A Method for Designing Multi-Band Rasoerbers for Wideband Applications

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This work was supported in part by the National Natural Science Foundation of China under Grant 62001095 and Grant U20B2043, and in part by the Fundamental Research Funds for the Central Universities of China under Grant ZYGX2018KYQD200.

ABSTRACT Rasoerbers with a single passband (narrow or wide) or multiple narrow passbands have been reported for stealth applications over the past few years. In this work, a method of designing the multi-band rasoerber with wide passband(s) is proposed for the stealth of wideband antennas. Firstly, the method of designing multi-band FSS is proposed based on the theory of N-band resonator, in which all the passbands exhibit second-order response. Secondly, a parallel resonator combining spiral inductor and interdigital capacitor is proposed to satisfy wide passband requirements at lower frequency of the operating band. Finally, to verify the proposed method, a dual-band rasoerber consisting of FSS and resistive layer is fabricated and measured. The measured results illustrate two passbands within 4.9-6 GHz (20.0%) and 8.6-9 GHz (6.3%), respectively. Three absorption bands with 48.4%, 25.7%, and 22.0% fractional bandwidths are also achieved.

INDEX TERMS Multi-band, wide-band, rasoerber.

I. INTRODUCTION

Frequency selective surfaces (FSSs) fabricated with all-dielectric [1], [2], all-metal [3], [4] and printed circuit boards (PCBs) [5]–[8] have been widely investigated for directivity improvement [9], beamsteering [10] and stealth [11] of antennas in recent years. Analytic methods based on the design principles of filters [5], [6] and optimization approaches using intelligent algorithms [12]–[14] have also been applied in FSS designs. However, FSSs exhibit only monostatic stealth ability for the stealth radome applications due to their strong reflective characteristics out of the passband(s). Hence, absorptive frequency-selective transmission devices, namely rasoerbers, have also been proposed for the multistatic stealth of antennas [15]–[40].

Although three-dimensional (3D) rasoerbers [15]–[19] exhibit better transmission selectivity and wider absorption bandwidth compared with their two-dimensional (2D) counterparts, the 2D rasoerbers [20]–[40] composed of lateral resistive layer and frequency selective surface (FSS) have attracted more attention due to their compact geometry and convenience of manufacturing.

The associate editor coordinating the review of this manuscript and approving it for publication was Muhammad Zubair.
the requirements of multi-band applications, rasorbers with double and triple passbands were proposed, resulting in the corresponding A-T-A-T [37], A-T-A-T-A [38], A-T-A-T-A-T-A [39] and T-A-T-A-T-A [40] devices. The passbands of these rasorbers are achieved by combining several parallel resonant structures in both FSS and resistive layer, which can be potentially extended to other multi-band designs. However, the existing multi-band devices only exhibit narrow passbands that are not favored for multi-band antennas with wide operating band [42], [43].

Therefore, in this work the method to achieve wide passband(s) in a multi-band rasorber is proposed using high-order multi-band FSS and low-Q parallel resonator. Although several high-order multi-band FSSs have been previously reported [7], [8], a universal method of designing multi-band FSS with wide passband(s) has not been investigated. Hence, based on the theories of dual-behavior resonator filter [44], [45] and N-band resonator [46], a multi-band FSS design method is proposed, in which all the designed passbands exhibit second-order response. In addition, the wide passbands of existing rasorbers are achieved at higher frequencies of their operating bands [33]–[36]. Still, the wide passband may also be required at lower frequencies for dual-band antennas [42], [43]. Therefore, a parallel resonator consisting of spiral inductor and interdigital capacitor is proposed to achieve a wide passband at lower frequency. Moreover, the resultant dual-band rasorber with a wide passband at lower frequency and a narrow passband at higher frequency is fabricated and measured to verify the proposed method.

II. EQUIVALENT CIRCUIT MODEL ANALYSIS

A. EQUIVALENT CIRCUIT MODEL OF FREQUENCY SELECTIVE SURFACE

The equivalent circuit model (ECM) of the proposed N-band FSS is shown in Fig. 1(a). N (≥ 2) series L-C resonators are loaded in the first and third layers of FSS, and a single series $L_0-C_0$ resonator is loaded in the second layer. The resonant frequencies of each resonator are represented as $f_n$ (0 ≤ n ≤ N) where $f_n > f_{n+1}$.

In order to illustrate the operating mechanism of FSS, two equivalent transformations are implemented as shown in Fig. 1(a)-(c). Firstly, the transmission lines within the red dashed boxes of Fig. 1(a) are transformed into the π networks within the red dashed boxes of Fig. 1(b). By letting the ABCD matrices [41] of transmission line and π network equal to each other, $L_u$ and $C_u$ are derived as

$$L_u = hZ_0\sqrt{\mu_0\epsilon_0\epsilon_1}$$

(1)

and

$$C_u = \frac{h\sqrt{\mu_0\epsilon_0\epsilon_1}}{2Z_0}.$$  

(2)

$\mu_0$, $\epsilon_0$, and $Z_0$ are the permeability, permittivity, and characteristic impedance of free space, respectively. $\epsilon_1$ and $h$ are the relative permittivity and thickness of the dielectric substrates that are modeled as the transmission lines. Secondly, by ignoring the small capacitor $C_u$, the T network within the blue dashed box of Fig. 1(b) is transformed into the π network [41] within the blue dashed box of Fig. 1(c), where

$$Z_c = \frac{j\omega^2C_0L_u^2}{\omega^2L_0C_0} - 1$$

(3)

is inductive at frequencies above $f_0$ (i.e., $f > f_0$), and $\omega = 2\pi f$ is the angular frequency.

Since a series L-C resonator is capacitive (or inductive) below (or above) its resonant frequency, for $f_0 \leq f \leq f_1$ it is easy to know that in the green dashed boxes of Fig. 1(c), $C_u$ and $L_lC_l$ (i ≥ 1) are capacitive while $(2L_0+L_u)C_0/2$ is inductive. Thus, a transmission pole can be achieved when the reactances of capacitive and inductive parts cancel each other. Similarly for $f_n \leq f \leq f_{n+1}$ (1 ≤ n ≤ N − 1), $C_u$ and $L_lC_l$ (i ≥ n + 1) are capacitive while $L_lC_l$ (i ≤ n) and $(2L_0+L_u)C_0/2$ are inductive, resulting in other N − 1 transmission poles. Therefore, the circuits in the green dashed boxes of Fig. 1(c) are named N-band resonators (NBR), which are inductively coupled to each other to form an N-band FSS for $f_0 \leq f \leq f_N$.

It is worth noting that though N can be any integer greater than one theoretically, the number of passbands for a practical FSS is limited due to the size restriction of its unit cell. To demonstrate the performance of the proposed FSS, four examples (i.e. FSS I, II, III, and IV) are presented, and Fig. 2 gives the S-parameters of each FSS where the circuit parameters are optimized through manual tuning. As shown in Fig. 2(a)-(c), when $N = 2$ dual-band FSSs with adjustable transmission bandwidths is achieved. Fig. 2(d) indicates that when $N = 3$ a tri-band FSS is obtained. Hence, two or more passbands with second-order response can be achieved following the proposed method. Besides, in each case the transmission zeros induced by series $L_uC_n$ (0 ≤ n ≤ N) are observed on both sides of all passbands, which improves the roll-off performance of FSS and can potentially help to enhance the absorption bandwidth in rasorber design.
VOLUME 9, 2021

the transmission bandwidths of FSSs. Since parallel L-C resonator with low inductance and relatively high capacitance is realized by meander inductors. The lumped resistors are adjusted to match the air impedance conditions are set for the unit cell and Floquet Ports are used for excitations in full-wave simulation. Fig. 6 demonstrates the S-parameters of the FSS, in which the results achieved from calculation and simulation agree well with each other. The results reveal a wide passband (21.8 GHz to 26.4 GHz) and a narrow passband (3.7 GHz to 4.3 GHz). The S-parameters of the FSS, in which the results achieved from calculation and simulation agree well with each other.

The resitive layer whose ECM principle of the resistive layer presented in [39] and [40] can be extended to design rasorbers with two or more passbands. As examples, the resitive layer whose ECM is designed following [39] and the FSSs presented in Fig. 2(a)-(c) are used for rasorber design. The resultant ECM of the dual-band rasorber is shown in Fig. 3. In resistive layer, series L1-C1 is optimized to match the air impedance for the absorption of rasorber. Parallel Lp1-Cp1 and Lp2-Cp2 exhibit infinite impedances at their resonant frequencies. Thus, two passbands with low insertion loss of resistive layer are achieved. Since parallel L-C resonator with low (or high) Q-factor produces wide (or narrow) passband [41], the Q-factors of Lp1-Cp1 and Lp2-Cp2 are adjusted to match the transmission bandwidths of FSSs.

Fig. 4(a)-(c) give the calculated S-parameters of the proposed dual-band rasorbers where the circuit parameters are optimized through manual tuning. It is found that to achieve wide passband at lower frequency, the parallel L-C resonator with high inductance and relatively high capacitance is needed. Since there are few researches on the rasorber with wide passband at lower frequency of the operating band, rasorber I is chosen for the following design.

B. EQUIVALENT CIRCUIT MODEL OF RASORBER

The ECM principle of the resistive layer presented in [39] and [40] can be extended to design rasorbers with two or more passbands. As examples, the resistive layer whose ECM is designed following [39] and the FSSs presented in Fig. 2(a)-(c) are used for rasorber design. The resultant ECM of the dual-band rasorber is shown in Fig. 3. In resistive layer, series $R_L - L_C - C_0$ is optimized to match the air impedance for the absorption of rasorber. Parallel $L_{p1} - C_{p1}$ and $L_{p2} - C_{p2}$ exhibit infinite impedances at their resonant frequencies. Thus, two passbands with low insertion loss of resistive layer are achieved. Since parallel L-C resonator with low (or high) Q-factor produces wide (or narrow) passband [41], the Q-factors of $L_{p1} - C_{p1}$ and $L_{p2} - C_{p2}$ are adjusted to match the transmission bandwidths of FSSs.

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III. STRUCTURAL DESIGN AND FABRICATION

A. MODELING AND FULL-WAVE SIMULATION

To verify the proposed method, a single-polarized device following the ECM of rasorber I is designed. The unit cell structure of the corresponding FSS (i.e. FSS I) is shown in Fig. 5. In each layer, series L-C resonators are realized with rectangular patches and a pair of parallel strips are added in the middle layer to achieve $R_0$. Periodic boundary conditions are set for the unit cell and Floquet Ports are used for excitations in full-wave simulation. Fig. 6 demonstrates the S-parameters of the FSS, in which the results achieved from calculation and simulation agree well with each other. The results reveal a wide passband ($|S_{21}|\geq -1 \text{ dB}$) covering 4.64-5.92 GHz (24.2%) and a narrow passband within 8.31-8.8 GHz (5.7%).

Fig. 7 demonstrates the unit cell structure of rasorber I. The parallel strip capacitor in the center of resistive layer is $C_0$, and $L_0$ is realized by meander inductors. The lumped resistors

FIGURE 2. Performances of the proposed FSS predicted with ECM calculation. (a) FSS I with a wide passband at lower frequency and a narrow passband at higher frequency; ($L_p=3.7 \text{ nH}, C_p=0.9 \text{ pF}, L_1=12.8 \text{ nH}, C_1=0.04 \text{ pF}, L_2=6.0 \text{ nH}, C_2=0.04 \text{ pF}, h=1.5 \text{ mm}$). (b) FSS II with a narrow passband at lower frequency and a wide passband at higher frequency; ($L_p=8.2 \text{ nH}, C_p=0.3 \text{ pF}, L_1=18.7 \text{ nH}, C_1=0.06 \text{ pF}, L_2=6.6 \text{ nH}, C_2=0.03 \text{ pF}, h=1.7 \text{ mm}$). (c) FSS III with two wide passbands: ($L_p=9.3 \text{ nH}, C_p=0.4 \text{ pF}, L_1=20 \text{ nH}, C_1=0.05 \text{ pF}, L_2=4.4 \text{ nH}, C_2=0.05 \text{ pF}, h=2 \text{ mm}$). (d) FSS IV with three passbands: ($L_p=13.2 \text{ nH}, C_p=0.2 \text{ pF}, L_1=30 \text{ nH}, C_1=0.06 \text{ pF}, L_2=20 \text{ nH}, C_2=0.02 \text{ pF}, L_3=6.6 \text{ nH}, C_3=0.04 \text{ pF}, h=2 \text{ mm}$).

FIGURE 3. ECM of the dual-band rasorber.

FIGURE 4. S-parameters of (a) rasorber I, ($R_p=220 \Omega, L_p=10 \text{ nH}, C_p=0.09 \text{ pF}, L_1=10 \text{ mm}, L_{p1}=5.2 \text{ nH}, C_{p1}=0.18 \text{ pF}, L_{p2}=0.6 \text{ nH}, C_{p2}=0.54 \text{ pF}$) (b) rasorber II, ($R_p=280 \Omega, L_p=12 \text{ nH}, C_p=0.06 \text{ pF}, L_1=10 \text{ mm}, L_{p1}=2.3 \text{ nH}, C_{p1}=0.67 \text{ pF}, L_{p2}=4 \text{ nH}, C_{p2}=0.1 \text{ pF}$) and (c) rasorber III. ($R_p=260 \Omega, L_p=13 \text{ nH}, C_p=0.06 \text{ pF}, L_1=10 \text{ mm}, L_{p1}=7.3 \text{ nH}, C_{p1}=0.2 \text{ pF}, L_{p2}=5.3 \text{ nH}, C_{p2}=0.09 \text{ pF}$).

FIGURE 5. Unit cell structure of FSS I ($w_1=5 \text{ mm}, w_2=4.5 \text{ mm}, w_3=3.9 \text{ mm}, w_4=14 \text{ mm}, g_1=3.6 \text{ mm}, g_2=4 \text{ mm}, g_3=0.2 \text{ mm}, s_1=1 \text{ mm}, D=16 \text{ mm}$).
R. Li et al.: Method for Designing Multi-Band Rasorbers for Wideband Applications

FIGURE 6. Comparison between simulated and calculated results of FSS I.

FIGURE 7. Unit cell structure of rasorber I. ($d_1=4.45$ mm, $d_2=2$ mm, $d_3=2.25$ mm, $w_5=4.4$ mm, $w_6=0.2$ mm, $w_7=2.9$ mm, $w_8=0.15$ mm, $w_9=0.15$ mm, $s_2=0.5$ mm, $t_1=10$ mm, $t_2=0.254$ mm, $D_1=0.65$ mm, $D_0=1.25$ mm).

$R_s$ are loaded between $C_s$ and $L_s$. A commonly used interdigital resonator with high Q-factor is adopted to realize $L_{p2}-C_{p2}$. Since spiral inductor and interdigital capacitor exhibit relatively high inductance and capacitance densities among the printed lumped elements, respectively [47], a resonant structure consisting of rectangular spiral inductor and interdigital capacitor is proposed to realize $L_{p1}-C_{p1}$, which attains low Q-factor and low resonant frequency. The dimension of spiral inductors can be estimated as [48]

$$L(nH)=6.35 \times 10^6 \times \mu_0 n_t^2 D_{av} \left[ \frac{2.07}{\rho} + 0.18 \rho + 0.13 \rho^2 \right], \tag{4}$$

where

$$\rho = \frac{D_0 - D_i}{D_0 + D_i}, \tag{5}$$

$$D_{av} = 0.5 \times (D_0 + D_i), \tag{6}$$

and $n_f$ is the number of turns. The dimension of interdigital capacitor can be estimated as [47]

$$C(pF)= (\epsilon_r + 1) [n_f (n_f - 3)4.4 + 9.9] \times 10^{-3}, \tag{7}$$

where $l$ and $n_f$ are the length and number of fingers.

Fig. 8(a) and (b) give the simulated S-parameters of the proposed rasorber under different oblique EM wave incidence. It is found that the transmission/absorption performances of rasorber remain stable below 7 GHz for incident angle $\leq 40^\circ$. Although the transmission band is reduced with the increase of incident angle at higher frequencies, a narrow transmission band is still observed under an incident angle of $40^\circ$. Moreover, the current distributions of resistive layer are demonstrated in Fig. 9 to provide a better understanding of the operation mechanism of the proposed device [49]. Within two transmission bands, e.g., 5.2 and 8.5 GHz, strong resonant currents are observed around the parallel LC structures. Hence, transmission bands with low insertion loss are achieved. Within the absorptin bands, e.g., 10 GHz, strong surface currents are observed around the lumped resistors, resulting in efficient EM energy absorption.

B. FABRICATION AND MEASUREMENT

As shown in Fig. 10(a)-(d), the rasorber consisting of $15 \times 15$ unit cells with an overall dimension of $240 \times 240$ mm$^2$ is
TABLE 1. Measured performance comparison.

| Ref.      | Order of A$^1$/T$^2$ | BW$^3_{T}$ (GHz) | BW$^4_{A}$ | RT$^5_{FSS}$ | Polarization |
|-----------|----------------------|------------------|------------|--------------|--------------|
| [37]      | A-T-A-T              | N/A              | 43.7%+     | 37.7%+       | Single-order | Single       |
| [38]      | A-T-A-T              | 5.85-6.72 (13.8%)| 32.7%+     | 18.6%+       | Single-order | Dual         |
| [39]      | A-T-A-T-A            | 8.97-9.30 (3.6%) | 56.9%+     | 6.4%+        | Single-order | Dual         |
| [40]      | T-A-T-A-A            | 6.08-6.15 (1.1%) | 8.0%+      | 6.8%+        | Single-order | Single       |
| This work | A-T-A-T-A            | 4.90-5.98 (20.0%)| 48.4%+     | 25.7%+       | Second-order | Single       |

$^1$A = absorption band; $^2$T = transmission band; $^3$BW$^3_{T}$ = -1 dB transmission bandwidth; $^4$BW$^4_{A}$ = 80% absorption bandwidth; $^5$RT$^5_{FSS}$ = response type of FSS.

FIGURE 11. S-parameters of rasorber I under normal incidence.

Taconic RF-35 ($\varepsilon_r = 3.5$, $t_an\sigma = 0.0025$) are used for resistive layer and FSS, respectively. The thickness of whole device is 13.3 mm. Free-space measurement [50] shown in Fig. 10(e) and (f) are carried out to test the frequency response of the proposed device.

Fig. 11 gives the S-parameters of rasorber achieved from full-wave simulation and free-space measurement. The simulation results indicate that the device exhibits wave transmission ($|S_{21}| \geq -1$ dB) within 4.74-5.75 GHz and 8.3-8.69 GHz, and 80% wave absorption within 2.63-3.85, 6.19-7.88, and 9.15-11.06 GHz. Good agreements are achieved between measured and simulated results at low-frequency band, while a frequency shift is observed at higher frequencies. This might because of the manufacturing and measuring errors that are more sensitive at higher frequencies.

The measured performances of the proposed rasorber and other existing multi-band rasorbers are summarized in Table 1. It can be seen that the proposed method enables a rasorber with both wide (20%) and narrow (6.3%) transmission bands. The device also exhibits 96.1% fractional absorption bandwidth thanks to the improved roll-off performance of the NBR-based FSS.
IV. CONCLUSION

In this work, the method for achieving wide passband(s) in multi-band rasorber is proposed. A convenient approach for multi-band FSS design is presented by coupling two N-band resonators. In addition, a spiral-interdigital resonator with low Q-factor and low resonant frequency is designed to realize the wide passband at lower frequency of the operating band. A dual-band rasorber with both wide and narrow passbands is designed and fabricated to validate the proposed method. This method can be potentially used in other multi-band rasorber designs to fulfill the stealth requirements of antennas with diverse operating bands.

REFERENCES

[1] T. Hayat, M. U. Afzal, A. Labbakhsh, and K. P. Esselle, “Additively manufactured perforated superstrate to improve directive radiation characteristics of electromagnetic source,” IEEE Access, vol. 7, pp. 153445–153452, 2019.

[2] T. Hayat, M. U. Afzal, A. Labbakhsh, and K. P. Esselle, “3-D-printed phase-rectifying transparent superstrate for resonant-cavity antenna,” IEEE Antennas Propag. Lett., vol. 18, no. 7, pp. 1400–1404, Jul. 2019.

[3] A. Labbakhsh, M. U. Afzal, K. P. Esselle, and S. L. Smith, “Low-cost nonuniform metallic lattice for rectifying aperture near-field of electromagnetic bandgap resonator antennas,” IEEE Trans. Antennas Propag., vol. 68, no. 5, pp. 3328–3335, May 2020.

[4] D. Ferreira, I. Cuinas, R. J. S. Caldeirinha, and T. R. Fernandes, “3-D mechanically tunable square slot FSS,” IEEE Trans. Antennas Propag., vol. 65, no. 1, pp. 242–250, Jan. 2017.

[5] M. A. Al-Joumayly and N. Behdad, “A generalized method for synthesizing low-profile, band-pass frequency selective surfaces with non-resonant constituting elements,” IEEE Trans. Antennas Propag., vol. 58, no. 12, pp. 4033–4041, Dec. 2010.

[6] N. Behdad and M. A. Al-Joumayly, “A generalized synthesis procedure for low-profile, frequency selective surfaces with odd-order bandpass responses,” IEEE Trans. Antennas Propag., vol. 58, no. 7, pp. 2460–2464, Jul. 2010.

[7] M. Yan, S. Qu, J. Wang, A. Zhang, L. Zheng, Y. Pang, and H. Zhou, “A miniaturized dual-band FSS with second-order response and large band separation,” IEEE Antennas Wireless Propag. Lett., vol. 14, pp. 1602–1605, 2015.

[8] M. Yan, J. Wang, H. Ma, M. Feng, Y. Pang, S. Qu, J. Zhang, and L. Zheng, “A tri-band, highly selective, bandpass FSS using cascaded multilayer loop arrays,” IEEE Trans. Antennas Propag., vol. 64, no. 5, pp. 2046–2049, May 2016.

[9] A. Labbakhsh and K. P. Esselle, “Directivity improvement of a Fabry–Pérot cavity antenna by enhancing near field characteristics,” in Proc. 17th Int. Symp. Antenna Technol. Appl. Electromagn. (ANTEM), Jul. 2016, pp. 1–2.

[10] P. Das, K. Mandal, and A. Labbakhsh, “Single-layer polarization-insensitive frequency selective surface for beam reconfigurability of monopole antennas,” J. Electromagn. Waves Appl., vol. 34, no. 1, pp. 86–102, Nov. 2019.

[11] B. A. Munk, Frequency Selective Surfaces. Hoboken, NJ, USA: Wiley, 2000.

[12] A. Labbakhsh, M. U. Afzal, K. P. Esselle, and B. A. Zeb, “Multi-objective particle swarm optimization for the realization of a low profile bandpass frequency selective surface,” in Proc. Int. Symp. Antennas Propag. (I&SP), 2015, pp. 1–4.

[13] A. Labbakhsh, M. U. Afzal, K. P. Esselle, and S. Smith, “Design of an artificial magnetic conductor surface using an evolutionary algorithm,” in Proc. Int. Conf. Electromagn. Adv. Appl. (ICEAA), Sep. 2017, pp. 885–887.

[14] A. Labbakhsh, M. U. Afzal, and K. P. Esselle, “Multiobjective particle swarm optimization to design a time-delay equalizer metasurface for an electromagnetic band-gap resonator antenna,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 912–915, 2017.

[15] B. Li and Z. Shen, “Wideband 3D frequency selective rasorber,” IEEE Trans. Antennas Propag., vol. 62, no. 12, pp. 6536–6541, Dec. 2014.

[16] A. A. Omar, Z. Shen, and H. Huang, “Absorptive frequency-selective reflection and transmission structures,” IEEE Trans. Antennas Propag., vol. 65, no. 11, pp. 6173–6178, Nov. 2017.

[17] Y. Zhang, B. Li, L. Zhu, Y. Tang, Y. Chang, and Y. Bo, “Frequency selective rasorber with low insertion loss and dual-band absorptions using planar slotline structures,” IEEE Antennas Wireless Propag. Lett., vol. 17, no. 4, pp. 633–636, Apr. 2018.

[18] Z. Shen, J. Wang, and B. Li, “3-D frequency selective rasorber: Concept, analysis, and design,” IEEE Trans. Microw. Theory Techn., vol. 64, no. 10, pp. 3087–3096, Oct. 2016.

[19] Y. Yu, Z. Shen, T. Deng, and G. Luo, “3-D frequency-selective rasorber with wide upper absorption band,” IEEE Trans. Antennas Propag., vol. 65, no. 8, pp. 4363–4367, Aug. 2017.

[20] 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.

[21] W. Yu, G. Q. Luo, Y. Yu, Y. Pan, W. Cao, Y. Pan, and Z. Shen, “Dual-polarized band-absorptive frequency selective rasorber using meander-line and lumped resistors,” IEEE Trans. Antennas Propag., vol. 67, no. 2, pp. 1318–1322, Feb. 2019.

[22] X. Chen, Y. Li, Y. Fu, and N. Yuan, “Design and analysis of lumped resistor loaded metamaterial absorber with transmission band,” Opt. Exp., vol. 20, no. 27, pp. 28347, Dec. 2012.

[23] Q. Chen, S. Yang, J. Bai, and Y. Fu, “Design of absorptive/transmissive frequency-selective surface based on parallel resonance,” IEEE Trans. Antennas Propag., vol. 65, no. 9, pp. 4897–4902, Sep. 2017.

[24] M. Guo, Z. Sun, D. Sang, J. Xing, and Y. Fu, “Design of frequency-selective rasorbers based on centrosymmetric bended-strip resonator,” IEEE Access, vol. 7, pp. 24964–24970, 2019.

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

[26] Q. Guo, Z. Li, J. Su, L. Y. Yang, and J. Song, “Dual-polarization absorptive/transmissive frequency selective surface based on tripoles elements,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 5, pp. 961–965, May 2019.

[27] Q. Yu, S. Liu, A. Monorchio, X. Kong, Y. Wen, and Z. Huang, “A miniaturized high-selectivity frequency selective rasorber based on subwavelength resonance and interdigital resonator,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 9, pp. 1833–1837, Sep. 2019.

[28] Y. Wang, S.-S. Qi, Z. Shen, and W. Wu, “Tunable frequency-selective rasorber based on varactor-embedded square-loop array,” IEEE Access, vol. 7, pp. 115552–115559, 2019.

[29] L. Wu, S. Zhong, J. Huang, and T. Liu, “Broadband frequency-selective rasorber with varactor-tunable interabSORbed band transmission window,” IEEE Trans. Antennas Propag., vol. 67, no. 9, pp. 6039–6050, Sep. 2019.

[30] Y. Han, W. Che, X. Xiu, W. Yang, and C. Christopoulos, “Switchable low-profile broadband frequency-selective rasorber/absorber based on slot arrays,” IEEE Trans. Antennas Propag., vol. 65, no. 12, pp. 6992–7008, Dec. 2017.

[31] G. Qian, J. Zhao, X. Ren, K. Chen, T. Jiang, Y. Feng, and Y. Liu, “Switchable broadband dual-polarized frequency-selective Rasorber/Absorber,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 12, pp. 2508–2512, Dec. 2019.

[32] S. C. Bakshi, D. Mitra, and F. L. Teixeira, “FSS-based fully reconfigurable rasorber with enhanced absorption bandwidth and simplified bias network,” IEEE Trans. Antennas Propag., vol. 68, no. 11, pp. 7370–7381, Nov. 2020.

[33] X. Sheng, X. Gao, and N. Liu, “Design of frequency selective rasorber with wide transmission/absorption bands,” J. Phys. D, Appl. Phys., vol. 53, no. 9, pp. 09LT01, Dec. 2019.
M. Guo, Q. Chen, Z. Sun, D. Sang, and Y. Fu, “Design of dual-band frequency-selective rasorber,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 5, pp. 841–845, May 2019.

X. Zhang, W. Wu, J. Huang, W. Zhang, Y. Ye, and N. Yuan, “Dual-polarized frequency selective rasorber with two transmission bands,” IEEE Access, vol. 7, pp. 139795–139801, 2019.

M. Guo, Q. Chen, D. Sang, Y. Zheng, and Y. Fu, “Dual-polarized dual-band frequency selective rasorber with low insertion loss,” IEEE Antennas Wireless Propag. Lett., vol. 19, no. 1, pp. 148–152, Jan. 2020.

Q. Zhou, M. Guo, H. Moghadas, Z. Wu, P. Liu, and M. Daneshmand, “A frequency selective rasorber with three transmission bands and three absorption bands,” IEEE Access, vol. 7, pp. 160973–160981, 2019.

D. M. Pozar, Microwave Engineering, Hoboken, NJ, USA: Wiley, 2011.

C.-N. Chiu and W.-H. Chuang, “A novel dual-band spiral antenna for a satellite and terrestrial communication system,” IEEE Antennas Wireless Propag. Lett., vol. 8, pp. 624–626, 2009.

M. Zou and J. Pan, “Wide dual-band circularly polarized stacked rectangular dielectric resonator antenna,” IEEE Antennas Wireless Propag. Lett., vol. 15, pp. 1140–1143, 2016.

A. Manchec, C. Quendo, J.-F. Favenec, E. Riis, and C. Person, “Synthesis of capacitive-coupled dual-behavior resonator (CCDBR) filters,” IEEE Trans. Microw. Theory Techn., vol. 54, no. 6, pp. 2346–2355, Jun. 2006.

W. Feng, X. Ma, Y. Shi, S. Shi, and W. Che, “High-selectivity Narrow and wide-band input–reflectionless bandpass filters with interconnected dual-behavior resonators,” IEEE Trans. Plasma Sci., vol. 48, no. 2, pp. 446–454, Feb. 2020.

C. Quendo, A. Manchec, Y. Clavet, E. Riis, J.-F. Favenec, and C. Person, “General synthesis of N-band resonator based on N-order dual behavior resonator,” IEEE Microw. Wireless Compon. Lett., vol. 17, no. 5, pp. 337–339, May 2007.

I. J. Bahl, Lumped Elements for RF and Microwave Circuits, Norwood, MA, USA: Artech House, 2003.

S. S. Mohan, M. del Mar Hershenson, S. P. Boyd, and T. H. Lee, “Simple accurate expressions for planar spiral inductances,” IEEE J. Solid-State Circuits, vol. 34, no. 10, pp. 1419–1424, Oct. 1999.

A. Lalbakhsh, S. M. Alizadeh, A. Ghaderi, A. Golestanifar, B. Mohamadzade, M. B. Jamshidi, K. Mandal, and W. Mohyuddin, “A design of a dual-band bandpass filter based on modal analysis for modern communication systems,” Electronics, vol. 9, no. 11, p. 1770, Oct. 2020.

S. C. Bakshi, D. Mitra, and S. Ghosh, “A frequency selective surface based reconfigurable rasorber with switchable transmission/reflection band,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 1, pp. 29–33, Jan. 2019.

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