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Comparative Study of Slotless and Slotted Feedline Microstrip Patch Antennas for Multiband Millimetre-Wave Operation

Shahad D. Sateaa[1], Alaa Mohammed Abbas[2*], Sura M. J. Saied[3]
[1,3] Department of Unmanned Aerial Vehicle Engineering, Al-Nahrain University, Baghdad- Iraq
[2]Department of Chemical Engineering, Al-Nahrain University, Baghdad- Iraq

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ABSTRACT

Modern communication systems, such as fifth-generation (5G) networks, require antennas with a simple structure, lightweight, and high gain to achieve efficient performance. However, designing compact and effective antennas capable of working in the millimeter-wave (mmWave) band with multiband capability remains a challenge. This paper presents the design and simulation of two ultra-compact rectangular microstrip patch antennas with feedline transmission, fabricated on a compact Rogers RT5880 (lossy) substrate with a small size (1.52 mm×2 mm). The first design (RMSPA-I) is a traditional rectangular patch antenna without a slot, while the second (RMSPA-II) is incorporates an H-shaped slot on the patch plane and a slot on the ground plane to improve performance. Both designs achieve multiband operation, with RMSPA-I resonating at (2.3GHz and 95.3GHz), and RMSPA-II resonating at (2.3GHz, 73.5GHz, and 88.5GHz). The proposed designs demonstrate improved gain, VSWR, and return loss compared to existing works, while maintaining ultra-compact dimensions suitable for modern mmWave communication systems, including 5G and beyond.

Corresponding Author:

Shahad Dhari Sateaa
Department of Unmanned Aerial Vehicle Engineering, Al-Nahrain University
Baghdad, Iraq
Email: shahad.dhari@nahrainuniv.edu.iq

1. INTRODUCTION

The rapid evolution of wireless technologies, including mobile networks, satellite navigation systems, and microwave sensors, has created an increasing demand for antennas that combine compact dimensions, low weight, and cost-effectiveness with high efficiency and multiband functionality. These challenges have made microstrip antennas particularly attractive due to their inherently low profile, ease of manufacture, and compatibility with integrated circuits. However, achieving optimal performance across multiple frequency bands while maintaining a miniaturized form factor continues to pose a significant design challenge. Several techniques have been explored in the literature to realize multiband and high-efficiency microstrip antennas [1-6]. These include incorporating additional radiating elements within the patch [7-9], etching notches or slots in the radiating surface (slotted antennas) antenna [10-12], and using monopole antenna (MA) configurations [13-16]. In particular, introducing slots into the patch or ground plane has been shown to significantly enhance the antenna's impedance bandwidth, return loss, VSWR, and gain [17-25]. Recent studies have proposed various designs to improve antenna performance while minimizing the overall dimensions. For example, the work in [17] presented a slotless RMSPA with dimensions (6.285mm × 7.235mm) operating at 28GHz. Similarly, [18] achieved a three-band operation at (70.9GHz, 35.5GHz, and 23.9GHz) using a slotless patch sized (2.59mm×3.65mm). Other studies, such as [19-25], introduced different slot shapes and configurations to further improve multiband performance, yet many of these designs still exhibited relatively large dimensions or limited efficiency.

In summary, while previous studies have explored multiband microstrip antennas with various slot configurations, many of these designs either compromise on overall efficiency or require relatively large physical dimensions. This work introduces two highly compact RMSPA designs with a footprint of only (1.52mm×2mm), fabricated on Rogers RT5880 (lossy) substrate. The first design (RMSPA-I) is a traditional slotless patch, while the second (RMSPA-II) incorporates H-shaped slots on the patch and a slot on the ground plane to further improve performance. The proposed antenna achieved multiband operation with improved gain, return loss, and VSWR compared to similar works reported in the literature.

2. ANTENNA DESIGN METHOD AND CONFIGURATION

The RMSPA designs are based on standard rectangular patch and feedline equations. The main substrate and design parameters are:

- Substrate Height (h) =0.1mm.
- Dielectric constant (εr) = 2.2.
- Input impedance (Rin) = 50Ω.
- Loss tangent =(0.0009)

The patch and feedline dimensions were calculated using the following well-known formulas [26-27]:

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (1)$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12\frac{h}{w}}} \quad (2)$$

$$\Delta L = 0.412\, h\, \frac{(\varepsilon_{reff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W}{h}+0.8\right)} \quad (3)$$

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L \quad (4)$$

$$W_S = W * 2 \quad (5)$$

$$L_S = L * 2 \quad (6)$$

$$L_f = 3.96 * W_f \quad (7)$$

$$W_f = \frac{2h}{\pi}\left\{B - 1 - \ln(2B-1) + \frac{\varepsilon_r-1}{2\varepsilon_r}\left[\ln(B-1) + 0.39 - \left(\frac{0.61}{\varepsilon_r}\right)\right]\right\} \quad (8)$$

$$B = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}} \quad (9)$$

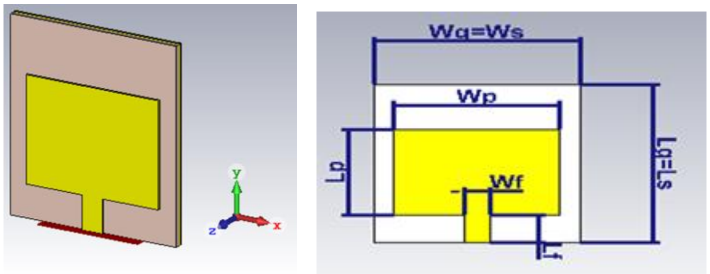
Where: W is the width of the patch, W_S is the width of the substrate, W_f is the width of the feed line, ΔL is the extension length, L is the actual length, L_S is the length of the substrate, L_f is the length of the feed line, ε_{reff} is the effective dielectric constant of MSPA, and εr is the substrate dielectric constant. These calculations defined the initial design parameters for both RMSPA-I and RMSPA-II, which are offered in the next section.

3. ANTENNA STRUCTURE AND DESIGN PARAMETERS

The two proposed antenna designs share the same footprint, substrate material, and feeding method, as described in Section 2. Both designs are fed using a microstrip line.

3.1 RMSPA-I: SLOTLESS DESIGN

The first design, RMSPA-I, is a traditional rectangular microstrip patch antenna printed over a ground plane. The patch is fed by a microstrip line, and no slots are included in the patch or ground. This simple configuration serves as a baseline to evaluate the benefits of introducing slots. The exhaustive measure of the RMSPA-I structure is recorded in Table 1, and the geometry of this design is illustrated in Figure 1.



(a) (b)

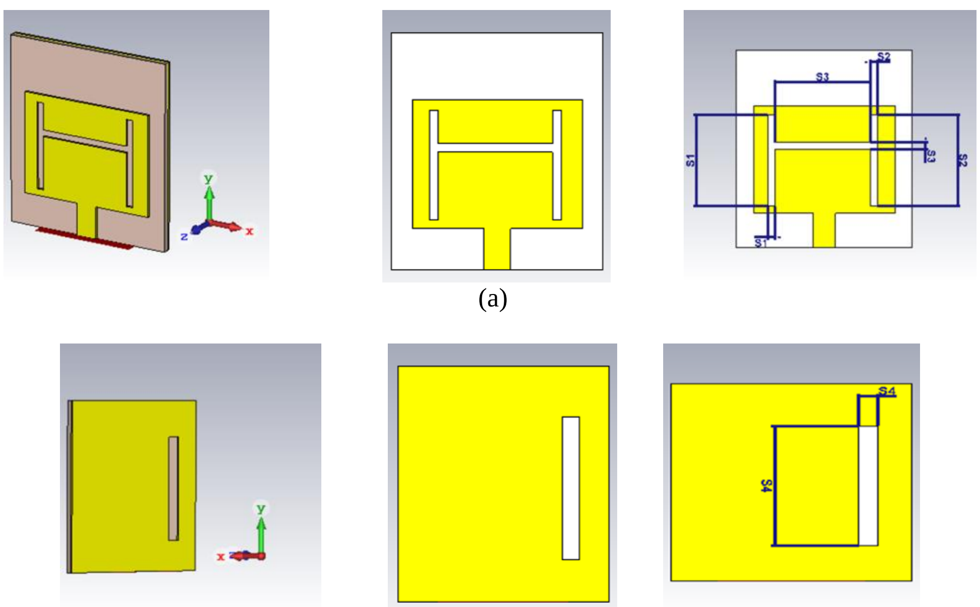
Figure 1. Rectangular microstrip patch feedline antenna RMSPA_I

Table 1. Optimized Design parameters of RMSPA

Parameter	Computed	Optimized
Patch width (W)	2.008mm	2mm
Patch length (L)	1.66 mm	1.52mm
Substrate width (W_S)	4.016 mm	2.5mm
Substrate length (L_S)	3.32 mm	2.5mm
Feedline width (W_f)	0.308mm	0.308mm
Feedline length (L_f)	0.456mm	0.487mm

3.2 RMSPA-II: H-SLOT AND GROUND-SLOT DESIGN

The second design, RMSPA-II, modifies the baseline geometry by etching an H-shaped slot on the patch plane. Additionally, a rectangular slot is introduced in the ground plane directly beneath the patch to further enhance multiband operation. These modifications are intended to develop the antenna's performance while maintaining the same compact size as RMSPA-I. The specific slot dimensions of RMSPA-II are summarized in Table 2, and Figure 2 displays the geometry of RMSPA-II.



(a)

(b)

Figure 2. RMSPA-II: (a) Front view; (b) Back view.

Table 2. Dimension of slots RMSPA_II

Slots Number	Dimension (mm)
S1	1.3×0.1
S2	1.3×0.1
S3	0.1×1.35
S4	1.7×0.2

4 SIMULATION RESULTS AND DISCUSSION

The presented antenna designs were simulated to evaluate their performance, using CST Microwave Studio for full-wave analysis. Several key performance metrics-such as gain, return loss, VSWR, and radiation pattern, were examined for both designs: RMSPA-I (without slot) and RMSPA-II with (H-shaped slots on the patch and slot on the ground).

4.1 RMSPA-I RESULTS

The first design, RMSPA-I, is a traditional rectangular microstrip patch antenna with a tiny size of (1.52mm×2mm). It exhibits dual-band operation with resonances at 2.3GHz and 95.3GHz, achieving return losses of -18.877dB and -37.48dB, respectively, as displayed in Figure 3. The Voltage Standing Wave Ratio values presented in Figure 4 are

1.2568 at 2.3GHz and equal to 1.0271 at 95.3GHz. The far-field radiation pattern and gain pattern are illustrated in Figures 5 and 6, showing a gain of approximately -49.05dBi at 2.3GHz and 6.336 dBi at 95.3GHz.

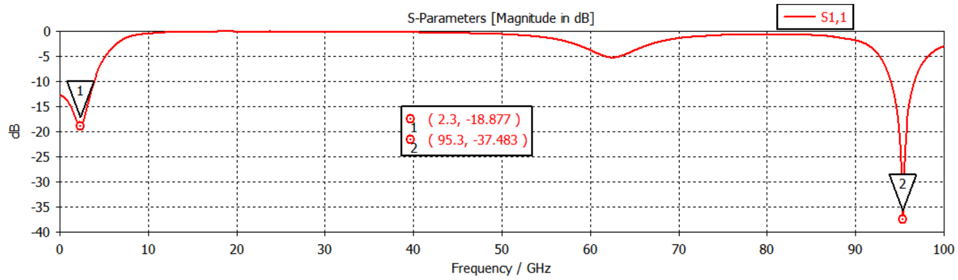


Figure 3. Return loss of RMSPA-I

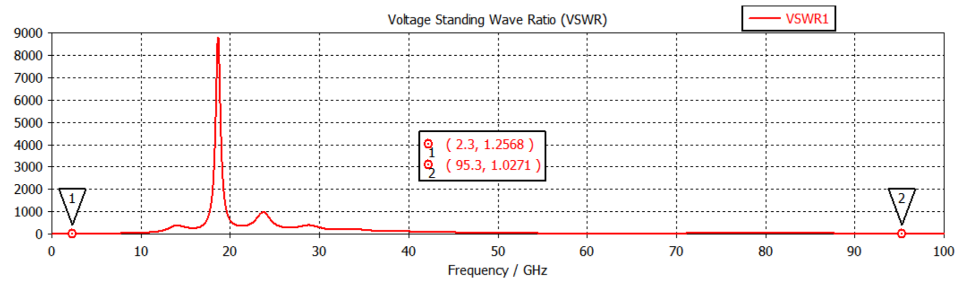


Figure 4. VSWR of RMSPA-I

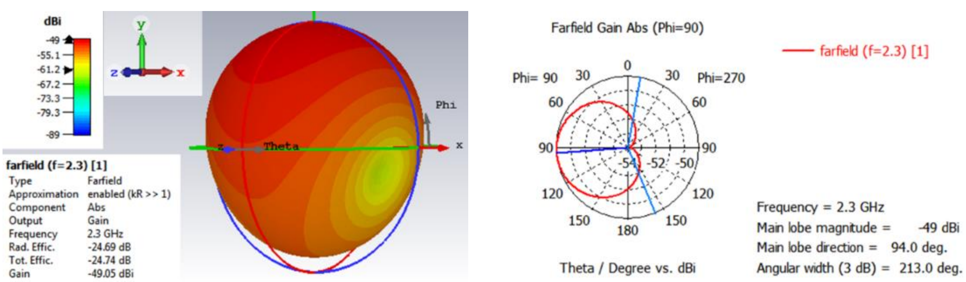


Figure 5. Radiation Properties of RMSPA-I Simulated at 2.3GHz

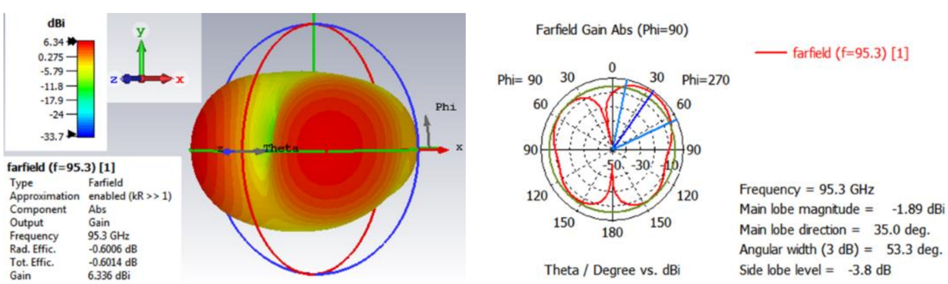


Figure 6. Radiation Properties of RMSPA-I Simulated at 95.3GHz

4.2 RMSPA-II RESULTS

The second design, RMSPA-II, integrates three H-shaped slots on the patch and one slot in the ground plane to enhance performance. This design also maintains the ultra-compact dimensions of (1.52mm×2mm) and achieves tri-band operation at (2.3GHz, 73.5GHz, and 88.5GHz), with return loss (-21.664dB, -44.117dB, and -13.095dB) respectively, as shown in Figure 7. The VSWR values are (1.18 at 2.3GHz), (1.0125 at 73.5GHz), and (1.5688 at 88.5GHz), as illustrated in Figure 8. The far-field radiation gain patterns for the three resonating frequencies are presented in Figures 9, 10, and 11, showing improvements compared to RMSPA-I, with gains of 50.20dBi at 2.3GHz, 4.316dBi at 73.5GHz, and 5.475dBi at 88.5GHz.

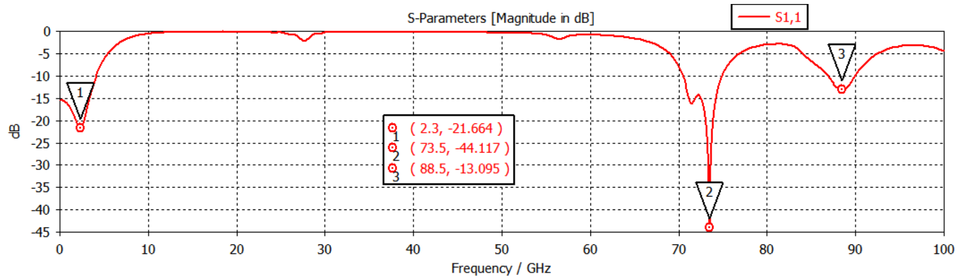


Figure 7. Return loss of RMSPA_II

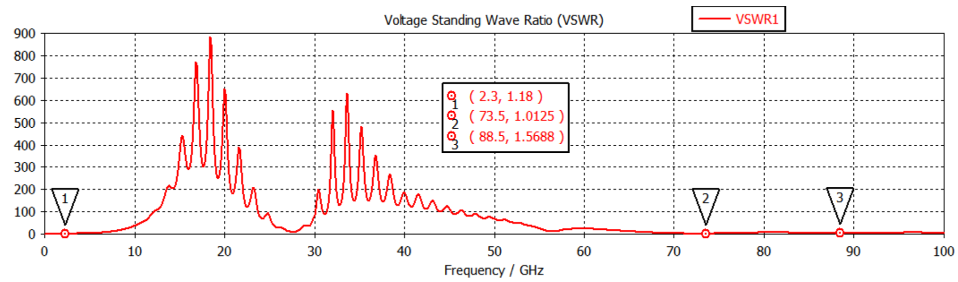


Figure 8. VSWR of RMSPA_II

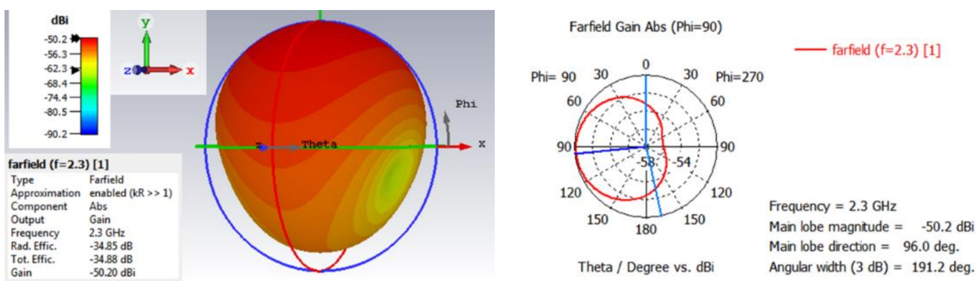


Figure 9. Radiation Properties of RMSPA-II Simulated at 2.3GHz

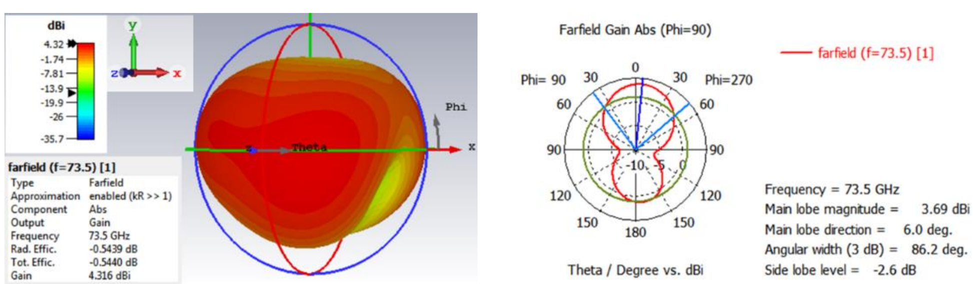


Figure 10. Radiation Properties of RMSPA-II Simulated at 73.5GHz

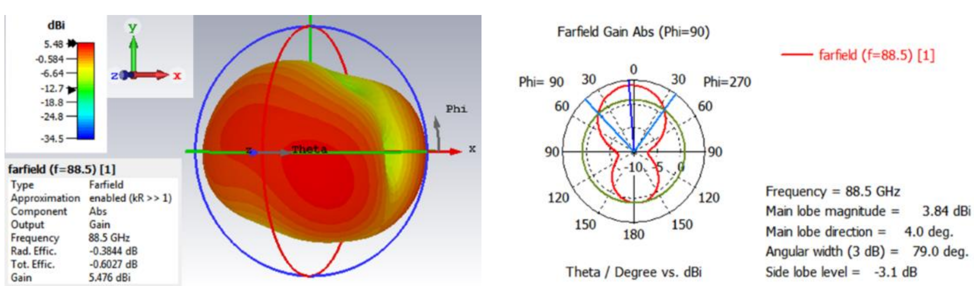


Figure 11. Radiation Properties of RMSPA-II Simulated at 88.5GHz

A detailed summary of the key performance parameters of both designs is provided in Table 3. The results demonstrate that adding H-shaped slots on the patch and one slot in the ground plane significantly improve the antenna's execution in terms of gain, return loss, and multiband operation while maintaining ultra-compact dimensions.

Table 3. Performance Parameters of RMSPA_II and RMSPA_I.

	Frequency	Return loss	VSWR	Gain (dBi)
RMSPA_I (without slots)	2.3 GHz	-18.877(dB)	1.2568	-49.05
	95.3 GHz	-37.483(dB)	1.0271	6.336
RMSPA_II (with slots)	2.3 GHz	-21.664(dB)	1.18	-50.20
	73.5 GHz	-44.117(dB)	1.0125	4.316
	88.5 GHz	-13.095(dB)	1.5688	5.475

5 COMPARISON WITH PREVIOUS WORKS

To assess the performance of the proposed designs, a comparison was made with related works reported in the literature. The conclusions of RMSPA-I and RMSPA-II are summarized alongside reference designs in Table 4, which highlights key parameters such as antenna dimension, resonating frequencies, VSWR, gain, and return loss. As shown in Table 4, RMASP-I A demonstrates competitive multiband performance at a significantly smaller footprint compared to previously reported spotless designs, demonstrating that acceptable efficiency can still be achieved without slotting. Meanwhile, RMSPA-II, which incorporates an H-shaped slot on the patch plane and an additional slot in the ground plane, achieves further enhancements in return loss and gain compared to existing slotted designs, while maintaining the same ultra-compact dimensions. These results confirm that the proposed designs successfully achieve both miniaturization and high efficiency, making them strong candidates for integration into modern mm-wave and multiband communication systems.

Table 4. Similarity with Previous Works

No. of Ref.	Size Plow	Frequency	Return loss	VSWR	Gain
[17]	(6.285×7.235) mm	27.954 GHz	-13.48(dB)	1.5376	6.63dBi
[18]	(2.59×3.65) mm	23.9 GHz 35.5 GHz 70.9GHz	-19.9737(dB) -22.7307 (dB) -21.9667(dB)	1.7483 1.2709 1.3881	4.435 dBi 3.6602 dBi 5.6402 dBi
[19]	(12.56×17.56)mm	1.635 GHz	-23.99(dB)	1.134	1.72 dBi
RMSPA_I	(1.52×2) mm	2.3 GHz 95.3 GHz	-18.877(dB) -37.483(dB)	1.2568 1.0271	-49.05 dBi 6.336 dBi
[19]	(12.56×17.56)mm	3.98GHz	-1557(dB)	1.399	2.85dBi
[20]	(2.16×3.26) mm	28GHz	-27.79(dB)	1.08	6.59dBi
[21]	(2.16×3.26)mm	28GHz	-39.37(dB)	1.022	6.37dBi
[22]	(22.6×39.9)mm	3.6GHz	-26(dB)	-	1.3dBi
[23]	(9.7×9.9)mm	10.04GHz 27.5GHz 37.8GHz	-13(dB) -23.5(dB) -10.5(dB)	-	-
[24]	(2.5×4)mm	73.7GHz	-39.9(dB)	-	6.08dBi
[25]	(6×6)mm	37GHz	-43.5(dB)	1.017	8.25dBi
RMSPA_II	(1.52×2) mm	2.3 GHz 73.5 GHz 88.5 GHz	-21.664(dB) -44.117(dB) -13.095(dB)	1.18 1.0125 1.5688	-50.20 dBi 4.316 dBi 5.475dBi

6 CONCLUSION:

Two ultra-compact rectangular microstrip patch antennas with feedline transmission, targeting multiband millimeter-wave applications. The first design employed a traditional patch without a slot (RMSPA-I), while the second (RMSPA-II) incorporates H-shaped slots on the patch plane and a slot on the ground plane to further improve performance. Both designs achieved notable multiband operation within a footprint of only (1.52 mm ×2 mm), with RMSPA-II showing superior return loss, gain, and impedance matching compared with RMSPA-I and other reported works. These results highlight the potential of the suggested designs for integration into compact, high-performance multiband communication systems.

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