Design of CPW-fed Star-Shaped Monopole Antenna for UWB Applications using Transmission Line Model

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Abstract This article presents a structure of coplanar waveguide (CPW)-fed star-shaped monopole antenna (SSMA) with a pair of quarter-circular-slit (QCS) and partly-hexagonal-ring-slit (PHRS) defected ground structure. By inserting a pair of QCS and PHRS on the rectangular ground plane, an excellent impedance bandwidth is achieved i.e., 139% (from 2.2–12.21 GHz). The dimension of the SSMA is about 0.286λ × 0.216λ mm², where λ is the wavelength in free space at the lowest operating frequency i.e. 2.2 GHz. The transmission line model (TLM) of the SSMA is presented and it shows the antenna behavior based on the effect of each element. It is observed that the characteristics of the TLM model are close to the simulation result using the CST simulator. From the results, it is observed that the proposed ultra-wideband (UWB) antenna close to omnidirectional radiation patterns and suitable for UWB Applications.

Keywords Coplanar waveguide, monopole antenna, ultra wideband, quarter-circular-slit, transmission line model

1 Introduction

In wireless communication systems, the application of ultra-wideband antenna is growing rapidly due to broad bandwidth, high speed data rate, flexible, robustness to fading, low cost, and capability of high security. These antennas covering the wider frequency range of 3.1–10.6 GHz are key components of such ultra-wideband (UWB) systems; hence, their design problem has become an active topic of research in recent years. A monopole antennas have drawn more attention in recent years for a suitable wider bandwidth and nearly omnidirectional radiation patterns. To enhance the impedance bandwidth, many techniques such as increasing
substrate thickness, modifying the radiator and ground plane [1]–[3] are adopted. Since limited space is available in electronic devices, a design of compact wide band antennas having good matching input impedance characteristics and better radiation patterns similar to larger size antennas are required. The wideband impedance bandwidth is achieved by using space-filling concepts, different fractal antennas, CPW-fed antennas with dual-reverse-arrow fractal structure, flexible bow-tie slot antenna, a rose-curve shape monopole antenna, wideband fractal shapes structure, and tapered slot antenna [4]–[10]. To achieve wider bandwidth and better impedance matching a semi-circular patch [11], quasi-radiating patch [12], modified meandered slot [13], microstrip-fed parasitic-coupled monopole hybrid design [14] and optimized surrogate-based patch [15] are proposed. However, the monopole antennas mentioned above have a large physical size and the complex geometry to realize in the required operating frequency bands. Therefore, a compact and simple monopole antenna with a wider bandwidth covering the UWB frequency band is necessary.

In this work, a compact simple star-shaped monopole antenna (SSMA) structure with wider impedance bandwidth and an acceptable level of in-band return loss is proposed. Since the design and the fabricated antenna has a pair of symmetrical quarter-circular-slit (QCS) and partly-hexagonal-ring-slit (PHRS) defected ground plane, three peaks resonant i.e., 2.8, 6.1, and 9.4 GHz are observed. As a result, wider impedance bandwidth, better impedance matching, and antenna close to omnidirectional radiation patterns. An excellent wider impedance bandwidth i.e., 135% (2.36–12.1 GHz) and good return loss are achieved. Then, an equivalent transmission line model (TLM) of the proposed antenna is developed. An optimization is used in Applied Wave Research (AWR) simulator to find the transmission line parameters such as resistance (R), inductance (L), and capaci-

Fig. 1 Geometrical configuration of 9-point star-shaped (a) one-equilateral triangles, (b) two-equilateral triangles, (c) three-equilateral triangles, (d) four-equilateral triangles, (e) merge all triangles and (f) nine-point star
tance (C) of the TLM equivalent circuit using the $S_{11}$ simulated parameters [16–18] of the proposed antenna.

![Fig. 2](image_url) (a) Geometry of the proposed SSMA top view and (b) prototype

### 2 Antenna configuration and analysis

The 12-point star has been designed using four circles having three corners to make equilateral triangles with each radius 11 mm, and thus 9-point star will be obtained as shown in Fig 1. The geometry of a compact CPW-fed SSMA is shown in Fig. 2. A wider impedance bandwidth and high gain performances are achieved by introducing a pair of quarter-circular-slit (QCS) and partly-hexagonal-ring-slit (PHRS). The proposed antenna having an area of $39 \times 29.5$ mm$^2$($S_L \times S_W$) and a thickness of 1.6 mm is fabricated on FR-4 substrate. The dielectric constant of the substrate is 4.3 and the loss tangent of 0.025. The electromagnetic software CST is used to design and optimize the proposed SSMA. The detailed optimized dimension of the SSMA is shown in Table 1.

| Parameters | Units (mm) | Parameters | Units (mm) | Parameters | Units (mm) |
|------------|------------|------------|------------|------------|------------|
| $S_L$      | 39         | $p_l$      | 3.5        | $m_1$      | 0.6        |
| $S_W$      | 29.5       | $p_g$      | 2.2        | $r_1$      | 4          |
| $W$        | 22         | $l_g$      | 17.8       | $w_f$      | 2.5        |
| $L$        | 37         | $l_f$      | 19.5       | $w_g$      | 12.7       |
| $p_w$      | 2.5        | $f_y$      | 1.05       | $h$        | 1.6        |

The SSMA design evolution is shown in Fig. 3a. The proposed SSMA width ($W$) and length ($L$) calculated for the entire geometry is given as;
\[ W = \frac{c}{2f_r \sqrt{((\epsilon_r + 1)/2)}} \]  \hspace{1cm} (1)

\[ L = \sqrt{3}W \]  \hspace{1cm} (2)

where \( c \) is the velocity of the light in vacuum, \( \epsilon_r \) is the relative permittivity of the substrate and \( f_r \) (\( = 3.5 \text{ GHz} \)) is the resonant frequency.

![Evolution of the SSMA design (a) Antenna 1, Antenna 2, Antenna 3 (proposed) and their corresponding (b) \( S_{11} \)](image)

The Antenna 1 is a simple CPW-fed star-shaped antenna whose simulated \( S_{11} \) result is shown in Fig. 3b. It is observed from Antenna 1, that the impedance bandwidth performance is from 2.63-6.49 GHz (normalized bandwidth 84.65%). It shows only one resonance band (it cannot provide better characteristics performance of \( S_{11} \leq -10 \text{ dB} \)) and its frequency can be expressed as [10],

\[ f_{\text{ext}} \approx \frac{c}{\sqrt{\epsilon_{eff} L_{\text{path}}}} \]  \hspace{1cm} (3)

where \( L_{\text{path}} \) is the external path length and \( \epsilon_{eff} \) is the effective dielectric constant.

Improved impedance bandwidth performance is shown in Fig. 3b for Antenna 2 in which a pair of QCS is introduced on the ground plane with radius \( r_1 = 4.0 \text{ mm} \). It is noted two resonant frequencies with poor return loss which can not provide a
wideband impedance bandwidth. In this final design, a pair of symmetrical PHRS is introduced on both sides of the ground plane to improve $S_{11}$ performance. An excellent wider impedance bandwidth i.e., 135% (2.36–12.1 GHz) and good return loss are achieved.

![Surface current density distribution of the SSMA at 2.8 GHz, 6.1 GHz and 9.4 GHz](image)

**Fig. 4** Surface current density distribution of the SSMA at (a) 2.8 GHz, (b) 6.1 GHz and (c) 9.4 GHz

The simulated surface current density distribution of the proposed SSMA at 2.8, 6.1, and 9.4 GHz are shown in Fig. 4a, 4b, and 4c, respectively. For detailed analysis, the surface current density distribution of different frequencies are plotted in Fig. 4. The results reveal that the surface current is the more concentrated at the bottom circumference at 2.8 GHz and less at 6.1 GHz of the star-shaped radiator. Also, it is observed in Fig. 4a and 4c, that a large surface electric current density flows along the contour of the star-shaped metallic radiator. In particular, at 2.8, 6.1, and 9.4 GHz, the surface current is concentrated near the feed line edge of the CPW ground plane, thereby fine-tuning impedance matching of the upper-side frequency bands. Therefore, an optimized partly-hexagonal-ring-slit (PHRS) thickness of $m_1 = 0.6$ mm, quarter-circular-slit (QCS) radius $r_1 = 4$ mm and feed gap $f_g = 1.05$ mm gives the best results with a wider bandwidth and a high gain.

![Simulated $S_{11}$ performance of the SSMA as a function of (a) r1 and (b) m1](image)

**Fig. 5** Simulated $S_{11}$ performance of the SSMA as a function of (a) $r_1$ and (b) $m_1$
2.1 Parametric study

The effects of QCS radius $r_1$ and PHRS thickness $m_1$ of the ground plane on $S_{11}$ results are shown in Fig. 5a and 5b respectively. It is found that the upper side-band frequency is reduced with increasing radius $r_1$ and impedance matching becomes poor for larger values. At $r_1 = 4.0$ mm, better return loss, as well as matching, is achieved. Similarly, it is found that the upper side-band frequency will reduce with the reduction of $m_1$ thickness of PHRS. The optimized slit thickness $m_1$ is found to be 0.6 mm for better results as shown in Fig. 5b.

![Equivalent transmission line model-RLC circuit elements of the proposed SSMA](image)

**Fig. 6** Equivalent transmission line model-RLC circuit elements of the proposed SSMA (a) basic patch antenna, (b) star-shaped step discontinuities, (c) all slit and gap structure and (d) simplified RLC circuit model

2.2 Transmission Line-RLC circuit model

The methodology to obtained the electrical equivalent circuit diagram of the proposed SSMA assuring transmission line model (TLM) is shown in Fig. 6. In this figure, the microstrip-feed line introduces the inductance $L_r$ which is shown in Fig. 6a. The star-shaped radiator of the proposed SSMA contains a 9-point circumference of the star, each step takes part in tuning the capacitive and inductive
coupling between the radiator and ground plane. Then, each star point is represented by the circuit as shown in Fig. 6b. Furthermore, $C_{g1}$ and $C_{g2}$ are the coupling capacitor. While $L_{g1}$, $L_{g2}$, $L_{g3}$, and $L_{g4}$ are caused by the inductances on both sides of the symmetric ground plane. The shunt capacitances $C_{g1}$ and $C_{g2}$ are due to the gaps between the feed line and CPW-fed ground plane as shown in Fig. 6c. Therefore, the radiating element of the designed SSMA is represented as several parallel circuits of series RLC as shown in Fig. 6d. An optimization process is performed by using the NI-AWR simulator and all the circuit parameters such as \( \text{R (\Omega)}, \text{L (nH)} \) and \( \text{C (pF)} \) are obtained as follows: \[ L_r = 0.015, \ L_p = 354, \ S_{L1} = 12.88, \ S_{L2} = 17.16, \ S_{L3} = 1.52, \ S_{L4} = 0.97, \ S_{L5} = 27490, \ S_{L6} = 792000, \ S_{L7} = 5920 \] all dimensions are in nH, \[ C_p = 3.811 \times 10^{-11}, \ S_{C1} = 0.675 \times 10^{-5}, \ S_{C2} = 0.3798, \ S_{C3} = 0.0647, \ S_{C4} = 0.6469, \ S_{C5} = 7.39 \times 10^{-12}, \ S_{C6} = 2.04, \ S_{C7} = 1.543 \] all dimensions are in pF and \[ Z = 50, \ S_{R1} = 2.11, \ S_{R2} = 2.17, \ S_{R3} = 5.87, \ S_{R4} = 3.6, \ S_{R5} = 3.41, \ S_{R6} = 3.4, \ S_{R7} = 2.62 \] all dimensions are in \( \Omega \). Finally, the proposed SSMA model gives approximately the same behaviour and a very wider impedance bandwidth by several adjacent resonances which can be represented by TLM-RLC circuits simulated result as shown in Fig. 7.

![Fig. 7](image)

**Fig. 7** Simulated and equivalent transmission line circuit model response of the SSMA

![Fig. 8](image)

**Fig. 8** Actual antenna measurement environment in an anechoic chamber
3 Simulated and experimental results

The performance of the SSMA is analysed using CST software and the results are verified with experimental results. The $S_{11}$ results are measured with a vector network analyzer (Anritsu MS46122B). The gain and radiation patterns are measured with an antenna measurement environment for 1–13 GHz band in an anechoic chamber (size: 6×4×6 mm$^3$) as shown in Fig. 8 and a photograph of the prototype shown in Fig. 2(b). It is observed from Fig. 9, that the $S_{11}$ measured impedance bandwidth nearly the same as the simulated result (139%) and the inset shows a photograph of the fabricated antenna. The measured and simulated peak gain of the SSMA boresight ($\phi = 0^\circ$, $\theta = 0^\circ$) is shown in Fig. 10. The measured peak gain for the lower side-band is <1.56 dBi, and the upper side-band is >3.6 dBi. The measured peak gain at the WiMAX band center frequency of 3.5 and 5.8 GHz are 2.55 dBi and 3.2 dBi, respectively. The measured peak gain at the WLAN 5.2 band center frequency of 5.2 and 5.5 GHz are 2.95 and 3.05 dBi, respectively. For X-band satellite communication 7.8–9.3 GHz, the measured peak gain from 3.0–1.75 dBi is achieved.

![Fig. 9 Measured and simulated $S_{11}$ performance of the SSMA](image)

![Fig. 10 Measured and simulated peak gain of the SSMA](image)
The measured and simulated radiation patterns of the proposed SSMA in the E- and H-plane at 2.8, 6.1 and 9.4 GHz are shown in Fig. 11. It is observed that the proposed SSMA exhibits nearly omnidirectional patterns in both planes. The E- and H-plane cross-polarization components are below -30 dBi in both measured and simulated results. Table 2 represents a comparison performance of SSMA with other antennas presented in the literature.
Table 2 Optimized parameters of the proposed SSMA

| Ref. | Antenna type | Dimension (mm$^2$) | Frequency (GHz) | Fractional BW (%) | Max. gain (dBi) |
|------|--------------|--------------------|-----------------|-------------------|-----------------|
| 1    | Monopole     | 42 × 50            | 2.69 – 10.16    | 116.30            | 6               |
| 2    | Monopole     | 35 × 20            | 3.00 – 10.5     | 111.11            | 4.16            |
| 3    | Monopole     | 28 × 30            | 2.95 – 13.95    | 130.17            | 3.2             |
| 4    | Bow-tie      | 80 × 60            | 2.21 – 4.0      | 57.7              | 6.20            |
| 5    | Tapered slot | 30 × 28            | 2.78 – 12.3     | 126.00            | 6.23            |
| 6    | Monopole     | 36.9 × 36.9        | 3.1 – 11        | 112.05            | 5.6             |
| 7    | Fractal      | 60 × 60            | 10 – 50         | 133               | 9.5             |
| 8    | Monopole     | 28 × 25            | 2.7 – 11        | 121.16            | 3.5             |
| 9    | Monopole     | 29.5 × 39          | 2.2 – 12.1      | 139.00            | 3.6             |
| 10   | Monopole     | 36.9 × 36.9        | 3.1 – 11        | 112.05            | 5.6             |

It is seen that this design performs better in almost all the parameters. The antenna type, dimension, bandwidth and max. gain are listed. The measured fractional bandwidth of the SSMA is exhibiting better 139% with a peak gain of 3.6 dBi within the −10 dB impedance band. Table 2 expresses the performance of the design antenna structure in obtaining enhanced impedance bandwidth and shows better radiation close to omnidirectional patterns with a compact size. Therefore, considering all the performance of the SSMA, it will be a good candidate for UWB applications.

4 Conclusions

The compact coplanar waveguide-fed SSMA using the quarter-circular-slit and partly-hexagonal-ring-slit defected ground structure is proposed and verified experimentally. The impedance bandwidth performance of the SSMA is significantly enhanced by introducing QCS and PHRS. The impedance bandwidth of the SSMA is 2.2–12.21 GHz (VSWR < 2) and broadside maximum gain 3.6 dBi. Owing to the advantages of high gain, good radiation pattern close to omnidirectional, wider bandwidth, and the compact size, the proposed SSMA is suitable for UWB applications.

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