



Design and Implementation of Trapezoidal Shaped Multiband Antenna for Sub-6 GHz 5G and wireless applications

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Abstract: In this article, a trapezoidal-shaped slotted multiband antenna is presented, incorporating a single-ring square metamaterial split-ring resonator (SRR) and a single-ring elliptical complementary split-ring resonator (CSRR). The proposed antenna design features a slotted radiating patch loaded with two SRR and one CSRR metamaterial cells, enabling it to resonate at five distinct frequency bands. These bands cover the Mobile Broadband Wireless Access (MBWA) protocols, 5G Sub-6 GHz NR frequency ranges, specifically n46/n47/n50/n51/n54/n96/n101/n102/n104, as well as the 3.35 GHz worldwide interoperability for microwave access (WiMAX), the 3.76-4.65 GHz Upper S band, the 5/5.8 GHz wireless local area network (WLAN), the 4.96-10.02 GHz C band, and the 10.35-15.96 GHz Upper X band for various wireless applications. The antenna, with compact dimensions of $36 \times 36 \times 1.6$ mm³, is fabricated to validate its simulated performance against measured results. The antenna demonstrates consistent radiation characteristics, gain, and efficiency across its resonant bands, which are essential for multi-standard wireless applications. It achieves an optimized peak gain of 4.51 dBi and a radiation efficiency of 88.92%.

Index Terms - 5G Sub-6 GHz NR Bands, Metamaterial cells, Slotted trapezoidal radiating patch, Wi-MAX, WLAN.

I. INTRODUCTION

The rapid growth of wireless communications has driven the need for 5G (fifth-generation) mobile technology, characterized by high data rates, reduced latency, energy efficiency, lower costs, and increased system capacity [1]. Within 5G mobile communication, the Sub-6 GHz band is defined to support various NR (New Radio)

bands, offering advanced features over 4G networks. The 5G frequency spectrum is categorized into two segments: frequencies below 6 GHz (FR1 NR bands) and those above 30 GHz (FR2) for wireless standards [2]. The transition from 4G to 5G has necessitated the exploration and development of planar multiband antenna designs [3–5]. Among these, frequency reconfigurable antennas for Sub-6 GHz 5G and WLAN applications remain an active area of research, with various design methodologies reported in [3]. A magneto-electric dipole antenna approach offering broadband performance and high front-to-back ratio (FBR) is discussed in [4], while a wideband multiple-input multiple-output (MIMO) antenna array design is proposed in [5] to enhance bandwidth and 5G NR band compatibility for mobile devices. Multiband functionality in antenna designs is often achieved through techniques such as slotting, metamaterial loading, and advanced feeding mechanisms [6–11]. Specifically, the integration of metamaterial cells like split-ring resonators (SRRs) and complementary split-ring resonators (CSRRs) enables multiband operation within compact antenna structures [12–15]. Fractalization is another approach used to introduce multiple resonant bands, catering to diverse wireless communication requirements [16, 33]. A hybrid design combining fractal techniques with metamaterial loading has been implemented to support multiple wireless standards [17–22, 34–35]. In [23], a slot-antenna array with wideband

performance and high isolation was designed on an FR4 substrate to cover the 5G NR bands N77/N78/N79. Similarly, a dual-band, low-profile, quad-port printed antenna for 5G applications was proposed in [24], utilizing the 3.3–3.8 GHz spectrum (n77 band) with a 10 dB impedance bandwidth, addressing critical requirements for fifth-generation wireless communication. The multi-unit wideband MIMO antenna array approach is well-suited for mobile devices aiming to enhance bandwidth and ensure compatibility with 5G NR communication bands [25–27]. A slot-antenna array, designed on an FR4 substrate, offers wideband operation and high isolation while supporting multiple resonating bands, achieving both gain and bandwidth enhancement [28–32].

This article introduces a novel trapezoidal-shaped slotted penta-band antenna, incorporating metamaterial loading and a trapezoidal-shaped partial ground plane. The antenna is designed to operate across multiple wireless standards, including Mobile Broadband Wireless Access (MBWA) protocols, 5G Sub-6 GHz NR frequency bands, WLAN, WiMAX, the C band, and the upper X-band. The design process begins by embedding an elliptic single

complementary split-ring resonator (ESCSRR) and rectangular slots into the trapezoidal-shaped radiating patch and ground plane. To further enhance performance, two square single split-ring resonators (SSSRs) are integrated into the patch, enabling the antenna to support a wide range of operational states. These include MBWA protocols (IEEE 802.20: 1.6–2.2 GHz), WiMAX (3.5 GHz), 5G Sub-6 GHz NR frequency bands (n46/n47/n50/n51/n54/n96/n101/n102/n104), WLAN (5.0/5.8 GHz), the C band (4–8 GHz), and upper X-band wireless applications.

II. ANTENNA GEOMETRICAL CALCULATIONS

This section details the design process of the proposed trapezoidal-shaped multiband antenna, which incorporates a slotted trapezoidal ground plane and a metamaterial loading technique. The antenna is constructed on an FR-4 dielectric substrate with dimensions of $36 \times 36 \times 1.6 \text{ mm}^3$. The substrate features a thickness of 1.6 mm, a dielectric constant (ϵ_r) of 4.4, and a loss tangent (δ) of 0.02. The evolution of the proposed penta-band antenna, inspired by metamaterial techniques, is illustrated in Figure 1, with corresponding S-parameter variations shown in Figure 2. Table 1 presents the various characteristics of the antenna design across design stages I to III.

Table 1. Evolutionary Development Stages of the Proposed Antenna

Design Steps	Formation of top and bottom section of antenna	Resonating band (in GHz)	Bandwidth (in %)	Modes of Wireless Applications achieved	Causes
I	Top part: Trapezoidal radiating section connected to a rectangular-shaped feedline Bottom part : Defected Trapezoidal Ground Structure (DGS)	Sim.: 3.01–15.38	Sim.: 134.53	No. of Applications – 1 Single band (UWB)	The wideband characteristics is achieved using a trapezoidal slotted radiating patch combined with a trapezoidal-shaped Defected Ground

					Structure (DGS).
II	Top part: Trapezoidal radiating section with elliptic single complementary split-ring resonator Bottom part : Defected Trapezoidal rectangular slotted Ground Structure (DGS)	Sim.: 1.44–2.31, 3.07–4.68, 5.12–15.16	Sim.: 46.40, 41.55, 99.01	No. of Applications – 3 Triple band (L, S, and C/X wireless communication bands)	The current perturbation effect is induced by the slotted patch area and the inclusion of an elliptic single complementary split-ring resonator along with slotted defected ground plane.
III	Top part: Trapezoidal radiating section with elliptic single complementary split-ring resonator and two square single split-ring resonators Bottom part : Defected Trapezoidal rectangular slotted Ground Structure (DGS)	Sim.: 1.29–2.28, 2.99–3.54, 3.76–4.65, 4.96–10.02, 10.35–15.96	Sim.: 55.46, 16.84, 21.16, 67.55, 42.64	No. of Applications – 5 Penta a band (5G Sub-6 GHz NR Bands, L - band, Middle/Upper S - band, Lower C - band, WiMAX/WLAN, and Upper X - band)	The slotted trapezoidal patch structure incorporating a single complementary split-ring resonator and attached with two square single split-ring resonators, is connected to a rectangular feedline and a trapezoidal slotted defected ground plane. This configuration induces current perturbations and negative permeability characteristics, enabling a penta-band resonating state suitable for 5G NR bands and other wireless applications.

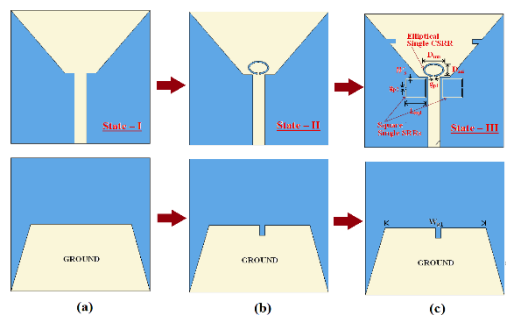


Figure 1. Design of evolutionary stages of the proposed antenna. (a) Antenna 1, (b) Antenna 2, (c) Proposed antenna.

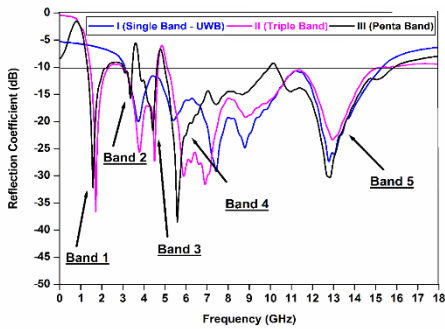


Figure 2. Simulated S_{11} of the evolutionary stages of antenna.

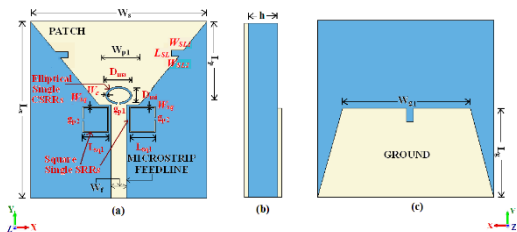


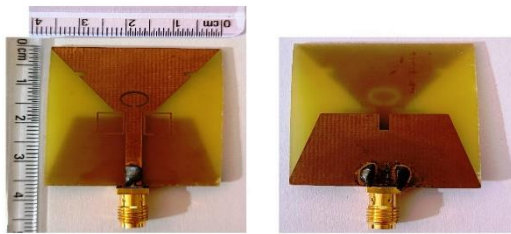
Figure 3. Antenna Geometry: (a) Front, (b) Side, (c) Back view.

Through the design evolution, the optimized radiating structure incorporates a metamaterial-inspired slotted trapezoidal patch and a trapezoidal partial ground plane. The antenna geometry, including its front, back, and side views, is illustrated in Figure 3, with the optimized dimensions (in millimeters) provided in Table 2. Simulations and

performance characterization were conducted using CST Microwave Studio (MWS) [36]. The fabricated prototype of the proposed antenna is shown in Figures 4(a) and 4(b).

Table 2.Optimized dimensions of the proposed antenna.

Sr.No.	Parameter	Dimension (mm)
1	L_s	36
2	W_s	36
3	h	1.6
4	L_p	17
5	W_{p1}	8
6	W_f	3.12
7	W_{g1}	24
8	L_g	18
9	D_{ma}	3.1
10	D_{mi}	2.2
11	W_e	0.7
12	g_{p1}	0.5
13	L_{sq1}	5.5
14	W_{sq}	0.2
15	g_{p2}	0.5
16	L_{SL}	1
17	W_{SL1}	2.1
18	W_{SL2}	1.3



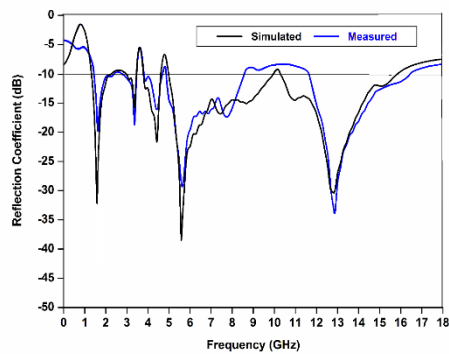
(a)

(b)

Figure 4. Fabricated prototype of proposed antenna: (a) front, (b) back.

The measurement procedure is conducted using a far-field measurement system within an anechoic chamber. During simulation, the antenna demonstrated five operating modes based on $S_{11} < -10$ dB impedance bandwidths, achieving bandwidths of approximately 990 MHz (1.29–2.28 GHz, 55.46%), 550 MHz (2.99–3.54 GHz, 16.84%), 890 MHz (3.76–4.65 GHz, 21.16%), 5060 MHz (4.96–

10.02 GHz, 67.55%), and 5610 MHz (10.35–15.96 GHz, 42.64%). Experimental measurements revealed corresponding bandwidths of 880 MHz (1.35–2.23 GHz, 49.16%), 540 MHz (2.96–3.50 GHz, 16.72%), 860 MHz (3.76–4.62 GHz, 20.52%), 3730 MHz (4.89–8.62 GHz, 55.22%), and 4580 MHz (11.96–16.54 GHz, 32.14%). These results are illustrated in Figure 5 and summarized in Table 3.

**Figure 5.** Simulated and measured S_{11} of the proposed design.**Table 3.** Analysis of the achieved operating bands.

Sr. No.	Operating Modes (in GHz)		Bandwidth (in %)		Microwave bands	Wireless Applications
	Sim.	Exp.	Sim.	Exp.		
1	1.29–2.28	1.35–2.23	55.46%	49.16%	(i) L band	Military telemetry, GPS, mobile phones (GSM)(1.61 GHz)
					(ii) 5G NR bands	n50 (1.432-1.517 GHz), n51 (1.427-1.432 GHz), n54 (1.670-1.675 GHz), n39 (1.880-1.920 GHz), n101 (1.900-1.910 GHz)
2	2.99–3.54	2.96–3.50	16.84%	16.72%	Middle S band	Worldwide Interoperability for Microwave Access (3.35 GHz)
3	3.76–4.65	3.76–4.62	21.16%	20.52%	Upper S band	Weather radar, surface ship radar, amateur radio
4	4.96–10.02	4.89–8.62	67.55%	55.22%	(i) C band	Wireless Local Area Network (5.0/5.8 GHz, IEEE 802.11a/j)

					(ii) 5G NR bands	n46 (5.150-5.925 GHz), n47 (5.855-5.925 GHz), n96 (5.925-7.125 GHz), n102 (5.925-6.425 GHz), n104 (6.425-7.125 GHz)
5	10.35–15.96	11.96–16.54	42.64%	32.14%	Upper X- Band	Terrestrial Broadcast, Radar Communication, Space Communication

2.1 Metamaterial Square Single Split-ring Resonator (SSSR)

The proposed metamaterial SRR cell, shown in Figure 6(a), consists of a single square metallic ring with a split gap. To confirm the metamaterial characteristics of the proposed SRR cell, a waveguide setup is established for experimental analysis. This setup is achieved by implementing an electric (PEC) and magnetic (PMC) boundary environment, as illustrated in Figure 6. Electromagnetic waves are transmitted from one port to another, passing through the SRR structure. As the E-field induces a potential difference across the split

gap, a surface current is generated, which subsequently produces a magnetic field. This configuration enables the measurement of S-parameters (S_{11} and S_{21}), as shown in Figure 6(a), allowing for the determination of the effective dielectric parameters (μ_{eff} and ϵ_{eff}). The electrical equivalent circuit, comprising R, L, and C components, is depicted in Figure 6(b) and described in [37]. For practical validation, the SRR cell is inserted into a waveguide arrangement, and S-parameters (S_{11} and S_{21}) are measured using a Vector Network Analyzer (VNA) [37–38].

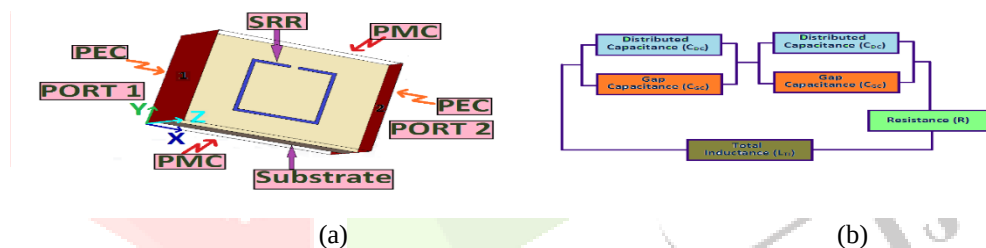


Figure 6. (a) Waveguide setup, (b) an equivalent model.

As illustrated in Figure 6(a), the magnetic environment is configured to pass through the SRR structure, inducing an electromagnetic field (EMF) coupled with the square metallic ring. This interaction generates a conducting current that flows along the outer metallic ring and across the split gap, creating a capacitive effect (distributed capacitance). This setup establishes a resonating condition, with the resonant frequency determined as follows [38]:

$$f_{re} = \frac{1}{2\pi\sqrt{L_{to-eq} C_{to-eq}}} \quad (1)$$

Where, L_{to-eq} = total equivalent inductance and C_{to-eq} = total equivalent capacitance. The effective medium permeability of the SRR structure [39] is described by the following equation:

$$\mu_{\text{ef}} = n_{re} \times Z_{im} \quad (2)$$

where n_{re} = Refractive index and Z_{im} = Impedance. Figure 7 presents the graphical representation of the S-parameters (S_{11} and S_{21}) obtained using the proposed setup shown in Figure 6(a). The graph highlights the passband behavior of the cell at 3.35 GHz. The Nicolson-Ross-Weir method [39] is applied to derive the permeability (μ) characteristics, as depicted in Figure 8. At 3.35 GHz, the real values of μ are negative, confirming that the SRR exhibits single-negative material properties, demonstrating metamaterial characteristics, as shown in Figure 8.

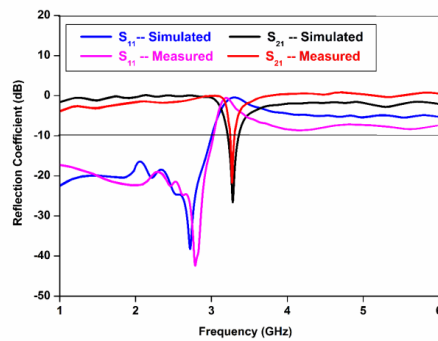


Figure 7. Simulated and measured S-parameters (S_{11} and S_{21}).

2.2 Metamaterial Elliptic Single Complementary Split-ring Resonator (ESCSRR)

This section outlines the design methodology of the proposed metamaterial CSRR structure. The CSRR cell is designed as an elliptic single complementary split-ring resonator (ESCSRR), as illustrated in Figure 9(a). The effective dielectric properties (permeability and permittivity) and resonant characteristics of the CSRR cell are analyzed through both simulation and experimental setups using a waveguide arrangement (Figure 9). This setup facilitates the measurement of S-parameters, which are used to determine the effective dielectric parameters (μ_{eff} and ϵ_{eff}) of the metamaterial CSRR cell. The electrical equivalent circuit of the

$$f_{\text{res}} = \frac{1}{2\pi\sqrt{L_M C_M}} \quad (3)$$

$$C_M = (N_R - 1) J_0 / 2 \{ [2 L_{\text{In-CSRR}} - (2 N_R - 1)(W_{\text{In-CSRR}} + g_{p1})] \} \quad (4)$$

$$J_0 = \epsilon_0 \{ T(\sqrt{1 - T^2}) / T(t) \} \quad (5)$$

$$t = (g_2/2) / \{ (W_{\text{In-CSRR}}) + (g_{p1}/2) \} \quad (6)$$

$$L_M = 4 \mu_0 \{ [L_{\text{In-CSRR}} - (N_R - 1) \{ W_{\text{In-CSRR}} + g_{p1} \}] [\ln(0.98/q) + 1.84 q] \} \quad (7)$$

$$q = \{ (N_R - 1)(W_{\text{In-CSRR}} + g_{p1}) \} / \{ 1 - (N_R - 1)(W_{\text{In-CSRR}} + g_{p1}) \} \quad (8) \text{ where,}$$

$T(t)$ = Complete elliptic integral of the first kind, N_R = Number of rings associated with proposed CSRR, $L_{\text{In-CSRR}}$ = Length of internal ring of CSRR, $W_{\text{In-CSRR}}$ = Width of internal ring of CSRR, and g_{p1} = gap.

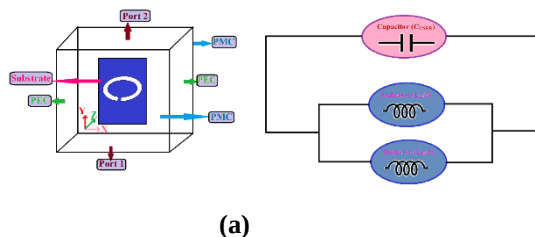


Figure 9. (a) Waveguide setup: Proposed CSRR, (b) An equivalent model.

The CSRR can be described as a dual-element configuration of the SRR cell, based on the principle of duality. The proposed CSRR cell functions as a passband filter and achieves an operating resonant frequency of 9.72 GHz. As shown in Figure 10 (waveguide arrangement), a comparative analysis of the S-parameters (S_{11} and S_{21}) reveals the passband behavior of the CSRR at the targeted frequency of 9.72 GHz. The S-parameters (S_{11} and S_{21}) are extracted using effective medium theory [41].

Figure 11 illustrates the magnetic resonator behavior of the proposed CSRR cell and its negative permittivity characteristics at 9.72 GHz. The orthogonal orientation of the E-field induces the negative permittivity property at

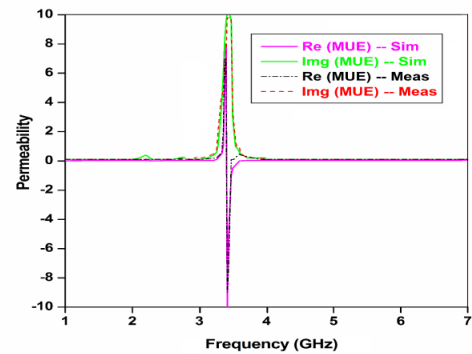


Figure 8. Simulated and measured permeability

CSRR structure is represented by an LC parallel tank configuration, comprising inductance (L) and capacitance (C) components, as illustrated in Figure 9(b). This equivalent model defines the resonant operating frequency [40]. To experimentally measure S_{11} and S_{21} , the proposed CSRR cell is placed inside the waveguide setup and connected to a Vector Network Analyzer (VNA).

As depicted in Figure 9 (simulated waveguide setup), an external H-field is applied to the CSRR structure, generating an EMF that couples with the single elliptic complementary split-ring. The resonant frequency of the CSRR can be determined using the following equation [40]:

the desired resonant frequency. From the S-parameter observations in Figure 10, the transmission coefficient (S_{21}) is near zero (< -1 dB), while the reflection coefficient (S_{11}) falls below the reference level (-10 dB) at the target frequency of 9.72 GHz. This S-parameter behavior confirms the passband feature of the proposed CSRR cell at the operating frequency. The simulated and experimental permeability of the CSRR are also shown in Figure 11. Notably, the real part of the permeability (Real ϵ) is negative at 9.72 GHz, verifying that the proposed CSRR exhibits metamaterial properties, specifically negative permittivity characteristics.

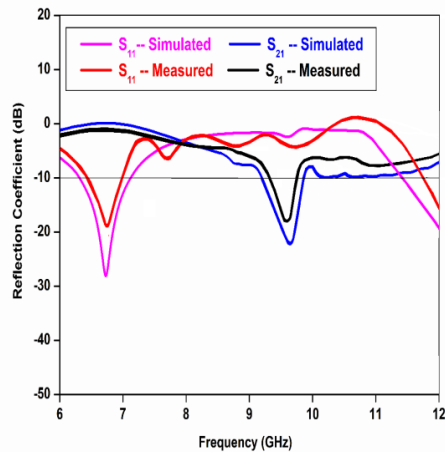


Figure 10. Simulated and measured S-parameters (S_{11} and S_{21}).

2.3An electrical equivalent model configuration

The lumped equivalent model of the proposed design, shown in Figure 12, consists of inductor (L) and capacitor (C) components. This model is designed based on the slotted patch, metamaterial cells, and feed equivalent. The equivalent circuit for

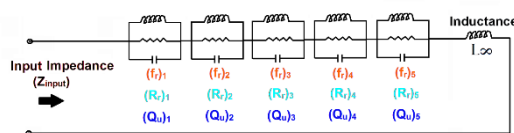


Figure 12. An electrical equivalent model of proposed antenna.

3. Results and discussion

Figure 13 illustrates the surface current vector distribution of the proposed antenna during simulation at resonant frequencies of 1.61, 3.35, 4.41, 5.80, and 12.85 GHz. At the lower operating frequency of 1.61 GHz, the surface current reaches its peak at the edges of the trapezoidal slotted radiating patch and the rectangular feedline section. At 3.35 GHz, the surface current is concentrated around the two similar single-ring square metamaterial split-ring resonators located at the neck of the trapezoidal radiating patch. At 4.41 GHz and 5.80 GHz, the surface current is strongest across the metamaterial SRR cells, the radiating part, and the feedline. At the highest

the radiating slotted patch with metamaterial cells loading represents a parallel combination of resistance (R_1, R_2, R_3, R_4, R_5), inductance (L_1, L_2, L_3, L_4, L_5), and capacitance (C_1, C_2, C_3, C_4, C_5), as illustrated in Figure 12. The expressions for the L and C components are provided in equations (9) and (10).

$$Leq = 0.0021l_{th} [\ln\{(2l_{th})/(w_{th} + t_{hk})\} + \frac{1}{2} + 0.2243 \{(w_{th} + t_{hk})/(l_{th})\}] \quad (9)$$

$$Ceq = (S_{Ar}\epsilon_o\epsilon_r)/d_{sp} \quad (10)$$

resonant frequency of 12.85 GHz, the surface current reaches its maximum near the proposed single-ring elliptical complementary split-ring resonator (CSRR), which contributes to the 12.85 GHz band. The surface current distribution shown in Figure 13 demonstrates that the inclusion of metamaterial SRR and CSRR cells within the radiating slotted patch alters the current direction, leading to the formation of new resonant bands. This modification results in improved impedance matching and a broader bandwidth, supporting the claim that the proposed antenna outperforms existing alternatives in terms of efficiency.

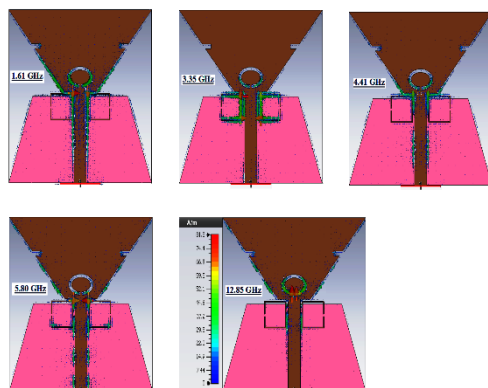


Figure 13. Simulated surface current distribution at 1.61, 3.35, 4.41, 5.80, and 12.85 GHz.

Figures 14 and 15 illustrate the comparative plots of the proposed antenna's peak gain and radiation efficiency, respectively. Table 4 provides the peak gain values and radiation efficiency percentages at various resonant frequencies and corresponding wireless standards. As observed in Table 4, the

proposed design achieves a maximum peak gain of 4.19 dBi and a radiation efficiency of 88.92% in the upper X band. Additionally, the average efficiency of the proposed design exceeds 70% across all the achieved wireless standards.

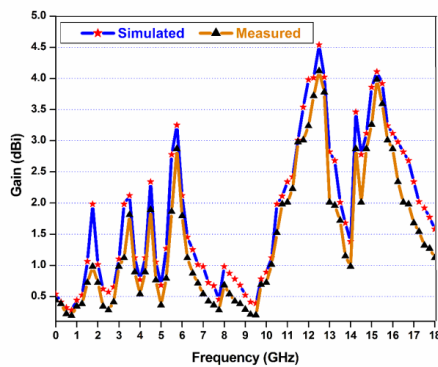


Figure 14.Metamaterial inspired trapezoidal slotted multiband antenna – Gain vs frequency.

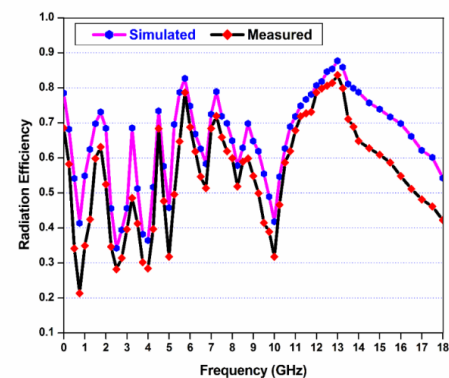


Figure 15.Metamaterial inspired trapezoidal slotted multiband antenna – Radiation efficiency vs frequency

Table 4. Comparison of Antenna Peak Gain and Radiation Efficiency (Simulated and Measured Modes)

Wireless Communication modes	Antenna peak gain (in dBi)		Radiation efficiency (in %)	
	Simulated	Experimental	Simulated	Experimental
L band (1.61 GHz)	1.98	1.12	65.81	62.34
Upper S band WiMAX (3.35 GHz)	2.12	1.74	68.72	49.98
Lower C-band (4.41 GHz)	2.23	1.86	70.14	68.71
Middle C-band WLAN, 5G NR (5.80 GHz)	3.04	2.91	78.36	73.52
Upper X/Lower KU band(12.85 GHz)	4.51	4.19	88.92	82.76

Figure 16 displays the simulated and measured co-polarization and cross-polarization radiation patterns for both the E-plane and H-plane at frequencies of 1.61 GHz, 3.35 GHz, 4.41 GHz, 5.80 GHz, and 12.85 GHz for the metamaterial-inspired trapezoidal slotted multiband antenna. To further assess the radiation characteristics, the proposed antennas tested in an anechoic chamber. The

results show that the antenna exhibits a near dipole-like and omnidirectional radiation pattern in the E-plane and H-plane at all resonant frequencies. There is strong agreement between the experimental and simulated radiation patterns at each resonant frequency. Furthermore, the antenna demonstrates low cross-polarization levels, generally below -15 dB.

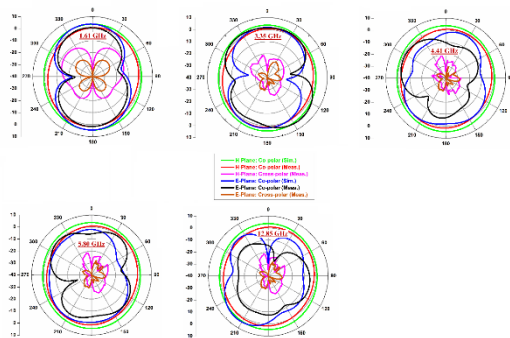


Figure 16. Metamaterial inspired trapezoidal slotted multiband antenna – Patterns (Sim. & Meas.) at resonant frequencies 1.61 GHz, 3.35 GHz, 4.41 GHz, 5.80 GHz, and 12.85 GHz.

Table 5 presents a comparative analysis of the proposed design against previously published metamaterial inspired multiband antennas based on various characteristics. From the observations in Table 5,

the proposed antenna demonstrates enhanced performance characteristics compared to the antennas reported in the literature

Table 5. Comparison of the Proposed Antenna with Existing Designs.

Ref	Year	Size (mm ³)	Fractional bandwidth (%)	Gain (dBi)	Efficiency (%)	Operating States	Applications Covered (GHz)
[10]	2013	52.6×30×1	47.27/38.88	-0.56 /-0.62	89.2/98.1	2	GPS/WLAN (1.5/2.4)
[11]	2018	32×38×1.6	8/6/5/69.3	3.8 (Avg. Gain)	89% (Avg. Rad. Eff.)	4	WLAN/WiMAX/ITU/X Band (2.4/3.35/5.8/7.5)
[14]	2019	35×34×1.6	11.81/4.27/4.29/6.62/3.27/4.22/8.13	1.94/2.2/1.66/3.87/3.65/4.06/4.14	41.5/48.6/58.1/60.1/84.4/78.7/82.1	7	WLAN/WiMAX/ C/X /Ku Band (2.4/3/3.5/5/5.8/11.8/13.1)
[21]	2020	30×44×1.6	8.80/38.78/15.54/35.45	2.63/2.58/2.82/2.99	33.5/38.8/84.4/72.8	4	WLAN/WiMAX/WAVE/C/X Band (2.4/3.5/5.8/7.9)
[42]	2020	25×25×1.6	7.7/6.51/6.49/8.61/4.94	2/2.9/2.5/4.42/3.01	--	5	IoT/WLAN/Wi-Max/ C-band (3.82/4.11/4.48/ 4.90/6.04)
[43]	2021	36×32×1.6	84/85.32/35.45/10.79/15.82	--	--	5	LTE 2300/LTE 2500/Bluetooth/WLAN/WiMAX/ ITU band (2.4/4.8/7.8/11.7/16.5)
[44]	2021	50×50×0.8	16.17/ 17.85/ 48.30	5.42/6.52/7.67	--	3	Wi-Fi/WLAN/ X-band (2.4/5.8/9.98)
[45]	2022	150 × 75 × 0.8	46.71	5.01	50-63	1	5G NR bands N77/N78/N79 (3.2-5.15 GHz)
[46]	2022	150 × 75 × 7.8	60.87	--	38-83	1	5G NR n77/n78/n79 and WLAN-5 GHz (3.2-6.0 GHz)
[47]	2023	58.6 × 58.6 × 0.8	14.08	4.8	76	1	5G NR n77 (3.3-3.8 GHz)
[48]	2024	35 × 30 × 1.6	40.8/22.3	3.87/3.93	80.12/82.34	2	Wi-Fi, 5G NR communication, IoT Applications (3.5/5.3)

[4 9]	2 024	31. 8 × 27.6 × 1.6	43/ 25/ 15	1.5/ 4.1/ 6.5	Less than 75	3	5G NR sub-band, X band, and Ku band (12–14 GHz) for upper resonance (3.5/ 8.5/ 13.7)
[5 0]	2 024	33× 22×1.6	21.54/ 13.63/ 10.61/ 35.03/ 23.74	2.51/ 1.52/ 1.51/ 2.48/ 3.62	81.28/ 79.98/ 82.34/ 76.84/ 86.52	5	5G Sub-6 GHz NR Bands (5G FR1-n48/n78/n79/n96), WiMAX (3.5 GHz), WLAN (5.0), upper X band (10.03-14.29 GHz), and upper KU band (15.74-19.98 GHz)
[5 1]	2 024	37× 22×1.6	24.77/ 14.03/ 36.04/ 46.21/ 14.35	2.36/ 2.72/ 3.41/ 3.18/ 4.38	63.56/ 71.07/ 48.42/ 69.82/ 72.87/ 86.23	5	S band WLAN/ S band WiMAX/ C band WLAN / X- Band (Satellite communication, radar, terrestrial broadband, space communication)/ 5G NR bands (n41: 2.496-2.690 GHz, n46: 5.15-5.925 GHz, n47: 5.855-5.925 GHz, n53: 2.483-2.495 GHz, n102: 5.925-6.425)/ Lower Ku band (Molecular rotational spectroscopy) (2.4/3.65/5.0/ 5.8/8-12/)
Proposed antenna		36 × 36 × 1.6	55.46/16.84/21. 16/67.55/42.64	1.98/ 2.12/ 2.23/ 3.04/ 4.51	65.81/ 68.72/ 70.14/ 78.36/ 88.92	5	L band: Military telemetry, GPS, mobile phones (GSM) (1.61 GHz)/ 5G NR bands: n50 (1.432-1.517 GHz), n51 (1.427-1.432 GHz), n54 (1.670-1.675 GHz), n39 (1.880-1.920 GHz), n101 (1.900-1.910 GHz), n46 (5.150-5.925 GHz), n47 (5.855-5.925 GHz), n96 (5.925-7.125 GHz), n102 (5.925-6.425

							GHz), n104 (6.425-7.125 GHz) / Middle S band: Worldwide Interoperability for Microwave Access (3.35 GHz) / Upper S band: Weather radar, surface ship radar, amateur radio / C band: Wireless Local Area Network (5.0/5.8 GHz, IEEE 802.11a/j) / Upper X-Band: Terrestrial Broadcast, Radar Communication, Space Communication (1.61, 3.35, 4.41, 5.0/5.8, 12.85)
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4. Conclusion

A metamaterial-inspired trapezoidal slotted multiband antenna is designed to achieve a penta-band configuration. The proposed design resonates at frequencies of 1.61 GHz, 3.35 GHz, 4.41 GHz, 5.0/5.8 GHz, and 12.85 GHz, effectively covering a wide range of wireless communication modes: L-band (military telemetry, GPS, mobile phones, GSM, 5G NR bands), Middle S-band (Worldwide Interoperability for Microwave Access), Upper S-band (weather radar,

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Declarations

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surface ship radar, amateur radio), C-band (Wireless Local Area Network - WLAN), and Upper X-band (terrestrial broadcast, radar communication, space communication). At its resonant frequency, the antenna achieves an optimized gain of 4.51 dBi and an efficiency of 88.92%. The antenna maintains an average radiation efficiency of over 70% across all operating wireless communication standards.

Conflicts of interest: The authors declared that they have no conflict of interest.

Availability of data and material: The data generated during this study are included within this article.

Code availability: Not applicable.

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