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RESEARCH ARTICLE

Improved Bandwidth of Microstrip Wide-Slot Antenna Using Gielis Curves

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ABSTRACT The development of a broadband printed wide-slot antenna based on Gielis curves is presented in this article. The printed wide-slot antenna can be conveniently reshaped to achieve ultra-wideband performance by using superformula. The distinct advantage of employing the superformula in design of wide-slot antenna lies in its ability to define nearly any geometric shape including non-standard, complex and non-intuitive for the wide-slot and by finely tuning just six parameters. To demonstrate the capabilities of the proposed approach, a simple prototype is fabricated and tested. The satisfactory correspondence between the measurement and the simulation results confirms the effectiveness of the antenna being proposed. The experimental findings reveal that the antenna's impedance bandwidth, where the VSWR is less than 2, spans from 2 to 13.9 GHz, encompassing a range that is 150% wide. Furthermore, the antenna demonstrates a realized gain ranging between 3.8 to 6.4 dBi within its operational frequency spectrum. These results indicate that the antenna exhibits the efficiency and functionality required for application in wideband communication systems.

INDEX TERMS Microstrip-fed, superformula, ultra-wideband, wide-slot antenna.

I. INTRODUCTION

Microstrip antennas have long been favored for use in various wireless systems due to their lightweight, low-cost, compact profile, and seamless integration with other RF components. However, a notable limitation of this type of antennas is their narrow relative bandwidth. Enhancing the bandwidth of microstrip antennas is a common challenge, and numerous strategies have been employed to address this issue. A survey of the literature on wideband antennas reveals that wide-slot antennas are recognized as suitable candidates to obtain broadband characteristics for wireless applications [1], [2], [3].

Researchers have explored various methods to enhance the bandwidth of wide-slot antennas, broadly categorizing these techniques into two groups. The first group involves strategies such as rotating the wide square slot [4], using multiple resonance technique [5], [6], inserting parasitic patches and tuning stubs [7], [8] and applying different feed shapes, like T- and cross-shapes, fork-like shape and square patch [9], [10], [11]. A survey of literature indicates that the second group is based on defected ground structures (DGS) including the use different shapes for slot such as triangular, tapered rectangular, E-shaped, circular and fractal geometries [12], [13], [14], [15], [16] to increase the antenna's bandwidth. In [12], a printed E-shaped wide-slot antenna was proposed with an impedance bandwidth of 121% from 2.8 to 11.4 GHz. A microstrip fractal-shaped wide slot antenna was designed in [13] with 63% impedance bandwidth (2.71-5.18 GHz) which is about 3.5 times that of the corresponding conventional printed wide-slot antenna. The main drawback of microstrip fed wide-slot antennas with wide impedance bandwidth is their size. For instant, the antenna proposed in [16] has wide impedance bandwidth of 148.6% and an acceptable gain of 4.7 dBi, its size is large. To remove this challenge, wide-slot antennas with irregular shapes and parasitic

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elements are merged together [11], [17], [18], [19], [20], [21], [22], [23]. For instance, an irregular polygonal shaped wide-slot has been proposed in [11] with reduced size and an impedance bandwidth of 127.5%. A printed reconfigurable wide-slot antenna has been proposed in [17] exhibits the bandwidth from 3-13.6 GHz (127.7%). Recently, a microstrip wide-slot antenna based on a self-shape blending algorithm has been designed in [21] for working from 2.07 GHz to 5.94 GHz to cover WLAN and WiMAX bands. More recently, a compact circularly polarized wide-slot antenna with 16.2% bandwidth and gain larger than 2.5 dBi has been proposed in [22]. Considering the extent and variety of the researches done in increasing the wide-slot antennas bandwidth by changing the shape of the wide-slot, it is required to provide a general method for the investigation of the effect of the wide-slot with an arbitrary shape in the performance of this type of antenna.

This work introduces a novel approach to designing ultra-wideband printed wide-slot antennas. The proposed method employs the superformula to achieve the appropriate shape for the wide-slot, and obtain the desired bandwidth. To the best knowledge of the authors, the design of microstrip-fed wide-slot antennas based on supershapes has not reported in the literature. The superformula is a generalization of the Lame curve to describe complex and non-intuitive geometries [24], [25], [26]. In recent years, the application of the superformula and complicated shapes in the development and design of various antennas has gained interest. This includes innovations in printed dipole [27], patch antennas [28], [29], [30], dielectric resonator antennas [31], ultrawideband monopoles [32], 3-D printed antennas [33] and lens antenna [34].

The main novelty of the work presented in this paper is based on employing supershapes to improve bandwidth of printed wide-slot antennas for the first time. The distinct advantage of employing the superformula in wide-slot antenna design lies in its ability to define nearly any geometric shape including non-standard, complex non-intuitive for the wide-slot and by finely tuning just six parameters. It is worth noting that without employing the superformula, achieving the optimal shape for the wide-slot within the search space proves challenging and time-consuming, even with advanced optimization techniques. To demonstrate the capabilities of the proposed approach, we present a design of a supershaped wide-slot antenna with an impedance bandwidth of 150% over the frequency band of 2-13.9 GHz and the realized gain of 3.8 to 6.4 dBi within its operational frequency spectrum. With these parameters, the antenna demonstrates superior performance compared to other broadband wide-slot antenna reported to date.

The structure of this paper is outlined as follows. Section II addresses the supershaped wide-slot antenna configuration. The simulation results, discussions and their details are presented in Sec. III. Fabrication and measurement results of the proposed wide-slot antenna are provided in Sec. IV.

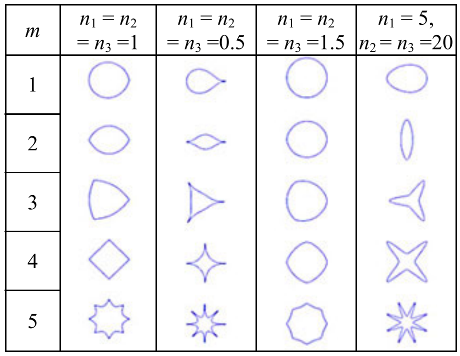

FIGURE 1. Some examples of supershapes with different parameters.

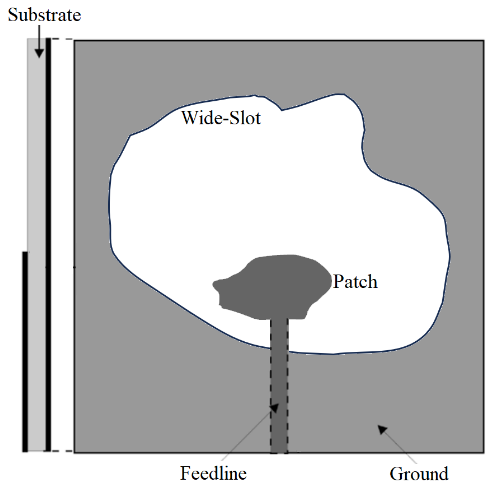

FIGURE 2. Configurations of the microstrip-fed supershaped wide-slot antenna.

II. ANTENNA CONFIGURATION

Johan Gielis introduced the superformula in 2003 to define a wide variety of natural and abstract shapes, such as rectangle, circle, leaf and flower shapes, star-shaped geometris and so on [24]. The general formula in polar coordinates for the supershape is given by:

$$r(\varphi) = \left[\left| \frac{1}{a} \cos\left(\frac{m}{4}\varphi\right) \right|^{n_2} + \left| \frac{1}{b} \sin\left(\frac{m}{4}\varphi\right) \right|^{n_3} \right]^{-1/n_1} \tag{1}$$

where in r and φ are the radius and the angle, respectively, and m, n_1, n_2, n_3, a and b represent 6 arbitrary numerical parameters. This equation, which is an adaptation of the circle equation, can define a wide range of geometric shapes through the adjustment of six parameters. The function of each parameter has been investigated in detail in the previous studies [24], [25], [26]. A few examples are plotted in Fig. 1.

The arrangement of the printed wide-slot antenna with arbitrary shapes for wide-slot and patch is depicted in Fig. 2. The shapes of feed and slot strongly affect the printed wide-slot antennas' bandwidth due to change in the coupling between wide-slot and microstrip line. Up to now, different feed shapes such as polygons, radial stub, cross geometry, T-shaped and fork-like and various slot shapes such as, square,

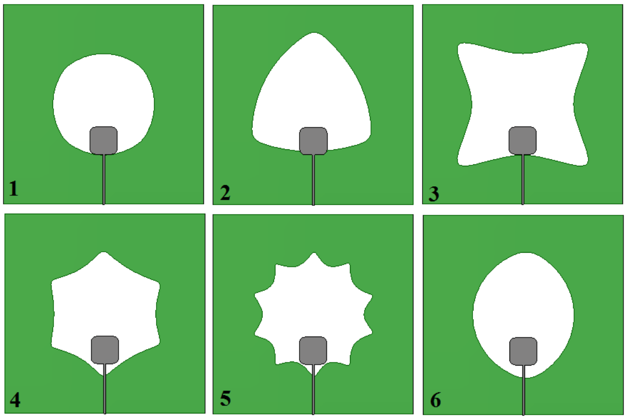

FIGURE 3. Configurations of six microstrip-fed supershaped wide-slot antennas.

TABLE 1. Parameters of six supershaped antennas.

Design	m	n_1	n_2	n_3	a	b
1	4	100	13	10	1	1
2	3	11	13	11	1	1
3	4	6	12	12	1	1
4	6	16	11	10	1	1
5	10	16	13	11	1	1
6	2	15	11	10	1	1

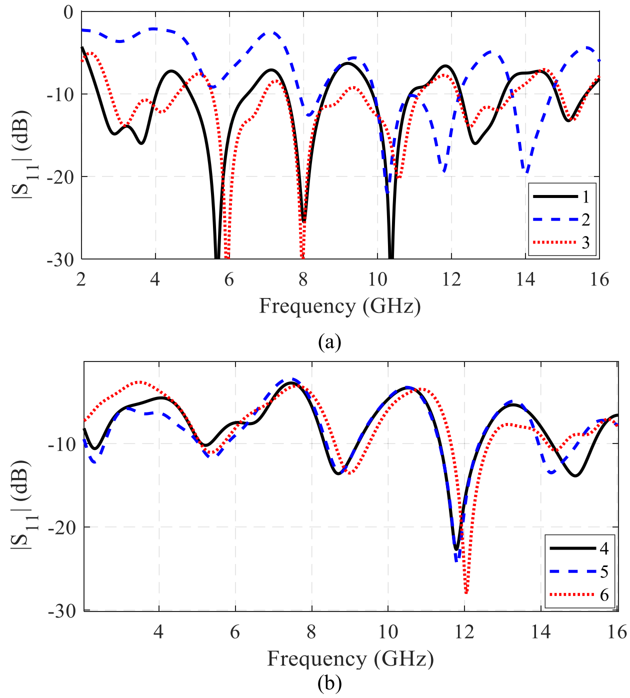

FIGURE 4. $|S_{11}|$ of six supershaped wide-slot antennas.

circular and diamond shaped have been used in the literature. By adjusting the six parameters of the Gielis formula, diverse potential supershape slots can be explored and etched from the ground plane of microstrip antenna. The superformula facilitates the creation of unconventional and innovative geometries for the microstrip-fed wide slot antenna. It is important to highlight that without employing the superformula, finding the optimal shape for the wide-slot within the search space becomes challenging and time consuming, even with advanced optimization techniques.

III. SIMULATION RESULTS AND DISCUSSIONS

A. INITIAL SIMULATION

To investigate the influence of slot shape on antenna's impedance bandwidth, six distinct antennas, designed using the superformula, are demonstrated in Fig. 3. Table 1 provides their geometrical parameters. A scale factor of 26 is used to simply change the wide-slot dimensions. A 50-Ω microstrip line is connected to a square patch patterned on an inexpensive and easily available 0.8 mm FR-4 substrate with $\tan\delta = 0.025$ and $\varepsilon_r = 4.35$. The feed line and patch are placed symmetrically concerning center line of substrate. The feed line width is assumed to be 1.5 mm to realize a 50-Ω microstrip line. On the substrate's opposing side, a supershaped slot is etched on the ground plane. As discussed in [13], to achieve a wide-slot antenna with operating frequency f_0, the circumference of the slot should be approximately equal to:

$$\frac{2c}{f_0\sqrt{\varepsilon_{r,\text{eff}}}} \tag{2}$$

where c is the light speed in the free space and $\varepsilon_{\text{r,eff}}$ is the effective relative permittivity. This can be used to assign initial values for the geometrical parameters of the structure in the optimization process.

The initial simulations are performed using the time-domain analysis tools provided by CST Microwave Studio. Fig. 4 depicts the simulation results of the six printed supershaped slot antennas. Observe that there are some resonance frequencies between 2 GHz and 16 GHz, and the shape of wide-slot has a significant effect on the antenna's impedance bandwidth. Thus, it is expected that by properly adjusting six parameters of superformula, the antenna's bandwidth and matching can be enhanced.

B. OPTIMIZATION

To achieve the desired frequency range of operation, appropriate dimensions of feed line (l_f), rounded square patch (w_p, r_1, r_2) and supershape slot (m, n_1, n_2, n_3, a, b), have to be found by optimization. Briefly, the design procedure of broadband wide-slot antenna based on using supershapes can be expresses as follows:

- The design frequency is determined as the center of the desired working bandwidth.
- The initial shape of the rectangle or circle is selected for the wide-slot with the circumference approximately given by (2).
- For simplicity, the parameters a and b are initially selected equal to 1 and the overall size of shape can be adjusted by scale factor s.

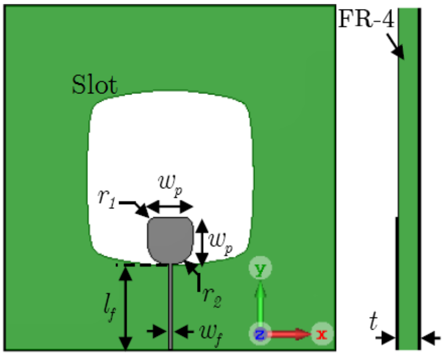

FIGURE 5. Geometry of optimized microstrip-fed supershaped wide-slot antenna.

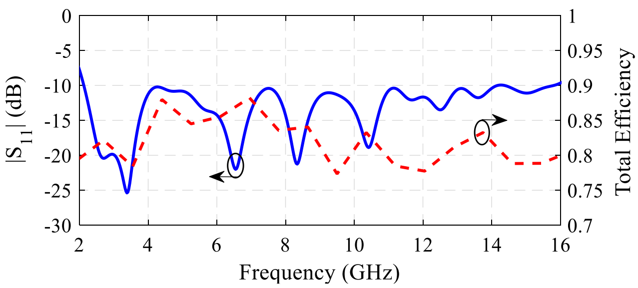

FIGURE 6. Simulated $|S_{11}|$ and total efficiency of optimized supershaped wide-slot antenna.

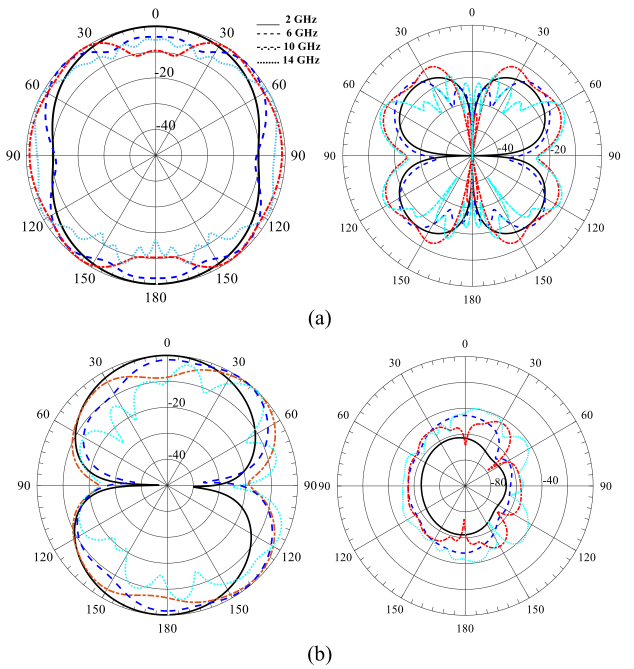

FIGURE 7. Co- and cross-polarized radiation patterns of optimized supershaped wide-slot antenna in (a) xz-plane and (b) yz-plane.

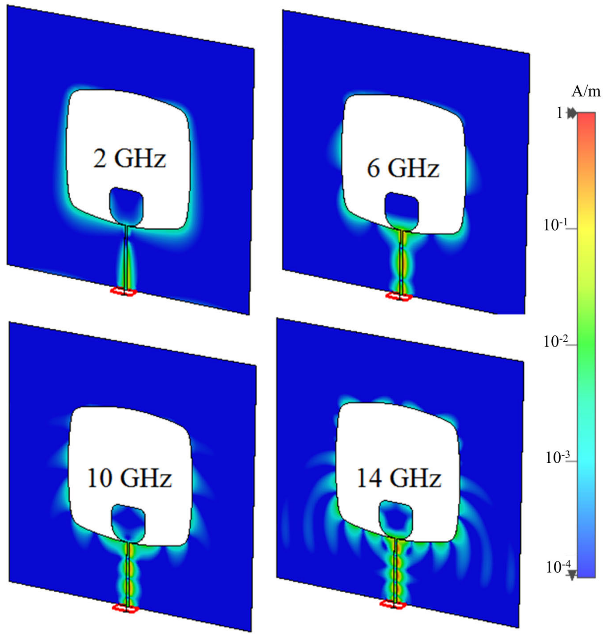

FIGURE 8. Normalized surface current distribution of the antenna at 2, 6, 10 and 14 GHz.

TABLE 2. Comparison of reported microstrip fed wide-slot antenna.

Ref.	Frequency (GHz)	Bandwidth (%)	Peak Gain (dBi)	Effective Size (λ_g^2)
[3]	1.8-2.4	50	5.5	0.82 × 0.82
[6]	1.8-5.7	104	4.5	1.87 × 1.87
[7]	2.8-11.8	123	5.5	1.12 × 1.12
[9]	2.42-8.48	110	6.5	4.2 × 4.2
[12]	2.8-11.4	121	7	2.97 × 2.97
[14]	3-11.2	115.6	5.4	1.22 × 1.22
[15]	1.22-5.97	133	NA	0.78 × 0.78
[16]	0.9-6.1	148.6	4.7	5.4 × 5.4
[11]	1.15-5.2	127.5	5.67	1.53 × 1.53
[17]	3-13.6	127.7	0.5	1.15 × 1.15
[18]	3-8	91	5	0.82 × 0.82
[19]	1.45-4.86	108	5.38	1.26 × 1.26
[20]	3.65-8.75	83	5.8	0.68 × 0.68
[21]	2.07-5.94	97	4.65	1.03 × 1.03
[22]	3.3-3.88	16.2	3.1	0.85 × 0.75
[23]	3.2-8	85.7	3.6	0.50 × 0.50
This Work	2-13.9	150	6.4	1.91 × 1.91

- According to Fig. 3, the allowable ranges of n_1, n_2 and n_3 that control the shape and its curvature of are assumed to be (1-10), (1-100) and (1-30), (1-30) and (1-30) respectively.

The optimization is carried out using the Trust Region Framework algorithm within CST Microwave Studio. To fulfill the desired requirements for the bandwidth and the gain, error function is defined as

$$\text{error} = \left(\frac{1}{M} \sum_{m=1}^{M} \left(|S_{11}(f_m)|^2 + |G(f_m) - G_{\min}|^2 \right) \right)^{0.5} \quad (3)$$

where in S_{11} and G are the desired input reflection coefficient and the gain of the antenna (in dBi), respectively. In the optimization process, the minimum gain of antenna ($G_{\min}$) is

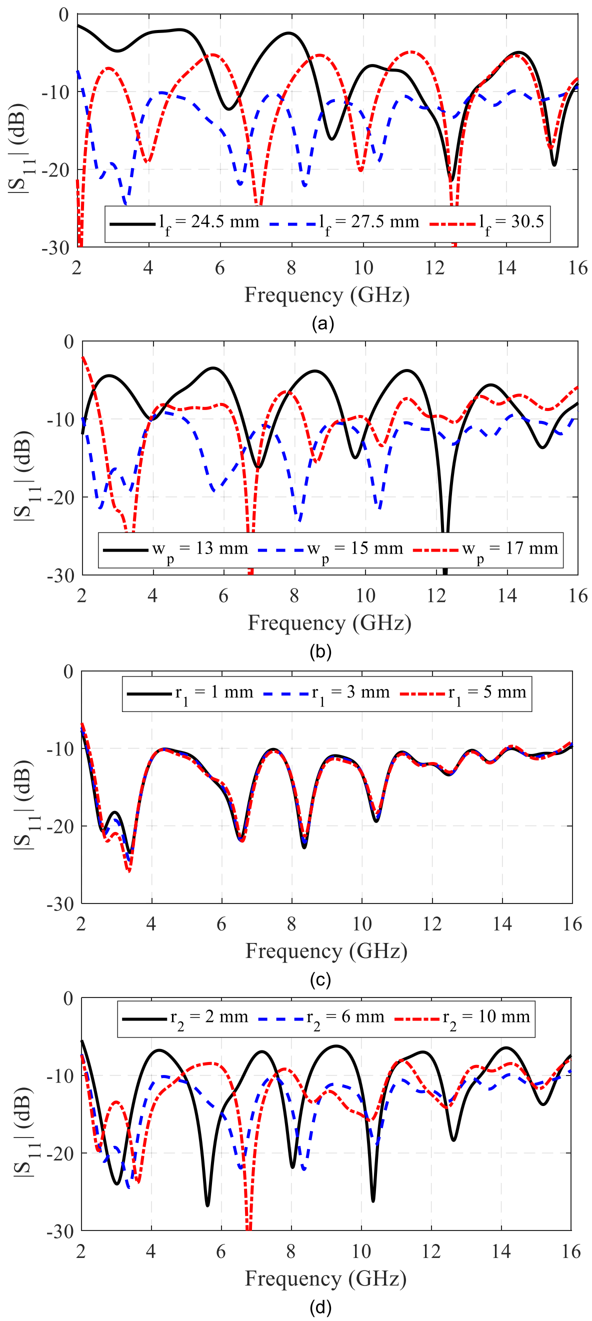

FIGURE 9. Effect of design parameters on the $|S_{11}|$ of the antenna.

assumed to be 4 dBi according to previously reported results in the literature for the other broadband wide-slot antennas.

The final antenna structure with optimized values $m = 4$, $n_1 = 16.09$, $n_2 = 12.77$, and $n_3 = 10.25$ is illustrated in Fig. 6. The optimized parameters of microstrip feed line and patch are the following: $l_f = 20.5$ mm, $w_p = 13.5$ mm, $r_1 = 3$ mm and $r_2 = 6$ mm. Figure 6 indicates simulated input reflection coefficient and total efficiency of the optimized antenna. As noted, the impedance matching of antenna is improved from 2 to 16 GHz (155%) for $|S_{11}| < -10$ dB. The total efficiency of antenna is higher than 77% which is similar the efficiency of the broadband wide-slot antenna presented in [14]. Figure 7 indicates the antenna's radiation patterns in principal planes. Observe that the proposed antenna shows usable nearly omni- and bi-directional radiation characteristics in xz- and yz-planes, respectively.

FIGURE 10. Geometry of optimized microstrip-fed supershaped wide-slot antenna.

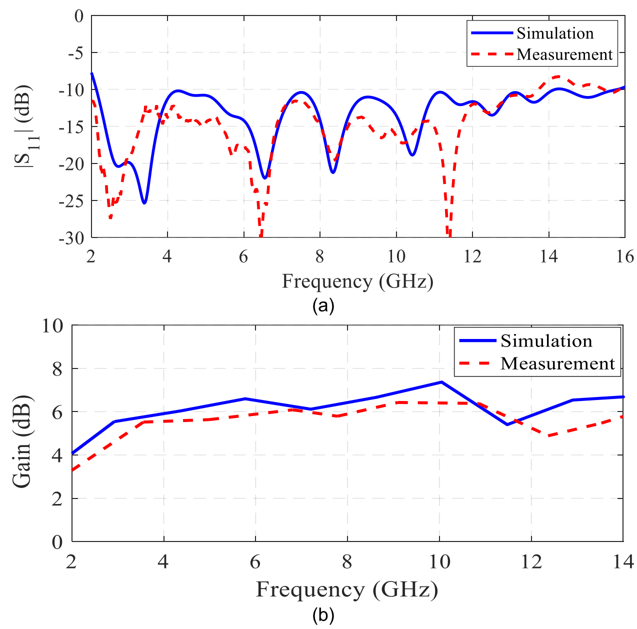

FIGURE 11. Simulation and measurement results of printed wide-slot antenna. (a) $|S_{11}|$ and (b) gain.

It is worth noting that at higher frequencies, there are some distortions in the radiation patterns. In the other word, the radiation patterns are found to be tilted, and the maximum radiation direction is not in the broadside direction of the slot antenna that is in yz-plane. This may be attributed to the substantial electric dimensions of the wide slot and the excitation of unwanted high-order modes. Similar distortion and tilting in the radiation pattern of simple wide-slot antennas at higher frequencies were reported in [3], [9], and [14]. It can also be seen in the full-wave simulated surface current distribution of the antenna at higher frequencies, as shown in Fig. 8.

C. PARAMETRIC STUDY

The dimensions and positioning of the radiating patch are crucial. A parametric study for l_f, w_p, r_1 and r_2 was carried out to assess the effects of these specific parameters on the antenna's bandwidth. Fig. 9 illustrates the antennas' simulated $|S_{11}|$ for

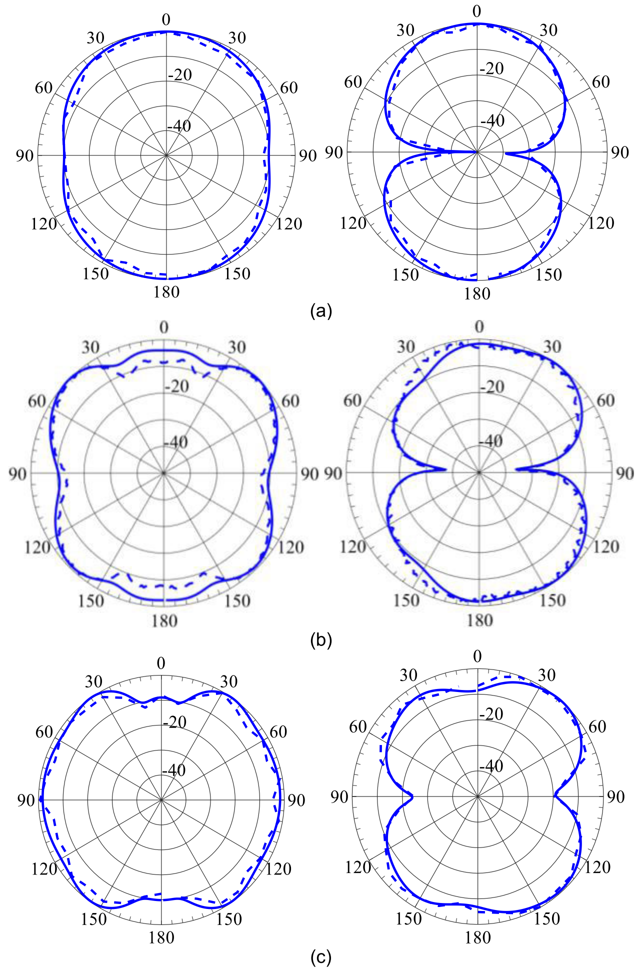

FIGURE 12. Simulated (solid curves) and measured (dashed curves) normalized radiation patterns in E- and H-planes at (a) 2 GHz, (b) 6 GHz and (c) 10 GHz.

different feed line and patch parameters. The results indicate that the performance of the antenna is substantially affected by the rounded corners of the square patch adjacent to the feed line, and by the patch's dimensions and location, while changing the two other rounded corners of the patch does not have a significant effect on the antenna matching.

IV. FABRICATION AND MEASUREMENT

To confirm the simulation results and establish the proof of concept, a prototype of the proposed antenna was built and evaluated. Fig. 10 displays a photograph of the fabricated antenna. Measurements were conducted using the Agilent 8722ES vector network analyzer. Fig. 11 illustrates the measured and simulated results for $|S_{11}|$ and gain of the antenna versus frequency ranging from 2 to 16GHz comparative analysis. Observe that the simulation results are confirmed by measurements. The discrepancy between the experimental and simulation results can be attributed to the electromagnetic performance and dispersion of substrate, fabrication tolerances and the effect of the feeding connector. It seems that the dielectric loss of utilized FR-4 substrate is higher than the value assumed in simulation, which leads to around 1 dB reduction in the measured gain. The measured bandwidth of $|S_{11}| < -10$ dB is 150% in the frequency range from 2 to 13.9 GHz with an average gain of 5.5 dBi.

The normalized radiation patterns of the antenna at 2, 6 and 10 GHz in two main planes is illustrated in Fig. 12. The simulated results align reasonably well with those observed in experiments, indicating acceptable agreement. The main reasons of the differences are the dispersion of FR-4 substrate and measurement uncertainty.

Finally, the proposed design was evaluated by comparing its specifications and performance with those of similar antennas previously reported in the literature, as detailed in Table 2. The dimensions of the antennas are normalized to the guided wavelength (λ_g) at the central frequency of return loss bandwidth for each antenna (VSWR < 2). The proposed antenna showed the maximum gain of 6.4 dBi with broad bandwidth of 150% and a reasonable size in comparison with other similar antenna structures. In the future, we intend to use this design to realize a high gain broadband cavity-backed microstrip-fed wide-slot antenna array [35].

V. CONCLUSION

The paper presents the design of a broadband microstrip-fed wide-slot antenna with a slot shaped using a superformula. By choosing the appropriate supershape for the slot, an antenna with significantly enhanced impedance bandwidths is achieved. The experimental findings indicate that the antenna design achieves an impedance bandwidth ($|S_{11}| < -10$ dB) of 150% centered around 7.95 GHz. The proposed antenna has can be scaled to use in various ultra-wideband applications.

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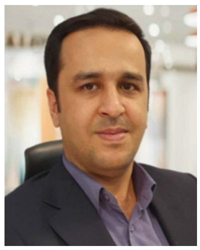

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