A novel wideband circularly-polarized microstrip antenna array based on DGS for wireless power transmission

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ABSTRACT

The requirement for applications operating at a variety of frequencies in a unified wireless device has greatly enhanced in recent years. For this purpose, multi-functional wireless components are essential. This paper presents a new design of a wideband circularly-polarized microstrip antenna array with defected ground structure (DGS). A previous design was introduced which cover the C-band at 5.8 GHz and operates in the industrial scientific medical (ISM) band for wireless communication applications. The proposed antenna has excellent performances which include good input impedance matching with a fed of the circular polarization at 5.8 GHz. The proposed design is validated and optimized by adding a new design of defected ground structure. This aperture geometry enables the antenna to operate in a wideband. The obtained results show that the modified antenna has a good performance in terms of return loss, bandwidth, gain and radiation pattern and demonstrate that the proposed antenna offers a good solution for multi-standard wireless communication applications.

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1. INTRODUCTION

As the demand increases day by day, the production of energy increases and the usage of cables and batteries is forbidden due to the difficulty of implementation in some inaccessible areas and the limited life of batteries, even for low power batteries, requiring inconvenient periodical replacement [1]. The wireless power transmission (WPT) has attracted enormous attention in recent years as one of the technologies capable of changing the way energy is distributed. It is a process of transmitting electrical energy without the need of a cable from a power source to an electrical load. It is the preferred choice in cases where interconnecting wires are impractical, unsafe or impossible [2]-[4].

Specifically, a WPT system converts direct current (DC) into microwaves and transmits them in free space to a target. After being transmitted, any system that requires power has the task of receiving and converting the microwaves back into useful DC power [5], [6]. The apparatus used for this reception and conversion is called a rectenna (rectifying antenna), this expression being derived by the fact that a rectenna is composed of an antenna coupled to a rectifier circuit [7]. The block diagram of a rectenna contains mainly a receiving antenna followed by a radio frequency (RF)-DC rectifier circuit and a resistive load.

The most important equipment in the wireless communication system is the antenna. An antenna is a transducer, which is used to convert one form of energy into another [8], [9]. It is meant to receive or transmit electromagnetic waves from a source to one or more destinations. During the design of a compact telecommunication system, the goal is always to achieve a high-quality circular polarization (CP) which provides robust communication capabilities without the need to align the polarization between the transmit and receive antennas [10].

Circular polarization, compared to linear polarization, has drawn a great deal of interest in modern wireless communication systems owing to their inherent advantages including greater mobility, better penetration over time, insensitivity to multipath reflection, suppression of polarization loss, and immunity to Faraday rotation effects introduced by the ionosphere [11]-[13]. Lately, great attempts have been made to design CP patch antennas with compact size and high gain for simple integration with other microwave circuits and high signal to noise ratio. The microstrip patch antennas constitute an interesting selection based on their small profile, low weight and low manufacturing cost and ease of integration [14], [15].

Two of the major disadvantages of this kind of structure are the poor gain and the very narrow impedance bandwidth, both of which need attention because the quality of the antenna relies on them [16], [17]. Hence, a lot of research has been carried out to surmount them since for many applications, there is a necessity of designing antennas with very high directional characteristics (very high gain) to comply with the requirements of long-distance communication [18], [19]. which would be difficult with a single element. This may be realized by forming a combination of several radiating elements into a unique configuration. This new form of antenna is known as an array [20], [21]. In some situations, the usage of a conventional antenna array may not meet the requirements caused by its bigger geometrical dimensions compared to its reserved space in the system housing.

The focus of the researchers has been on developing methods for the miniaturization and multiutilities of antennas and integrated circuits. Numerous applications require a significant effort to provide a small antenna array with acceptable performance in terms of bandwidth, gain and efficiency. In fact, different strategies are already proposed to reduce the size of the antenna array and make it multi or wide-use. Recently, the defected ground structure (DGS), defective microstrip structure (DMS) and electromagnetic bandgap structure (EBG) [22], [23] have received a lot of attention due to their ease, as well as the flexibility to be introduced in the designs of the structures. Several configurations of DGS have been exploited to miniaturize antenna or rather antenna array. With the introduction of new DGS structures in the ground plane of the antenna without altering these geometric dimensions, the array characteristics, such as gain, radiation efficiency and bandwidth are ameliorated while still retaining the same volume of the patch antenna [24], [25].

In this work, a new design of DGS etched in the ground plane of a novel design of microstrip patch antenna array. The novelty of the design comes from the addition of two unique shapes of DGS etched in the two bottom corners of the ground plane. Compared with the primary design of a planar array arrangements with four elements resonating at 5.8 GHz, the antenna characteristics are ameliorated without change these basic dimensions with a wide bandwidth about 1.2 GHz which make it able to support certain recent wireless communication standards.

2. DESIGN PROCEDURES

2.1. Circular polarized antenna array design for wireless power transmission

To develop the suggested concept, we have started from a 4×1 antenna array. The whole geometric structure and the dimensional parameters of the basic structure are clearly indicated in Figure 1. The circularly polarized array antenna that has been designed consists of four radiating elements printed on a low-cost flame-retardant (FR) 4 epoxy substrate, having a dielectric constant ε_r = 4.4, thickness h = 1.6 mm and loss tangent of 0.025, supported by a ground plane of 80 mm × 40 mm. The elements of this antenna array are excited by single corporate feeding networks and arrangements. This feed arrangement consists of matching transformer, quarter wave transformer ($\lambda/4$), coupler and power divider for better impedance matching between the feed and the radiating elements. The antenna array elements are separated by an edge-to-edge distance of 0.9 λ_0 where λ_0 is the free space wavelength of the resonant frequency of 5.8 GHz. The physical dimensions of the radiating array are presented in Table 1.

The dimensions of the initial antenna array are optimized by using two different solvers. Figure 2 shows the initial antenna array simulated return loss coefficient as a function of frequency. It's observed that the designed antenna array provides a good matching input impedance with a good return loss of -21 dB in the first simulator and -17.62 dB in the second, at operating frequency of 5.8 GHz, which cover industrial scientific medical (ISM) band.

The design of this initial antenna array is for the purpose of meeting the requirements of power transmission through wireless links in the case of long distance which necessitates the conception of antennas with very high directive rather than high gain characteristics and a wide band of circular polarization. The employing of the antenna array not only enlarged the axial ratio bandwidth but also increase the gain value. The Figure 3(a) and Figure 3(b) present a comparison of the curves for the axial ratio and gain between the antenna element and the array antenna respectively. Besides, we note favorably that the gain is improved with a value of 6.79 dBi. The 3 dB axial ratio is about 1.2 dB at the operating frequency 5.8 GHz with a bandwidth nearly even 140 MHz, which is significantly better than that of the single element. It can very well meet the requirements of indoor wireless applications.

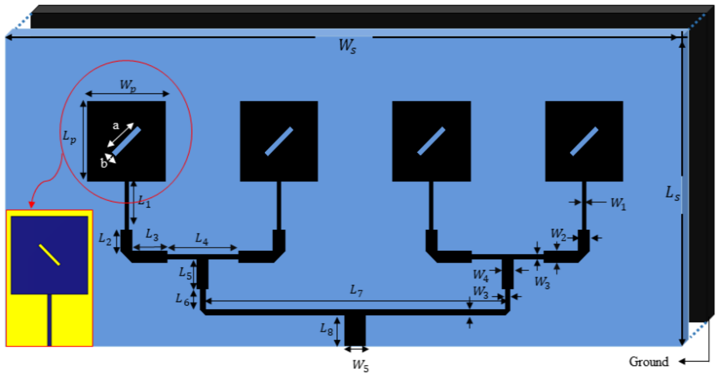


Figure 1. Geometry of the circular polarized antenna array 4×1

Table 1. Dimension of the designed CP antenna array

Parameter	W_s	W_p	W_1	W_2	W_3
Value	80 mm	11.35 mm	0.5 mm	1.657 mm	0.706 mm
Parameter	W_4	W_5	L_s	L_p	L_1
Value	1.657 mm	3 mm	40 mm	11.25 mm	7 mm
Parameter	L_2	L_3	L_4	L_5	Z_0
Value	5 mm	10.533 mm	43.674 mm	5	50 Ω
Parameter	Z_1	Z_2	a	b	t
Value	100 Ω	70.71 Ω	5.35 mm	0.5 mm	0.035 mm

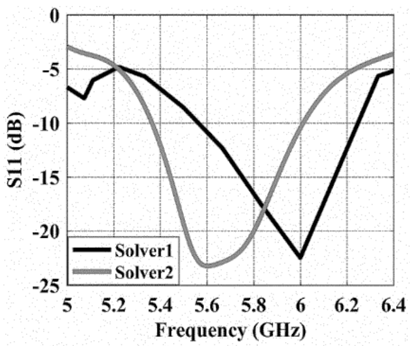
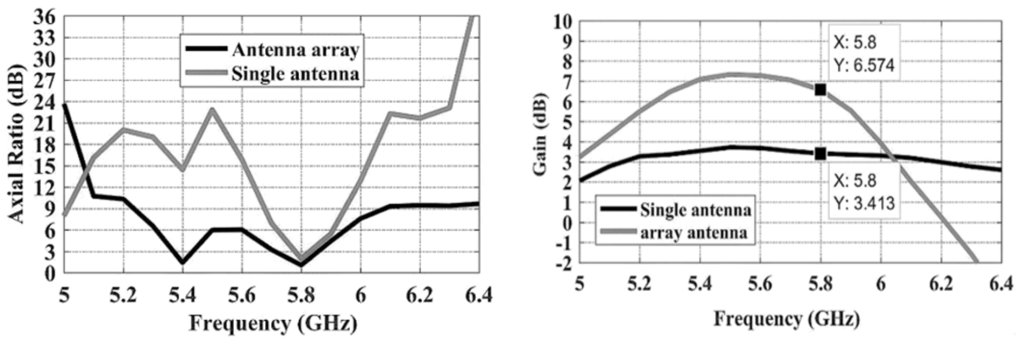


Figure 2. Comparison between the antenna reflection coefficient obtained by both simulators



(a) (b)

Figure 3. Comparison between the antenna element and array in terms of (a) axial ratio and (b) gain

2.2. Defected ground structure geometry

To enhance the performance of several microwave circuit devices or to fine-tune and refine the frequency response of microstrip components, a slot or an opening in the ground plane is purposely modified. The modifications of the ground plane are typically referred to as defects, and from there becomes the name for this class of components. The defect ground structure is created by etching a slot in the ground plane. The distribution of the shielded current in the ground plane is disturbed, depending on the shape and size of the defect, resulting in an excitation and controlled propagation of electromagnetic waves through the substrate layer. DGSs can be classified into two categories based on their configuration: one group consists of structures based on a single defect which are used to vary the frequency response of a printed circuit board, whereas the other comprises structures based on a small number of defects, in either a periodic or non-periodic arrangement, employed to enhance the characteristics of single defects. The idea in this research is focused on the same objective but with the use a new structure of defected ground structure. The concept of the geometry of the defect explored in the present design is simple as shown in Figure 4. This DGS shape is composed of four rectangle-shaped defect areas linked together in the form of stairs etched in the two lower corners of the rear metal ground plane, where W_{DGS1}, W_{DGS2}, L_{DGS1} and L_{DGS2} are the horizontal and vertical length of the slot. The defect dimensions are not randomly chosen, but rather are carefully selected to achieve the desired electromagnetic effect. For which purpose a parametric study has been performed as a function of the number of rectangle units in the DGS and the vertical length of the slot L_{DGS1}. Figure 5(a) and Figure 5(b), Figure 6(a) and Figure 6(b) illustrates the evolution in terms of reflection coefficient and axial ratio respectively. After many optimizations, the dimensions of the DGS are $W_{DGS1} = 16\ mm$, $W_{DGS1} = 4\ mm$, $L_{DGS1} = 19\ mm$, and $L_{DGS2} = 4\ mm$.

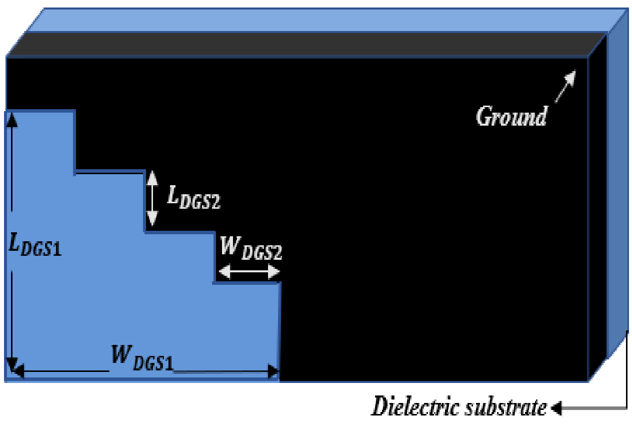
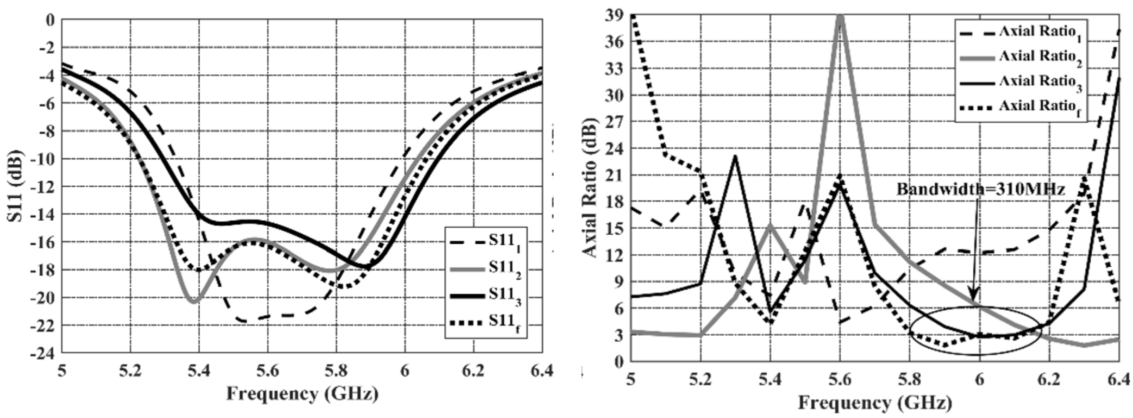
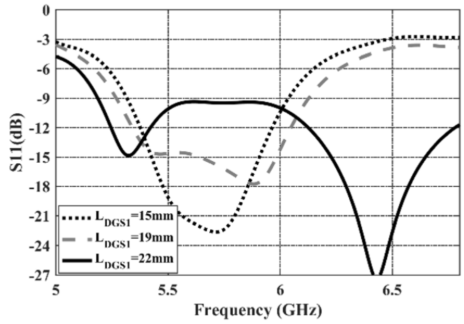


Figure 4. Geometry of the proposed defected ground structure

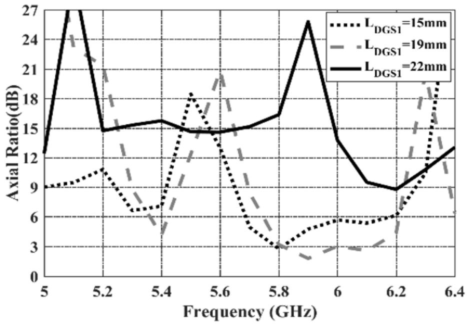


(a) (b)

Figure 5. Simulated curves for varying the number of rectangle units in the DGS of (a) the reflection coefficient and (b) the axial ratio



(a)



(b)

Figure 6. Simulated curves for varying L_{DGS1} of (a) the reflection coefficient and (b) the axial ratio

3. RESULTS AND ANALYSIS

3.1. Printed circularly polarized antenna array with defected ground structure

The proposed microstrip patch antenna with defected ground structure shown in Figure 7 was modeled, optimized and simulated using a 3D electromagnetic (EM) solver. Furthermore, the proposed approach is much more compact compared to several ground structures previously reported in the literature. The effect of introducing the DGS into the ground plane of the microstrip antenna on the resonant frequency as well as on the axial ratio, gain and radiation pattern is shown in Figure 8(a) and Figure 8(b), Figure 9 and Figure 10 respectively, by comparing the results of the antenna array without and with DGS. It is apparent that the insertion of the DGS geometry into the antenna ground plane plays a very appreciable role, as well as impacting very strongly on the expected good performance.

In absence of DGS, we have seen from the Figure 2, the initially antenna array resonates at 5.8 GHz with a bandwidth of 606 MHz which covers the operating frequency of the ISM band. Always in this context, using the optimal placement and suitable size of the DGS, the resonant frequency is also 5.8 GHz while the bandwidth is about 804 MHz which means a difference of nearly 200 MHz of the impedance bandwidth between the antenna array without and with DGS as indicated in the Figure 8. As the same figure indicates, that employing the defected ground plane beneath the printed antenna array not only enlarged the impedance bandwidth, but also enlarge the axial ratio bandwidth. Moreover, as can be clearly seen from the graph, the simulated axial ratio bandwidth of the antenna array with DGS is about 320 MHz, while the axial ratio bandwidth of the antenna array without DGS is only 140 MHz. Thus, we can say that we have obtained very acceptable results for circular polarization. In compliance with some reports in the literature, the aperture achieved by the geometry of DGS greatly affects the gain and the radiation pattern in a defensive manner. As can be seen in Figure 9, the addition of the DGS motif has no great impact on the gain, although there is a small degradation of approximately 0.5 dBi and 1 dBi, the gain still remains higher than 5dBi in the whole band. The simulated radiations patterns of the proposed antenna array with and without defected ground structure presented in Figure 10(a) and Figure 10(b) respectively ensures that the addition of DGS has not a great effect in the radiation of the antenna. From the radiations plot, it is evident that the conventional antenna array without DGS radiate in one side and has a half-power beamwidth of 107.1° and 33.3° for the E plane and the H plane respectively. Whereas the 3-dB beam-width of the proposed antenna array with DGS is about 104.6° and 29.6° for the E plane and the H plane respectively.

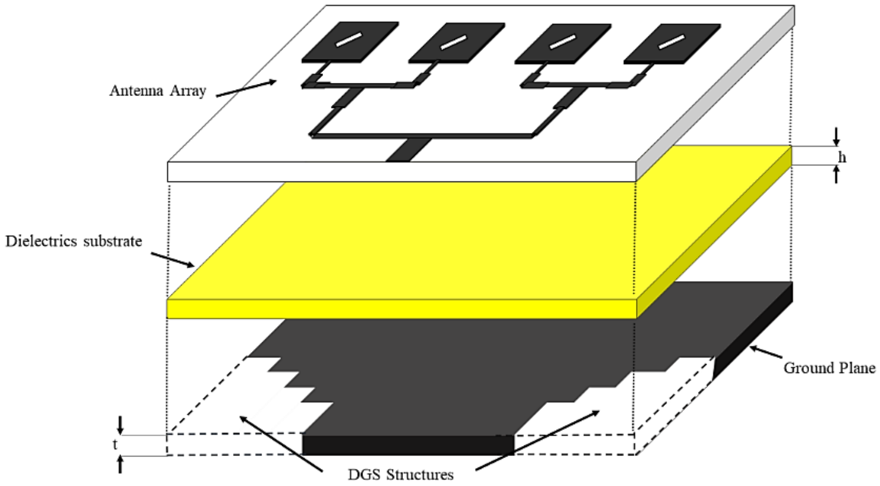
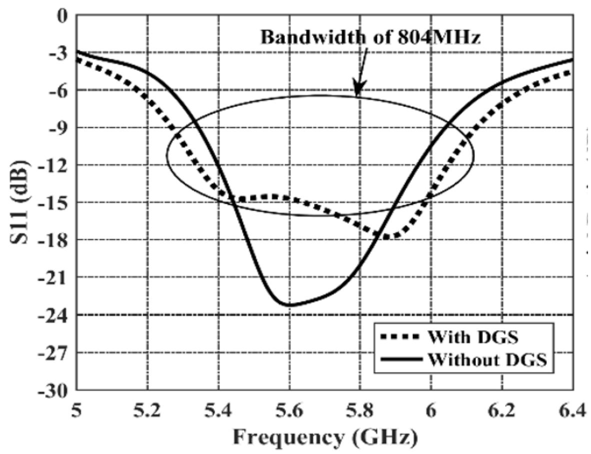
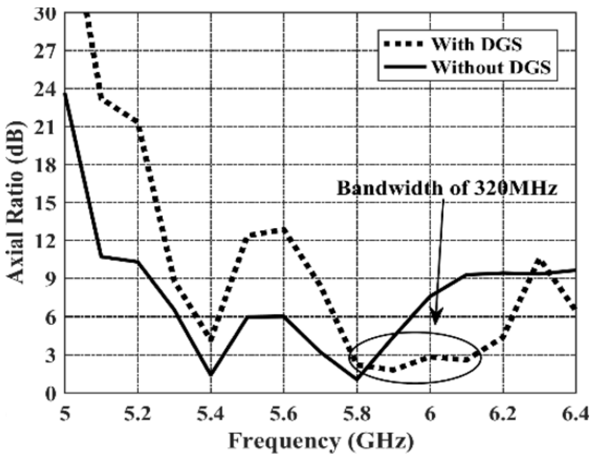


Figure 7. Configuration of the proposed 4×1 CP antenna array with DGS



(a)



(b)

Figure 8. Comparison between the antenna array without and with DGS in terms of (a) reflection coefficient and (b) axial ratio

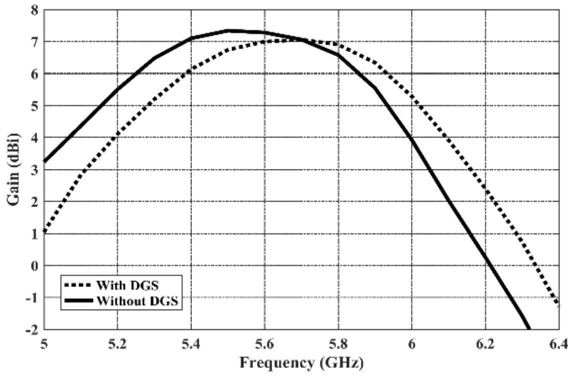
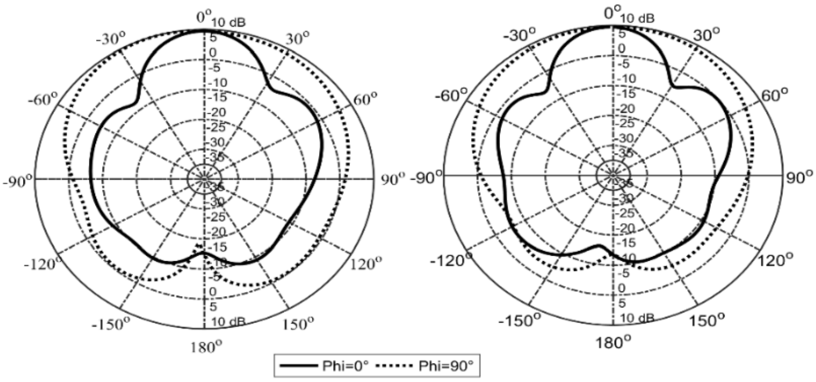


Figure 9. Comparison between the antenna array without and with DGS in terms of gain



(a) (b)

Figure 10. Simulated radiation patterns of the proposed antenna array: (a) without DGS and (b) with DGS

Lastly, Table 2 presents a comparison based on the performance as between the proposed CP array antenna and other antenna arrays that have been appearing in previously published papers in terms of dimensions, impedance bandwidth, axial ratio bandwidth and gain. To more accurately evaluate the performance of the proposed antenna Array. As a result, it is found that the proposed CP array antenna has the widest bandwidth regarding impedance and axial ratio as well as a very high CP quality. In addition, the proposed antenna has an acceptable gain with a relatively small size among those antennas.

Table 2. Comparison of the proposed 4×1 antenna array with literature

Antenna array	Array size (mm²)	Operating bandwidth	Axial ratio bandwidth	Gain (dBi)
[2]	------	250 MHz	140 MHz	9
[7]	122×128	76.5 MHz	Linear Polarization (LP)	6.4
[25]	159×66.7	210 MHz	Linear Polarization (LP)	4.9
Proposed structure	80×40	804 MHz	320 MHz	5–7

4. CONCLUSION

To comply with the increasingly diverse standards of telecommunication systems today, multi-frequency or widedband antennas are considered the most reliable solution because of their capability to perform in different frequency bands using the simplest possible structure and to considerably increase the lifetime, by rapidly jumping from one frequency to another, which allows access to new standards which were not available when the antenna was created. This paper has presented a new approach to develop a very compact circularly polarized printed antenna array. Two unique symmetrical forms of DGS in the form of stairs etched into the two lower corners of the rear metal ground plane. Several advantages are offered by the proposed antenna at the same time, especially a good input impedance matching with a much larger operating bandwidth, thus providing of a wide axial ratio bandwidth. Additionally, a very good antenna gains and wide radiation patterns were also achieved.

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