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Compact Ultra-Wideband Printed Monopole Antenna with Improved Radiation Characteristics

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Abstract – **The ultra-wideband (UWB) performance in terms of thin substrate, small size, high gain, and low cross-polarization level are nicely presented in this paper. It is accomplished by adding two circular slots, one hexagonal patch, and also a radiating circular patch at the top of the antenna. Wider bandwidth is attained with the use of circular and hexagonal patches. The rectangular patch added at the ground plane is basically to improve impedance matching without affecting the other antenna performances. In order to validate simulated results, the proposed antenna is designed, fabricated, and tested in the laboratory. The measured absolute and fractional impedance bandwidth is achieved as 23 GHz, and 158%. The experimental results of the average peak realized gain of 6.9dBi, the average radiation efficiency (simulated) of 73.5%, and the cross-polarization level below -22dB have been achieved at the whole band (4-27GHz). The simulation and experimental results are in good agreement. Additionally, the antenna offers a compact size. Finally, a comparison table of this proposed work with the state-of-the-art is provided at the end. This UWB antenna is suitable for personal area network wireless connectivity, wide-range, low data rate communications, and radar and imaging systems applications.**

Keywords – **Compact; figure of merit (FOM); impedance bandwidth; improved gain; ultra-wideband (UWB)**

I. Introduction

Nowadays, the modern communications systems have increasingly relied on ultra-wideband (UWB) communications technology. Furthermore, it became possible to improve the designs of UWB channels and communication systems by using the complex antenna transfer function (CATF) of a UWB antenna. As far as the background theory is concerned, a compact ultra-wideband (UWB) antenna is an antenna that can operate over a wide range of frequencies with a small physical size. UWB antennas can transmit and receive signals with a bandwidth greater than 500 MHz or a fractional bandwidth more significant than 20%. A compact UWB antenna design typically involves various techniques [1, 2], such as frequency notching, parasitic elements, and metamaterials to achieve the desired frequency response.

One popular type of UWB antenna is the printed monopole antenna [3, 4], which consists of a printed metal strip on a dielectric substrate. Other types of UWB antennas include planar inverted-F antennas (PIFAs), slot antennas, and fractal antennas. These antennas are often used in wireless communication systems, radar systems, and medical imaging applications to get better outputs. Some advantages of UWB antennas include the ability to transmit large amounts of data over short distances, the resistance to interference, and low power requirements. However, they also have some disadvantages, such as reduced range compared to narrowband antennas and the potential to cause interference to other nearby radio systems. Overall, UWB antennas became an essential technology for various applications for their compact size particularly in applications where space is limited. There is a vast amount of literature available on compact ultra-wideband (UWB) antennas, which are typically designed to operate over a broad range of frequencies from a few hundred MHz to several GHz. Here are some resources that you may find helpful in learning about compact UWB antennas.

The planar shape that offers the widest input bandwidth has undergone significant research. In order to attain the ideal planar shape, many planar monopoles with various geometries have been experimentally characterized [5–13], and automatic design methods have been created [14, 15]. Two new compact wideband planar monopole antennas were presented in Refs. [16] with a truncated ground plane and L-shaped notch in the lower corner to obtain the highest impedance bandwidth. Additionally, various methods to increase the impedance bandwidth that do not need changing the planar antenna's design have been researched. These tactics essentially include modifying the structure to include a shorting post [17] or using two feeding points to excite the antenna [18].

Recently, there has been a resurgence in interest in UWB technology. As of 2019, smartphone manufacturers have begun implementing location estimation technology by including a UWB chip. In addition, many businesses are developing indoor location tracking systems based on UWB technologies in various market segments, such as smart factories, smart homes, etc. [19]. Because UWB signals are precise and dependable, their popularity has recently returned. Although alternative radio frequency signal-based locating systems like GPS, Wi-Fi, and Bluetooth exist they cannot be utilized indoors due to non-line-of-sight satellite transmissions, and other technologies need to offer sufficient accuracy and dependability [20, 21]. Keeping in mind that UWB short pulse signals can accelerate transmission, combat multipath fading and frequency selective fading, and provide excellent security and resolution for accurate indoor positioning systems [22]. Moreover, a few antennas based on

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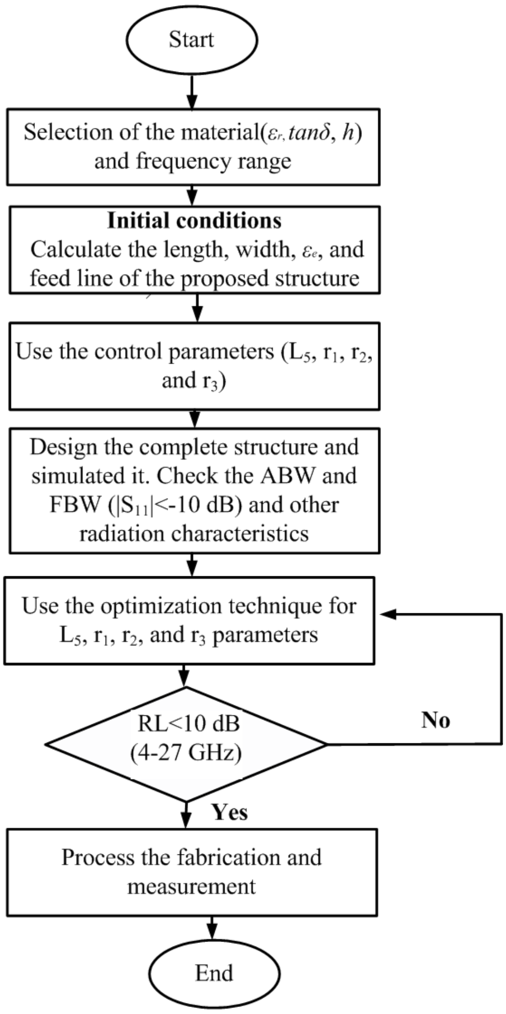


Fig. 1. Design process to determine the dimensions of the proposed UWB antenna (ABW: Absolute bandwidth; FBW: Fractional bandwidth; RL: Return loss).

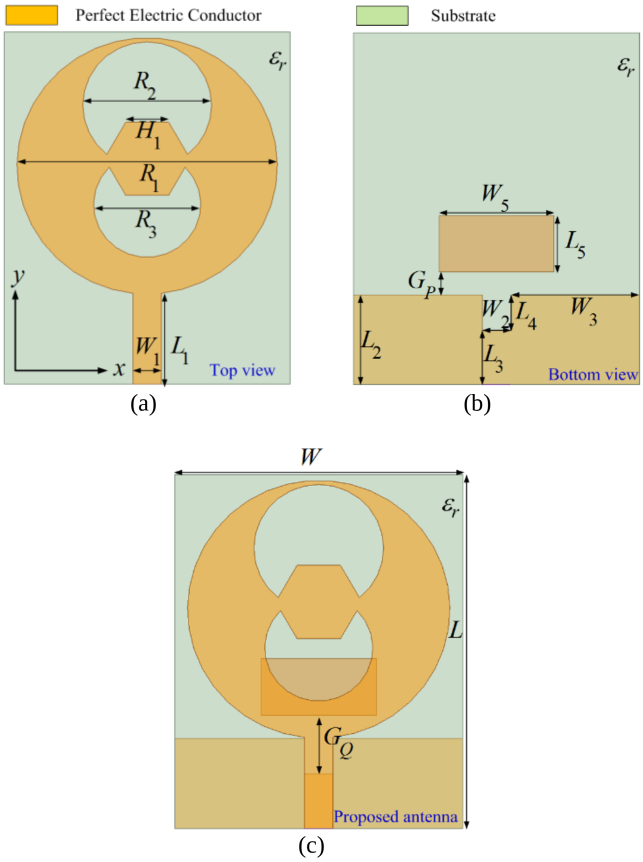


Fig.2. Proposed UWB antenna: (a) Top view, (b) Bottom view, (c) Proposed final antenna.

applications such as Wi-Fi, microwave access (WiMAX), wireless local area network (WLAN), C-and X-band have been implemented in monopole antenna [23–26]. Ref. [23], Using a microstrip line (50 Ω) is suggested to feed a frequency-reconfigurable honey-bee small microstrip monopole antenna, which can operate in dual-band and triple-band modes in eight different ways. Three PIN diodes embedded over the honey-bee limbs control the effective current distribution, changing the resonance frequency in eight modes in real-time. A heart- shape frequency reconfigurable monopole antenna with polarization diversity has been discussed in [24]. The antenna has four soldered positive-intrinsic-negative (PIN) diodes on its ring slot and two cross slots. The effective current direction has been varied by manipulating the four PIN diodes that make up the switch, resulting in four different polarization states. For Internet of Things (IoT) devices using the anticipated wireless standard Wi-Fi-6, a new reversible printable monopole antenna has been reported in [25]. The antenna has switched its operating frequency ranges from 2.4GHz to 5GHz (ISM bands) based on the effective resonant length. The constructed antenna has operated as a band-pass filter, reducing receiver complexity, and promoting network scalability. In order to achieve frequency reconfigurability, the antenna radiator has been integrated with a single PIN diode with a complete biasing circuit. A compact tri-band and broadband frequency reconfigurable antenna for cognitive radio applications has been discussed in [26]. This antenna combines a reconfigurable communication antenna with a UWB sensing antenna on the same substrate. A UWB-printed elliptical monopole antenna that can cover the entire UWB frequency spectrum from 3.1 to 10.6GHz and broadband up to 20 GHz is used as the sensing antenna. It operates in the frequency range of 2.72 to 23.8 GHz. Furthermore, a few UWB antenna performances are also studied [27]-[33]. It can be observed that the reported antennas performances are restricted in size, bandwidth, and gain. For an example, the absolute bandwidth (ABW) below 8 GHz have been achieved [27-30]. On the other hand, the ARB has been obtained of 11.4GHz in [31]. Recently, a few authors have been used the metasurface in order to enhance the gain and to obtain the good directivity, as reported in [34]-[36]. Similarly, the gain is not also significantly high as per requirement. In order to improve the impedance bandwidth, compact antenna, and improve gain, this work is mainly focused on achieving them.

This work mainly aims to obtain the ultra-wideband, compact size, low profile, reduced cross-polarization level, and improve the other antenna radiation characteristics. Furthermore, this paper presents a thin substrate ($0.0254\lambda_0$) realization with enhanced matching bandwidth. Initially, the patch is designed for a 3-30 GHz frequency range, and then additional steps toward improving the impedance bandwidth is considered. A combination of a circular radiating patch, and a hexagonal patch, along with two circular slots are implemented in the proposed design. In addition, a rectangular patch is used in the ground in order to improve the impedance bandwidth. The antenna is designed and tested to validate with simulation data.

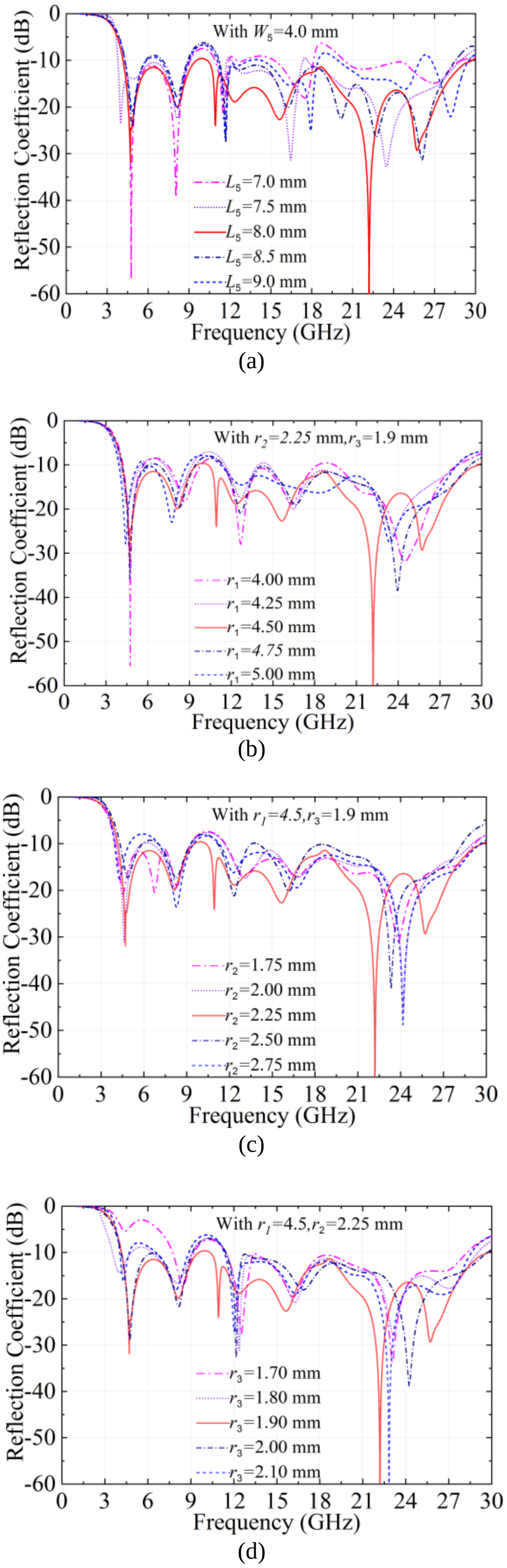


Fig. 3. Effects on $|S_{11}|$ with the different parameters: (a) L_5, (b) r_1 (c) r_2, (d) r_3

The paper is organized as follows. In Section 1, the necessity of using design techniques in antenna engineering is discussed with special emphasis on the present work. The details of the developed design procedure are discussed in Section II. Section III describes implementing the developed methodology for designing the UWB monopole antenna. The UWA antenna was taken as a candidate antenna to verify the developed methodology. Concluding remarks are provided in Section IV.

II. Design and Analysis of The Proposed Antenna

Initially, the design process to determine the dimensions of the proposed UWB antenna to follows the designed steps, as shown in Fig. 1. Fig. 2 shows the top view (left side, Fig. 2(a)), bottom view (right, Fig. 2(b)), and final (bottom, Fig. 2(c)) views of the proposed antenna. In Fig. 1(c), the antenna structure consists of three sections: a feeding section with an impedance matching section, a radiating patch (combination of circular and hexagonal slots), and a ground section. Initially, a simple patch antenna with a microstrip feed is designed and simulated. (see Fig. 2). A circular radiating patch is implemented with a diameter of $R_1 = 2r_1$. Thereafter another two circular slots are etched from that circular patch in order to obtain the symmetrical current distribution. Additionally, a hexagonal radiating patch is used at the patch's center, which enhances the antenna radiation characteristics. In addition, a rectangular patch is used at the ground part (see Fig. 2(b)) to provide a better impedance matching, and the matching section also helped to get a better match due to the electrical coupling. However, the dimensions of this rectangular patch are optimized to fix them, as shown in Fig. 2. In Fig. 3(a), when L_5 is varied from 3mm to 5mm with a step size of 0.5mm, the value of L_5=4mm provides the best impedance matching in the whole band.

The dimensions of proposed antenna are used as follows L_1 = 6.45, W_1 = 2, L = 19 W = 19, $R_1 = 2r_1$ = 9.1, $R_2 = 2r_2$ = 4.5, $R_3 = 2r_3$ = 3.75, H_1 = 3, L_2 = 6.36, L_3 = 3.86, W_5 = 8, W_3 = 9, W_2 = 2, G_P = 1.64, G_Q = 4.11, L_5 = 4, h = 0.508; unit: millimetres. The substrate thickness is 0.508mm, i.e., less than $0.045\lambda_0$ at mid frequency band (f_0=15GHz).

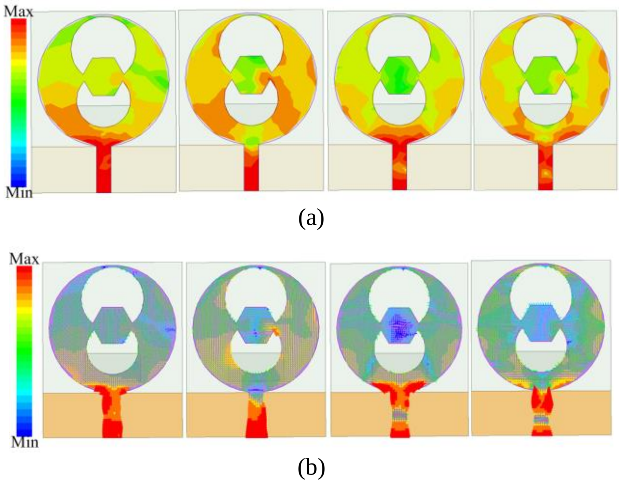
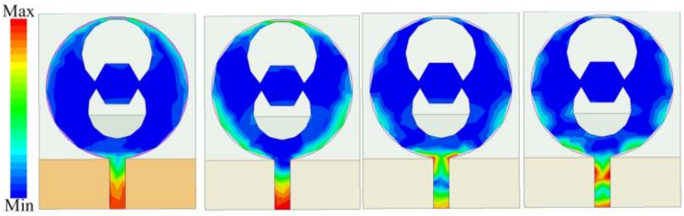
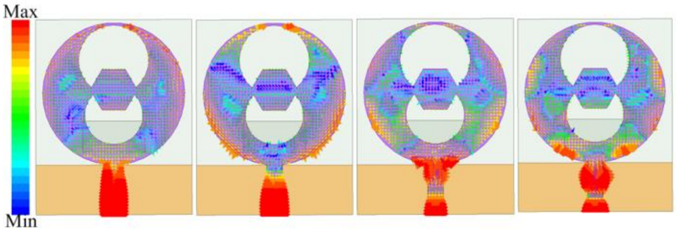


Fig. 4. Surface current distribution: (a) Magnitude, (b) Vector forms at 4.7, 8.2, 15.7, and 22.2 GHz (from left to right).



(a)



(b)

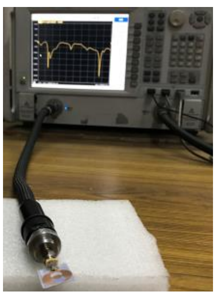
Fig. 5. Electric field distribution: (a) Magnitude, (b)Vector forms at 4.7, 8.2, 15.7, and 22.2 GHz (from left to right).

The structure is implemented with the Rogers RT Duroid 5880 (TM) material (ε_r = 2.2 and dissipation factor=0.0009). All the simulations were carried out using Ansys HFSS ver. 2020R2.

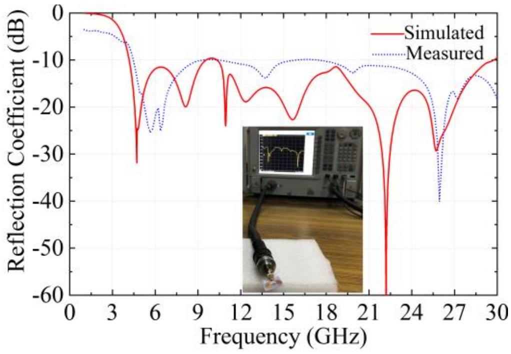
In order to fix the dimension of the circular shape of both slots and radiating patch, the dimensions are varied, as shown in Fig. 3. At the initial stage, the L_5 is varied from 7 to 9mm with a step size of 0.5mm, as shown in Fig. 3 (a). It can be noticed from this Fig. 3 the impedance matching obtained better than 10dB at L_5 =8mm. The radius of the radiating patch r_1 is varied from 4 to 5mm with a step size of 0.25mm along with the other parameter remains constant (r_2 and r_3) as shown in Fig 3(b). It can be observed from 3.5 to 30 GHz; the return loss is better than at r_1 =4.5mm and worst at 4 and 5mm. Similarly, the r_2 and r_3) are also varied with constant of r_1 =4.5mm (see Fig. 3(c) and (d)). As a result, the impedance matching is found better at r_2 and r_3 at 2.25 mm and 1.90 mm, respectively. These three parameters play a significant role in achieving the UWB bandwidth and provide better impedance matching.

In order to further explain the influence of the combination of circular slots and radiating patch, Fig. 3 compares the surface current distribution of both vectors (see Fig. 4(a)) and magnitude (see Fig. 4 (b)) form with the slot at the different resonant frequencies of 4.7, 8.2, 15.7, and 22.2GHz, respectively.

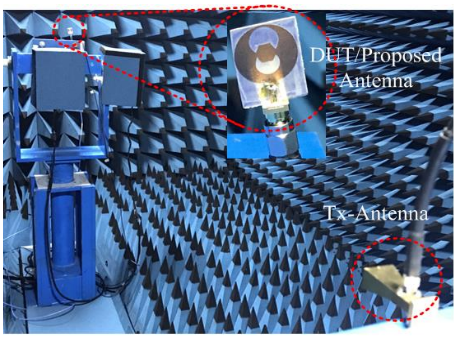
(a)



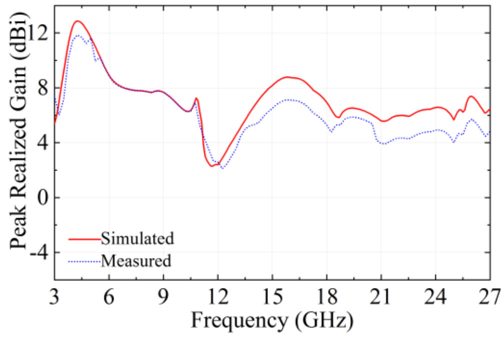
(b)



(c)



(d)



(e)

Fig. 6. Fabricated prototypes, simulated and measured results, and measurement setup of the proposed antenna: (a) Fabricated prototypes, top view (left), bottom view (right), (b) Measurement setup with VNA, (c) Reflection coefficient, (d) Measurement setup with Anechoic chamber, and (e) Peak realized gain

TABLE 1
COMPARISON OF COMETATIVE WITH PROPOSED ANTENNA

Ref.	Antenna Volume (mm^3)	Freq. (GHz)	Gain Min/Max (dBi)	FBW (%)	FOM
[37]	0.0399	3-11	-3.9 to 5.8	114	10565
[38]	0.0254	2.5-12.5	2.6/6.4	133	23195
[39]	0.095	1.5-5 25-29.3	3.8/7.8	107/ 15.8	2692/ 1001
[40]	0.007	3-12	-4 /5	NR	DI
This Work	**0.0315**	**4-27**	**2.11 / 11.68**	**158**	**24562**

DI=Data insufficient

As it is seen, the surface current flows to the broad-sight direction at four different resonant frequencies. And, of course, the coupling current in the middle of the patch is reduced. Hence the cross-polarisation level is reduced significantly. The effect is the same as that of all four resonant frequencies. Similarly, the electric field distribution (both magnitude and vector, as shown in Fig, 5 (a) and (b)) is also plotted, as illustrated in Fig. 5.

III. Simulation and Experimental Validation

The top and ground views of the fabricated antenna prototype are shown in Fig. 6(a). The measurement setup with VNA is illustrated in Fig. 6(b). The simulated and experimental results of the return loss are also illustrated in Fig. 6(c). The measured fractional bandwidth (FBW) of 158% and absolute bandwidth of 23 GHz is obtained. The experimental setup of the anechoic chamber where the measured radiation characteristics are shown in 6(d). Fig. 6(e) shows the experimental values of maximum and minimum peak gains of 11.68 and 2.11dBi (simulated: 12.87 and 2.27 dBi). The maximum and minimum simulated radiation efficiencies are observed as 87 and 60%, respectively, at the whole band (4-27 GHz). The measured and simulated normalized radiation patterns are plotted, as shown in Fig. 7 (a)-(d). The measured cross-polarization level below -22 dB (simulated: -22 dB) is achieved. One can easily observe the simulated and measured antenna characteristics and parameters are in good agreement. It is noted that the radiating patch increases with the decrease in resonant frequency. In light of this, the authors restricted the comparison of compact with reported in the lower or higher frequency range. However, the authors have introduced the figure of merit (FOM) in order to make a fair comparison with the reported previous work. The FOM is defined as:

$$FOM = \frac{Gain(\text{Absolute}-\text{scale}) \times \text{FBW}(\%)}{\frac{Volume}{\lambda_0^3}} . \quad (1)$$

Finally, a comparison table is presented to compare the similar types of UWB planar monopole antenna with the state-of-the-art in Table 2. The impedance bandwidth (both ABW and FBW), peak realized gain and radiation efficiency are higher than [37] – [40]. It can be observed that from Table 2, the proposed antenna is more compact than [37, 39] and a little bit higher than [38] and [40]. It is also noted from the experimental results that the low and high-loss substrates are well compared with the state-of-the-art.

IV. Conclusion

This work possesses the ultra-wideband with a low profile, compact size, low cross-polarization level, and more proficient radiation characteristics that are discussed in this paper. The demonstrated antenna has been designed, fabricated, and verified experimentally. The proposed antenna achieved a measured FBW of 158%, a maximum peak gain of 11.68dBi, a maximum radiation efficiency of 87%, and a cross-polarization level of less than -22dB at 9.85GHz over the whole band. The proposed antenna can be suitable for different applications like personal area network wireless connectivity, wide-range, low data rate communication, and radar and imaging systems.

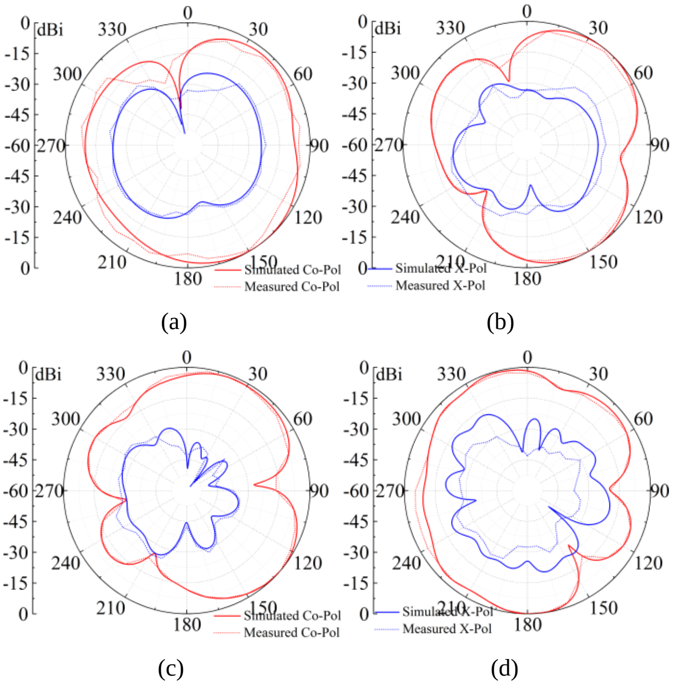


Fig. 7. The simulated and measured normalized radiation patterns of E-planes at different frequencies: (a) 4.7 GHz, (b) 8.2 GHz, (c) 15.7 GHz, (d) 22.2 GHz

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