M. Guo, Q. Chen, Z. Sun, D. Sang, and Y. Fu, “Design of dual-band frequency-selective absorber,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 5, pp. 841–845, May 2019.

[25] X. Xiu, W. Che, W. Yang, Y. Han, and Q. Xue, “Double-polarized dual-passband absorptive frequency-selective transmission structure,” IEEE Trans. Electromagn. Comput., vol. 62, no. 5, pp. 1951–1960, Oct. 2020.

[26] M. M. Zargar, A. Rajput, K. Saurav, and S. K. Koul, “Polarization-insensitive dual-band transmission passive rasorber designed on a single layer substrate,” IET Microw., Antennas Propag., vol. 14, no. 11, pp. 1296–1303, Sep. 2020.

[27] Z. F. Wang, “A high-transmittance frequency-selective rasorber based on dipole arrays,” IEEE Access, vol. 6, pp. 31367–31374, 2018.

[28] B. Zhang, C. Jin, X. Ye, and R. Mittra, “Dual-band dual-polarized quasi-elliptic frequency selective surfaces,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 2, pp. 298–302, Feb. 2019.

[29] G. Q. Luo, W. Yu, Y. Yu, H. Jin, K. Fan, and F. Zhu, “Broadband dual-polarized band-absorptive frequency-selective rasorber using absorptive Transmission/Reflection surface,” IEEE Trans. Antennas Propag., vol. 68, no. 12, pp. 7969–7977, Dec. 2020.

[30] H. Ye, J. Wei, L. Lin, F. Liu, L. Miao, S. Bie, and J. Jiang, “A frequency-selective surface rasorber based on four functional layers,” IEEE Trans. Antennas Propag., vol. 69, no. 5, pp. 5718–5723, Jul. 2020.

[31] J. Xia, J. Wei, Y. Liu, Y. Zhang, S. Guo, C. Li, S. Bie, and J. Jiang, “Design of a wideband absorption frequency selective rasorber based on double lossy layers,” IEEE Trans. Antennas Propag., vol. 68, no. 7, pp. 5718–5723, Jul. 2020.

[32] Q. Guo, J. Su, Z. Li, J. Song, and Y. Guan, “Miniaturized-element frequency-selective rasorber design using characteristic modes analysis,” IEEE Trans. Antennas Propag., vol. 68, no. 9, pp. 6683–6694, Sep. 2020.

[33] S. C. Bakshi, D. Mittra, and F. L. Teixeira, “Wide-angle broadband rasorber for switchable and conformal application,” IEEE Trans. Microw. Theory Tech., vol. 69, no. 2, pp. 1205–1216, Feb. 2021.

[34] H. Chen, W. Lu, Z. Liu, and Z. Jiang, “Flexible rasorber based on graphene with energy manipulation function,” IEEE Trans. Antennas Propag., vol. 68, no. 1, pp. 351–359, Jan. 2020.

[35] S. Ghosh and K. V. Srivastava, “An equivalent circuit model of FSS-based metamaterial absorber using coupled line theory,” IEEE Antennas Wireless Propag. Lett., vol. 14, pp. 511–514, 2015.

[36] S. Khan and T. F. Eibert, “A dual-band metasheet for asymmetric microwave transmission with polarization conversion,” IEEE Access, vol. 7, pp. 98045–98052, 2019.

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