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OPTIMIZED SUPER WIDEBAND MICROSTRIP PATCH ANTENNA FOR 6G AND BIOMEDICAL IMAGING APPLICATIONS

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Abstract
This paper presents the design and performance analysis of an optimized Super Wideband (SWB) Microstrip Patch Antenna (MPA) operating efficiently across an ultra-wide frequency range from 4 GHz to 100 GHz. The proposed antenna integrates a modified rectangular patch with a partial ground plane to enhance impedance bandwidth, gain, and radiation stability. Full-wave simulations using CST Microwave Studio (CST MWS) confirm broad impedance matching with $S_{11} < -10$ dB across the entire band and a minimum return loss of –44 dB at 60.31 GHz, demonstrating excellent impedance performance. The VSWR remains below 2 throughout the operational range, verifying efficient power transfer and minimal reflection. Radiation analysis at multiple frequencies (7.76 – 98 GHz) shows stable far-field patterns with peak gains between 1.8 dB and 12.3 dB, transitioning smoothly from quasi-omnidirectional to directional radiation with increasing frequency. The optimized geometry enables continuous multimode resonance, ensuring consistent gain and impedance behavior over the full spectrum. Owing to its compact structure, high gain, and wide operating bandwidth, the proposed SWB-MPA is a strong candidate for millimeter-wave, biomedical imaging, radar, and next-generation wireless communication systems.

Key words
Super Wideband (SWB), Microstrip Patch Antenna (MPA), Partial Ground Plane, Gain Enhancement, Bandwidth Optimization, CST Microwave Studio (CST MWS), Radiation Pattern, Biomedical Imaging.

INTRODUCTION

With the rapid evolution of wireless communication technologies, the demand for compact, high-performance antennas capable of supporting higher data rates, wider bandwidths, and improved radiation efficiency has increased significantly. To meet the requirements of emerging communication systems, especially 6G and millimeter-wave applications, researchers are increasingly focusing on SWB antenna designs. Unlike conventional Ultra-Wideband (UWB) systems, SWB antennas cover an exceptionally broad frequency range that includes multiple communication and radar bands, enabling faster and more reliable transmission of data, voice, and video signals across diverse applications [1].

Several bandwidth enhancement techniques have been explored to achieve SWB performance, including modifications to the ground plane and patch geometry [2]–[5], and the use of various feeding mechanisms such as microstrip tapered feeds [6]–[8] and coplanar waveguide (CPW) feeds [9]–[11]. Moreover, fractal and self-similar geometries have been proposed to reduce antenna size while maintaining wide impedance bandwidth [12].

A crescent-shaped radiating patch antenna with a slotted ground plane, operating from 2.5 to 29 GHz, was reported in [2], though it exhibited non-uniform gain performance. A frequency-selective structure-based SWB antenna covering 3–20 GHz was proposed in [3], but its low-frequency response limited compatibility with Bluetooth, GPS, and GSM systems. Ramanujam *et al.* [4] developed a hybrid SWB antenna fed by a stepped microstrip line with semi-circular parasitic patches, extending bandwidth from 24 to 40 GHz, though with unstable radiation patterns. Similarly, an octagonal ring-shaped antenna in [5] achieved 2.59–31.14 GHz coverage by employing a corner stub, enhancing impedance bandwidth. Other geometrical modifications, such as elliptical and fractal patches [6]–[13], have shown promising results but often suffer from limited gain or inconsistent far-field stability at higher frequencies.

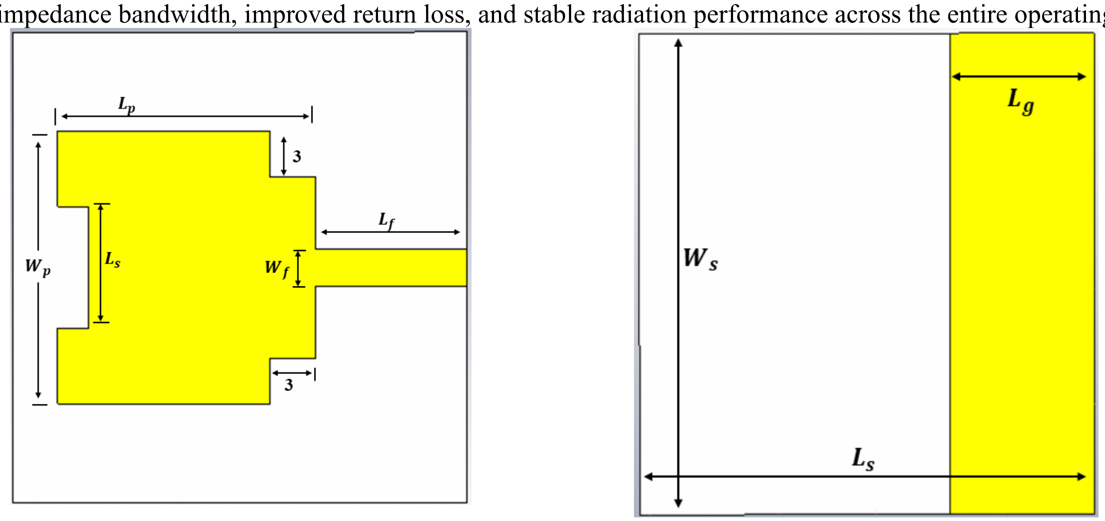
Despite these advancements, achieving consistent impedance matching, stable gain, and uniform radiation patterns across a frequency range extending beyond 60 GHz remains challenging. Most previously reported SWB designs exhibit either narrow effective bandwidths or performance degradation at higher millimeter-wave frequencies. These limitations hinder their applicability in modern broadband, radar, and biomedical imaging systems, which require wide spectral adaptability and compact form factors.

To address these challenges, this paper proposes an optimized SWB MPA employing a modified radiating patch and a partial ground plane. The optimized geometry excites multiple resonant modes that merge to produce a continuous 4–100 GHz bandwidth, offering enhanced impedance matching, gain stability, and radiation consistency across the entire spectrum. The proposed antenna's performance is validated through CST MWS simulations, demonstrating its suitability for 6G, radar sensing, and biomedical imaging, particularly microwave breast cancer detection.

Antenna design

The proposed antenna achieves Super Wideband (SWB) performance through a combination of patch geometry modification and partial ground-plane optimization. As illustrated in *Figure 1*, the structure comprises a rectangular radiating patch fed by a 50-Ω microstrip line and printed on a low-loss dielectric substrate. A truncated ground plane is implemented on the opposite side to enhance impedance bandwidth and improve electromagnetic coupling between the patch and ground [14], [15].The modified rectangular patch incorporates precisely engineered slots and cuts to generate multiple resonant modes across the 4–100 GHz band. These discontinuities modify the surface current paths, creating strong coupling and reducing impedance mismatches [15], [16]. A stub extension at the feed junction further improves current continuity and minimizes reflection losses [17].

The combined effect of the modified patch, feedline stub, and partial ground enables the excitation of multiple closely spaced resonant modes that merge into a continuous SWB response. This optimized configuration results in enhanced impedance bandwidth, improved return loss, and stable radiation performance across the entire operating range.



(a) (b)

Figure 1 Optimized SWB MPA model (a)Front view (b)Back view

The dimensional parameters of the proposed antenna are summarized in Table 1. The antenna is fabricated on a dielectric substrate (Rogers RT5880) with a thickness of 1.6 mm dilectric constant 2.2.

Table 1 Dimensional specifications of optimized SWB MPA model

Notation	Description	Value (mm)

L_p	Length of patch	17
L_f	Length of feedline	10
W_f	Width of feedline	2.5
L_s	Length of substrate	30
W_p	Width of patch	18
W_s	Width of substrate	31
L_g	Length of ground	9.5
S_h	Height of substrate	1.6

RESULTS

The proposed SWB MPA was analyzed using CST MWS to evaluate its impedance characteristics, VSWR, and radiation performance. The results confirm that the antenna achieves excellent impedance matching, stable gain, and consistent radiation behavior across a wide frequency range from 4 GHz to 100 GHz.

a. Transient Behavior of Antenna

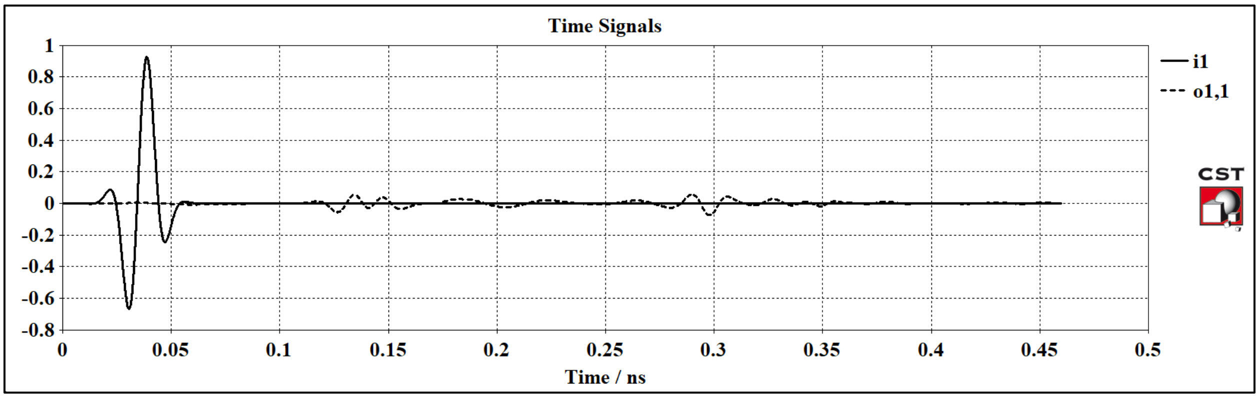


Figure 2 Transient behavior of SWB MPA

Figure 2 shows the transient behavior of the proposed MPA in which i1 indicates input excitation signal and o1,1 represents reflected signals at the same antenna. The time-domain response shows that the output pulse closely follows the input with minimal distortion and rapidly decays within 0.2 ns, confirming fast transient behavior, low ringing, and excellent wideband fidelity suitable for SWB applications.

Reflection Coefficient (S_{11})

The reflection coefficient remains below the standard threshold of –10 dB throughout the entire 4–100 GHz range, confirming efficient impedance matching and minimal reflection loss shown in Figure 3.

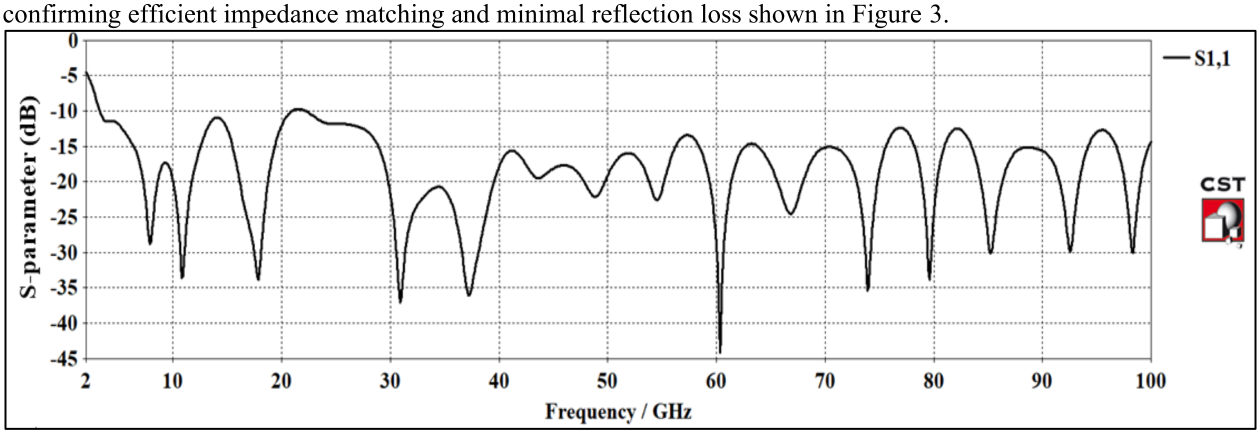


Figure 3 S11 response of optimized MPA

A particularly deep resonance of –44 dB occurs at 60.368 GHz, indicating nearly perfect impedance matching between the feedline and the radiating structure. Additional resonant dips are observed at 7.76 GHz, 11 GHz, 30.8 GHz, 37.84 GHz, 60.368 GHz, 74.064 GHz, 79.765 GHz, 85.456 GHz, 92.88 GHz, and 98 GHz corresponding to higher-order resonant modes of the modified patch.

The proposed geometry effectively merges adjacent resonant modes to produce a smooth and continuous S11 curve, demonstrating the suppression of impedance discontinuities commonly seen in conventional microstrip designs. The antenna thus achieves stable SWB operation across the C, X, Ku, Ka, V, W, and millimeter-wave bands without requiring structural reconfiguration.

Fractional bandwidth (FBW) of the optimized antenna can be calculated by [18],

$$FBW = \frac{BW}{f_c} \times 100\% = \frac{96}{(100+4)/2} \times 100\% = 184.615\%$$

b. VSWR

The VSWR analysis confirms excellent impedance matching of the proposed antenna across the 4–100 GHz frequency range shown in Figure 4. The VSWR remains consistently below 2, satisfying the IEEE efficiency criterion [18].

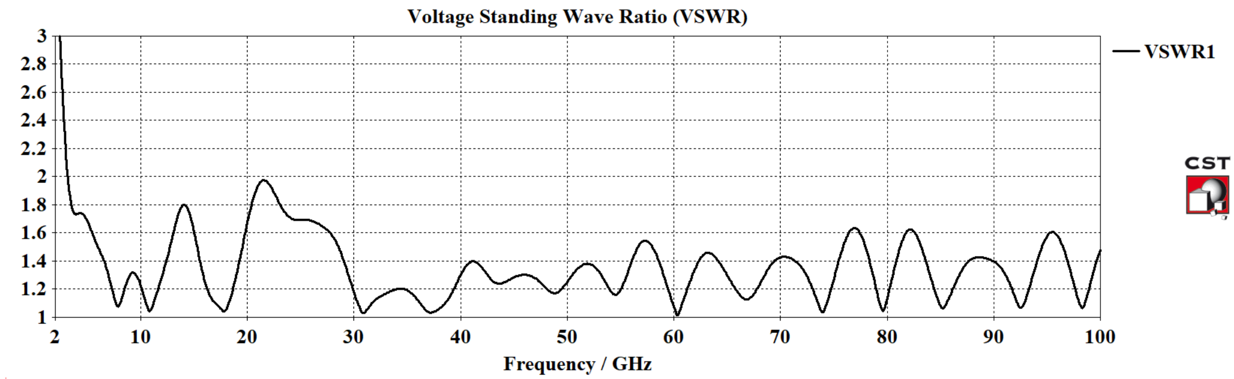
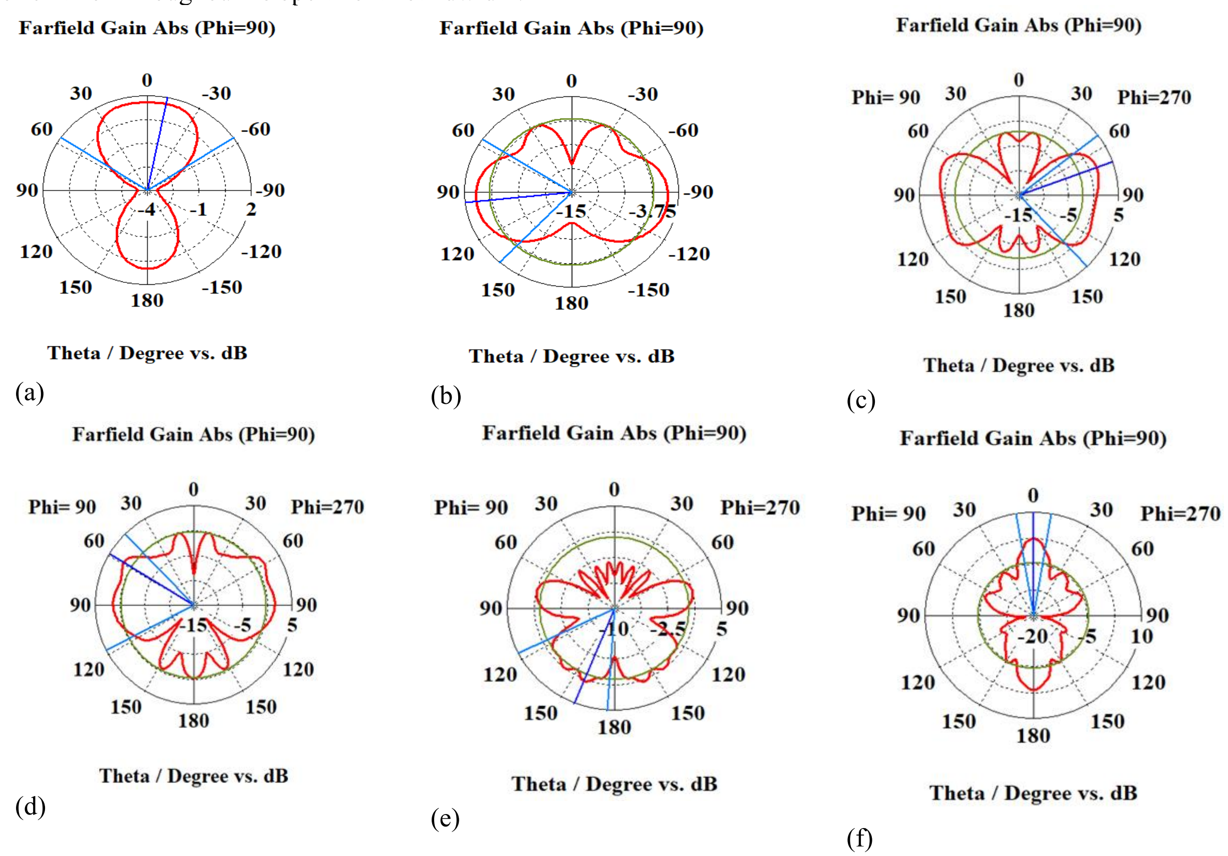


Figure 4 VSWR of optimized MPA

c. Radiation Pattern

A radiation pattern illustrates the spatial distribution of radiated energy from an antenna. It is typically represented in polar or 3D form to show the variation of radiated power with direction in space [11]. The simulated 2D and 3D patterns, shown in Figure 5, confirm that the antenna maintains consistent radiation behavior and stable beam orientation throughout its operational bandwidth.



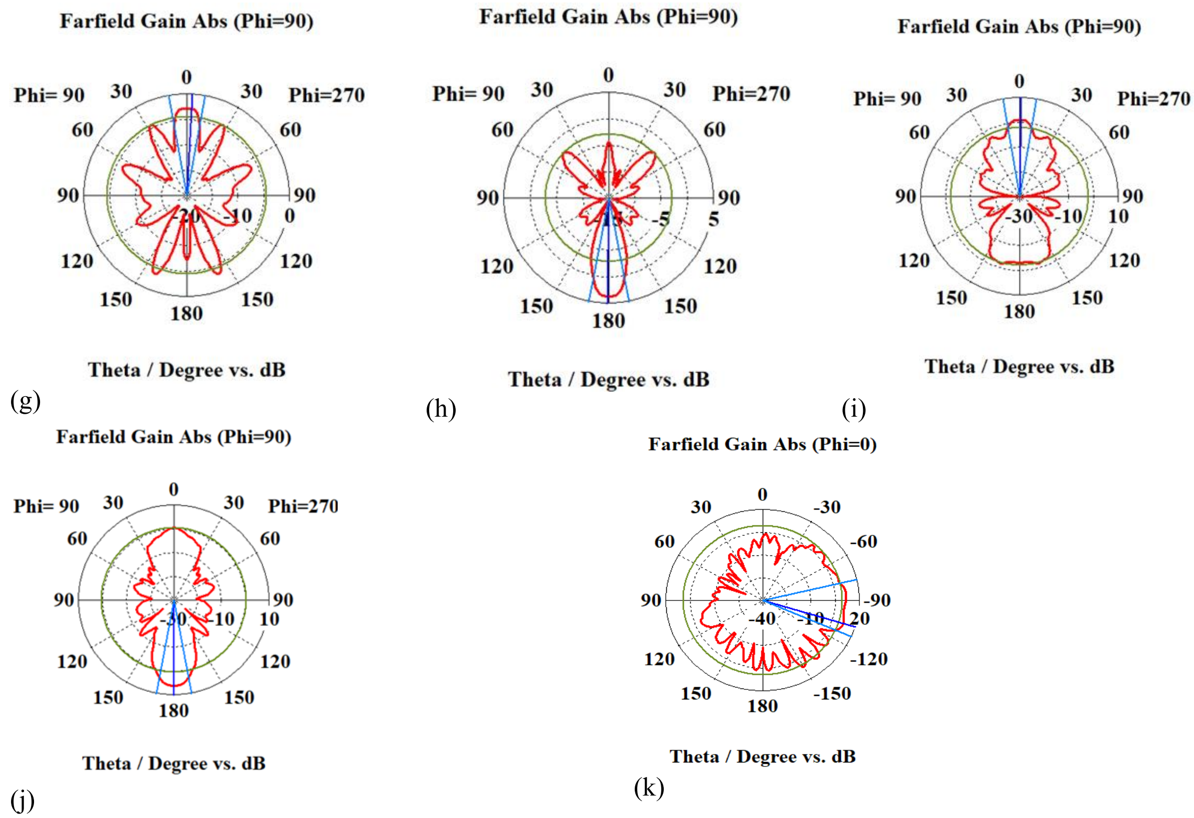


Figure 5 Radiation pattern of optimized MPA at various frequencies (a) at 7.76GHz (b) at 11GHz (c) at 18.128GHz (d) at 30.8GHz (e) at 37.84GHz (f) at 60.368GHz (g) at 74.064GHz (h) at 79.765GHz (i) at 85.456GHz (j) at 92.88GHz (k) at 98GHz

The far-field radiation patterns of the proposed Super Wideband Microstrip Patch Antenna (SWB-MPA) were analyzed at multiple frequencies across the 4–100 GHz range to evaluate stability and directivity. The simulated 2D and 3D patterns, shown in *Figure 4*, confirm that the antenna maintains consistent radiation behavior and stable beam orientation throughout its operational bandwidth.

At lower frequencies (7.76–11 GHz), the antenna exhibits quasi-omnidirectional radiation with wide angular coverage and minimal back-lobe radiation, resembling monopole behavior. As frequency increases to the mid-band (18–38 GHz), the pattern becomes broadside-oriented with improved directivity and uniformity, indicating efficient excitation of dominant patch modes. At higher frequencies (60–98 GHz), the antenna produces a highly directive beam with stable main-lobe orientation and strong back-lobe suppression due to the optimized partial ground plane. Minor side lobes appear beyond 80 GHz, typical of electrically large structures, but they have negligible effect on radiation efficiency.

d. Gain

Gain indicates how effectively an antenna directs its radiated power. A higher gain signifies stronger radiation in a desired direction instead of uniform dispersion in all directions [12].

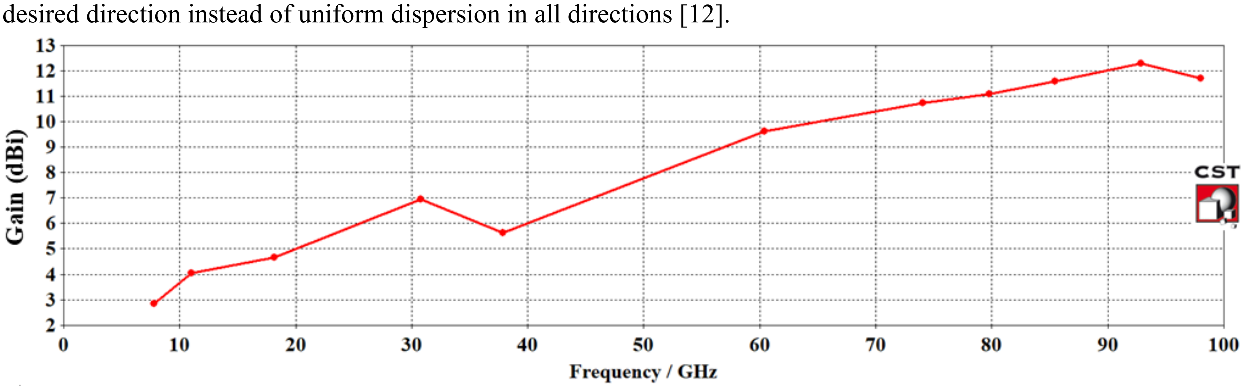


Figure 6 Gain versus frequency graph

The gain versus frequency curve, shown in Figure 6, demonstrates that the antenna maintains stable gain with increasing frequency, validating its wideband performance.

In the low-frequency region (7.76–11 GHz), the antenna achieves peak gains between 2 dB and 3.7 dB, consistent with monopole-like radiation. In the mid-band (18–38 GHz), gain gradually increases to approximately 4.5 dB as the radiation pattern becomes more directive. At higher frequencies (60–98 GHz), the antenna attains its maximum gain of 12.3 dB, confirming efficient radiation and high directivity at millimeter-wave bands.
The smooth gain progression across all regions reflects efficient mode excitation, low reflection loss, and minimal energy dispersion. These results demonstrate that the proposed antenna achieves stable gain, broad impedance bandwidth, and high radiation efficiency, reinforcing its suitability for 6G, radar, and biomedical imaging systems.

Ref.	**Size (mm^2)**	**Area (mm^2)**	**Bandwidth (GHz)**	**FBW %**	**BR**	**Gain maximum (dBi)**
[18]	148.51×83.94	12465	2-12	142	6:1	11.2
[19]	74 × 80	5920	1.05–32.7	187	31:1	-
[20]	60 × 60	3600	2.18–44.5	181	20.4:1	7
[21]	50 × 50	2500	2.1–11.6	138	5.5:1	-
[22]	38 × 55	2090	3–35	168	11.6:1	5.2
[23]	30 × 45	1350	3.15–32	164	10.1:1	-
[24]	32 × 32	1024	2.9–15	135	5.17:1	5
[25]	31 × 28	868	3–12.8	124	4.26:1	6.5
Prop.	30 × 31	930	4–100	184	25:1	12.3

i. Comparative analysis

To validate the performance of the proposed SWB MPA, a comparative analysis was carried out with previously reported designs available in the literature. The comparison considers key parameters including operating bandwidth, minimum S_{11}, VSWR, and peak gain, as summarized in Table 2.

Existing designs [18]–[25] generally operate below 42 GHz with moderate bandwidth and gain performance. In contrast, the proposed antenna achieves continuous operation from 4–100 GHz, a minimum reflection coefficient of –44 dB at 60.31 GHz, and VSWR < 2 across the band. The optimized structure also delivers a peak gain of 12.3 dB, significantly higher than conventional UWB antennas, which typically exhibit gains below 6 dB. These results confirm that the proposed SWB-MPA provides broader bandwidth, better impedance matching, and higher radiation efficiency.

CONCLUSION

An optimized SWB-MPA has been successfully designed and analysed for operation across 4–100 GHz. The proposed structure, incorporating a modified radiating patch, feedline stub, and partial ground plane, achieves a minimum reflection coefficient of –44 dB, VSWR < 2, and a peak gain of 12.3 dB. The antenna exhibits stable radiation patterns, high efficiency, and excellent impedance matching throughout the operating band. Comparative analysis confirms that the proposed design offers superior bandwidth, higher gain, and improved stability compared to conventional wideband antennas. Owing to its compact size, broad impedance bandwidth, and strong directional performance, the proposed SWB-MPA is a promising candidate for 6G wireless communication, radar sensing, and biomedical imaging applications, particularly microwave breast cancer detection.

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