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A novel frequency reconfigurable antenna for smart grid applications in TV white space band

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ABSTRACT

This paper presents the design and analysis of a frequency reconfigurable, aperture coupled rectangular patch antenna for use in smart grid applications in TV white space bands. The proposed antenna model has been realized on multi-substrate layers of Polylactic acid (PLA) material (εr=2.65, $tan\delta$=0.003) with a ground plane sandwiched in between them. An aperture has been made in the ground plane for coupling energy to the patch. The overall system dimensions are 270×270 mm. The feature of frequency reconfigurability has been achieved by incorporating a switch and varying the reactance of the feed line on the bottom substrate. A rectangular slot on the long feed line improves impedance matching. The ON and OFF states of the switch provide two operating frequency bands namely 630.13 to 636.7 MHz and 619.16 to 625.3 MHz respectively. The proposed aperture coupled reconfigurable system operates with a maximum gain of 6.4 dB and average efficiency of 78.5% in both bands. The measured results are satisfactory and the proposed antenna will be suitable for operation in the smart grid environment.

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1. INTRODUCTION

The modern smart power grid is intelligent in terms of power generation, transmission, distribution, and billing methods. An electrical grid can incorporate machine intelligence and communications to be called a smart grid. This can essentially be implemented using a two-way digital wireless technology. It can provide real-time information, to control appliances at consumers' premises resulting in increased reliability with an associated saving of energy and reduction of cost.

A smart grid in an urban scenario is presented in Figure 1. As shown in the figure, a collection of Meters suitably connected to a gateway comprises a home area network (HAN). Similarly, several gateways in turn connected to a data aggregate unit (DAU) will form a neighborhood area network (NAN). The function of these gateways is to transmit the meter data that it collects periodically within its home area network to the data aggregate unit. The gateway is then able to route the data from the meter to the data aggregate unit either by making use of a TV white space (TVWS) channel if it has been declared available by the white space database (WSDB), or through an industrial scientific and medical (ISM) band.

The multilayer smart grid communication network (SGCN) is spread across a large geographical area. Here, wired, as well as wireless communication mediums, can be engineered to meet the last/middle mile requirements of this entire region. Both wired and wireless communications are integral in the mix of communications technologies necessary to enable future smart grid communications. To extend network coverage and improve performance these hybrid networks exploit independent mediums [1]. the home area network (HAN) in the SGCN is responsible for providing communication access to smart devices and appliances along with smart meters in the home to the gateway. The key functionality of advanced metering infrastructure (AMI) helps in connecting the smart meters and other devices in the network through a two-way effective, efficient and reliable communication infrastructure [2].

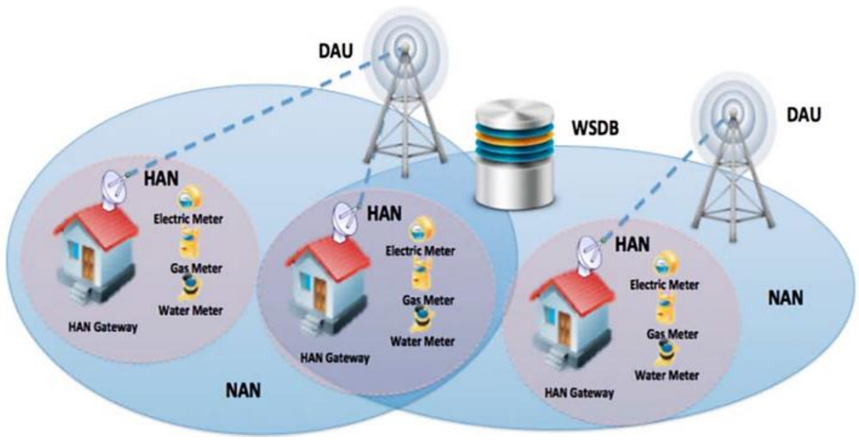

Figure 1. Smart grid: a possible scenario in a given geographical region [2]

With the volume of data traffic generated being high, fiber optic cables providing wired communication may be considered the best option. At the micro-grid level, however, the communication medium could be planned to be either wired or wireless. The communication infrastructure of the smart grid amalgamates heterogeneous communication technologies working on various standards and in diverse environments. Radio communication can be considered to be the technology for establishing secure connectivity in such a grid network. The prominent wireless technologies available for use at the micro-grid/HAN level are IEEE 802.11 (Wi-Fi), ultra-wideband (UWB), and IEEE 802.15.4 ZigBee. In [3] a smart grid is discussed in depth along with the kind of communication methods used. The components of a smart grid are introduced to facilitate an easy understanding, and communication methods and protocols are compared. The communication technologies are introduced as wireline and wireless classification where the key features are also tabulated.

The digital transformation of energy infrastructure is essentially implemented by the deployment of smart grids and microgrids. In study [4], innovative multi-layered architecture has been presented. Data transmission has been successfully performed by utilizing the Modbus TCP network. Signals from sensors, controllers, and software environments are properly shared by means of the multi-layered architecture.

A major challenge of an SGCN is the scarcity of spectrum resources. The radio systems operating in the 2.4 GHz ISM, license-free frequency band are Zigbee, Bluetooth, and Wi-Fi. These systems cause interference with each other which is quite notable. Also, microwave ovens, like some other domestic appliances may emit strong electromagnetic waves making the spectrum in a home area network subject to additional interference. It is advantageous to make use of cognitive radio (CR) technology in HANs [5]. Federal Communications Commission (FCC), and other Govt. agencies the world over have now enabled the usage of cognitive radio which enables dynamic spectrum access (DSA). In wireless communication making use of cognitive radio, the network or a wireless node changes/reconfigures its transmission or reception parameters to communicate efficiently and at the same time avoid interference with licensed or unlicensed users. The active monitoring of several factors in the overall radio environment, for example, the radio frequency spectrum can form the basis of reconfiguration.

The unused TV spectrum and digital dividend on conversion from analog to digital transmission techniques worldwide are referred to as TVWS. This band of frequencies can provide high bandwidths in AMIs and NANs and can be exploited for smart grid communication employing cognitive radio. The TV very high frequency (VHF)/ultra-high frequency (UHF) frequencies have several inherent advantages wherein it gives an alternative to reduce congestion and provide better indoor propagation characteristics compared to the unlicensed 2.4 GHz band. The power consumption is low at the lower end of the TVWS frequency band. In comparison to optical fiber connections, networks operating in the TVWS can cover a larger area with lower installation and maintenance costs. The penetrating characteristics of these frequencies make them an excellent option for providing connectivity to several households which are separated by walls. In the rural areas and thinly populated suburban areas, their long reach characteristic makes it suitable for connecting households that are far away from the network. The fact that the TVWS can cover a larger range for the last mile of smart grid communication is its greatest advantage. Depending on the white space band frequency in use along with the propagation environment, there could be a range advantage of the order of 3 to 40 times greater. Importantly, with range advantage considered three times, the area that could be covered will be nine times larger with the same transmission power [6].

The frequency reconfigurability feature allows the devices in the smart grid to operate utilizing the unused spectrum in the radio environment. Dynamic spectrum access enabled by cognitive radio technology is employed by the smart grid to make use of the underutilized or unused frequencies. This effectively increases efficiency, reliability, and flexibility in a cognitive radio-based smart grid network.

Recent advancements in wireless technology have made wireless networking adaptable for smart grid applications. Wireless networks have become preferred options for small distance connections which require low data rates. In the TVWS network, the effective isotropic radiated power (EIRP), for operation in the fixed mode could be up to 5 W. The high transmission power capability and better propagation characteristics result in better access to all the smart meters.

Cognitive radio communication, through the IEEE 802.22 WRAN standard, has several advantageous features when compared to other wireless or even wired communication techniques. IEEE 802.22 is the first standard in the realm of cognitive radio networks and is dedicated to wireless regional area networks (WANs) operating in TVWS. IEEE 802.22 WRAN is meant for long-distance communications of high-bandwidth and it allows CRs to make use of TVWS within the VHF and UHF channels [7]. The IEEE 802.11af and IEEE 802.11ah standards committees are the leading bodies to develop an IEEE 802.11 amendment for WLAN operation in TVWS. The smart grid application not being very bandwidth-intensive, a limited number of TVWS channels are required for this application. This paper involves the design of a frequency reconfigurable antenna operable in the TVWS band. The feature of reconfigurability enables the antenna to be employed in a frequency-agile environment of the cognitive radio.

Aperture couple feed is one of the efficient feeding techniques for improving the gain and efficiency of the antenna system and hence an aperture coupled patch antenna is considered here for implementation. The aperture coupled feed uses multiple substrates [8] with an aperture in the ground plane to couple the energy radiating element. A wideband compact patch antenna that uses an aperture coupling technique for CubeSat communications has been studied in [9]. The antenna operates from 2 to 2.45 GHz with an efficiency of 76%. In [10] the design of a circularly polarized, aperture coupled antenna integrated with solar panels for CubeSat applications to operate in 2.2 to 2.3 GHz band for downlink applications has been proposed. A microstrip antenna with frequency reconfigurable feature in the 3 to 10 GHz band has been discussed in [11]. Further, the addition of reconfigurability to the aperture feeding resulted in achieving greater bandwidths and an improvement in the performance of the system [12]. In these two slots have been etched for generating two different frequency bands 7.28 to 7.73 GHz and 8.55 to 9.12 GHz and employing defected structure for the ground plane. A circular-shaped patch antenna having slots with two different types of feeding techniques (CPW feed and microstrip feed) have been investigated in [13]. These two antennas work in the range from 470 to 806 MHz for TVWS usage and size has been reduced (20%) by the usage of the CPW feeding technique. In [14] a novel TV White space antenna system along with the characteristic mode analysis has been studied. This has been designed and prototyped on an FR4 substrate of thickness 0.8 mm and operates in the band 474 to 1,212 MHz. A meander line technique has been utilized in U shaped planar antenna [15] which operates for a TV white space band. For achieving the meandering technique several slots (21) have been etched at the lower part of the U shape. This U shape antenna operates from 470 to 798 MHz with a variable gain of 2.2 to 4.6 dBi. A triangular-shaped patch antenna having a wideband application of cognitive radio has been discussed in [16]. This structure uses a meandered strip for generating desired band 470 to 806 MHz. Variation in S-Parameters has been presented by changing different lengths of both the triangles on the front and rear sides. A rectangular slotted monopole antenna with symmetric defected ground structure (DGS) has been discussed in [17]. This antenna has been designed to operate from 470 to 790 MHz for TV white space applications. In order to obtain wideband performance E-shaped and U-shaped slots on microstrip patches have been suggested [18]–[24]. For moderately wide bandwidth, stacked patch antennas have been proposed where two patches are coupled to each other [25], [26]. In terms of obtaining wide bandwidth through feeding, aperture coupling is an attractive solution. Aperture coupled patch antennas [27], [28] are preferred particularly for phased arrays because of their advantage of integration to other active devices and circuits, e.g., phase shifters and power amplifiers.

In this article, an aperture coupled, rectangular patch antenna on a multilayer biodegradable polylactic acid (PLA) substrate with a reconfigurable feature has been proposed for use in the TV white space band. The proposed system has been made to switch between two operating bands with the use of a 10 K ohm resistor element inserted as a switch between the feed line and a parasitic strip on the lower substrate. Section 2 describes the antenna design configuration. Section 3 gives the comparison of simulated and measured results for the proposed TVWS system followed by the conclusion in section 4.

2. METHOD OF ANTENNA DESIGN

The design configuration for the proposed reconfigurable aperture coupled TVWS antenna system has been illustrated in Figure 2. In Figure 2(a) is depicted the front view and the bottom view is shown in Figure 2(b). The ground plane can be seen at Figures 2(c) and 2(d) depicts the side view. The antenna has been designed on a customized multilayer substrate with ground sandwiched between them. Both, the top and lower substrates are made up of biodegradable PLA material with a dielectric constant of 2.65 and a loss tangent of 0.003. They each have a thickness of 3 mm. The dimensions of the rectangular patch L1×W1 have been chosen to obtain a resonant frequency in the TVWS band. The patch is excited through an aperture of dimensions W3×L5 made on the ground plane. The patch is centered over the aperture for maximum coupling. The rectangular shape and dimension of the aperture have been optimized for maximum coupling and impedance match. The feed line is positioned at a right angle to the center of the aperture. The length of the feed line stub L2 is approximately $\lambda/4$. A slot of length L3 has been carved out of the feed line for improved impedance matching. A lumped switch has been placed in between the feed line stub L2 and a parasitic strip L4 to obtain a variable length of the tuning stub. This provides variation in the reactance value and results in generating two operating bands in the ON and OFF states of the switch. The proposed reconfigurable design has been simulated using finite element method (FEM) based solver Ansys HFSS version 19. The lumped switch plays a key role in changing the frequency of operation in the ON and OFF states. The TVWS system has been realized with an overall dimension of $270\times270\times6.035$ mm^3 and has been excited using a standard 50 Ω SMA connector. The optimized dimensions for the proposed design have been listed in Table 1.

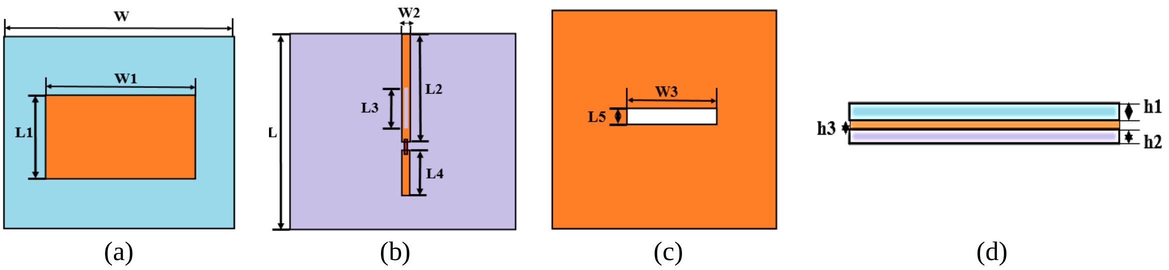

Figure 2. Geometric configuration of proposed reconfigurable TVWS system (a) front view, (b) bottom view, (c) ground plane and (d) side view

Table. 1. Optimized dimensions of antenna (all dimensions in mm)

L	270	L5	5
W	270	W1	190
L1	130	W2	8.4
L2	165	W3	50
L3	40	h1	3
L4	56	h2	3
h3	0.035		

3. RESULTS AND DISCUSSION

The above-proposed antenna system was designed on the FEM-based HFSS tool. The return loss scattering parameter was simulated and the observed values for both the switched ON and OFF conditions were well below -10 dbm. Similarly, the voltage standing wave ratio (VSWR) was also simulated for the ON and OFF conditions and observed values were found lying between 1 and 2. The same was simulated for the far-field parameters and the results obtained were found acceptable. The design was extended to fabrication and the fabricated prototype of aperture coupled reconfigurable design is shown in Figure 3. Figure 3(a) depicts the top view of the prototype antenna. In Figure 3(b) is the plane comprising the aperture, and Figure 3(c), displays the feed line on the bottom plane.

The fabricated prototype has been validated on the Keysight FieldFox microwave analyzer N9918A. The measured reflection coefficient and VSWR of the proposed design are well-matched with the simulated results in both operating bands namely 630.13 to 636.7 MHz with a bandwidth of 6.57 MHz and 619.16 to 625.3 MHz with 6.14 MHz bandwidth. The radiation patterns for the proposed model have been measured concerning a standard horn in an anechoic chamber and desired patterns have been obtained. The measured radiation patterns in both E and H-plane at different frequencies are matching with the simulated patterns. In addition, prominent performance parameters such as gain and efficiency have also been obtained for the desired operation. The proposed TVWS aperture coupled antenna operates with a peak gain of 6.4 dB and has an efficiency >78.5%.

(a) (b) (c)

Figure 3. Fabricated TVWS microstrip antenna (a) top view, (b) aperture view and (c) bottom view

3.1. Scattering parameters

The scattering parameter is a measure of how closely the input impedance of the prototype antenna is matched to the feed. A comparison of simulated and measured S11 for both the operating bands has been represented in Figure 4. Low reflected power at the input port has been obtained for both the simulated and the measured results in the OFF as well as the ON states of the switch.

The voltage standing wave ratio is a measure of the reflected power. The S11 and VSWR values are both indicative of the input power coupled to the antenna and consequently the power radiated by the antenna. The value of VSWR in both the operating bands is between 1 and 2. This is commensurate with the S11 results, as reflected in Figure 5.

3.2. Radiation patterns and efficiency

Figure 6 gives the normalized 2D radiation patterns in both the E plane and H plane in both ON and OFF states at 635 and 622 MHz respectively. The pattern has been observed to be almost omnidirectional in both E and H principal planes. Figure 6(a) depicts the E plane at 622 MHz during OFF conditions for both the simulated and measured states. Similarly, Figure 6(b) reflects the H plane at 622 MHz during the OFF state.

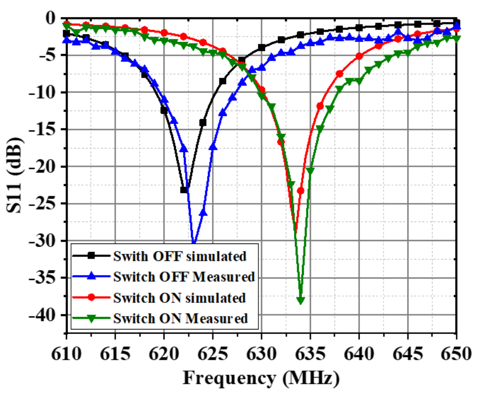

Figure 4. Simulated and measured reflection coefficient

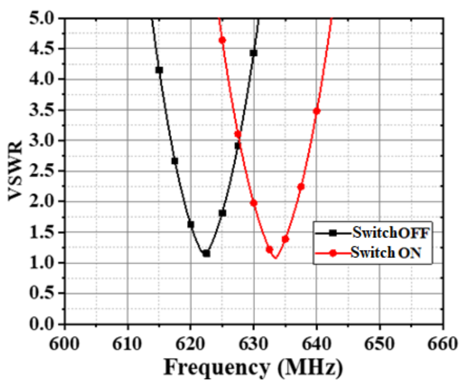

Figure 5. VSWR vs frequency of the proposed antenna

Figure 6(c) depicts the E plane at 635 MHz during ON conditions for both the simulated and measured states. Similarly, Figure 6(d) reflects the H plane at 635 MHz during the ON state. The simulated and measured gain plot for the proposed system in both the frequency states has been given in Figure 7. The gain has been found to have a value of 6.4 dB from simulations and 6 dB from actual measurements. The obtained gain values augur well for the proposed smart grid applications covering the large geographical region. The proposed system operates with an efficiency of 78.5% as shown in Figure 8 which suggests its suitability for TV white space smart grid applications.

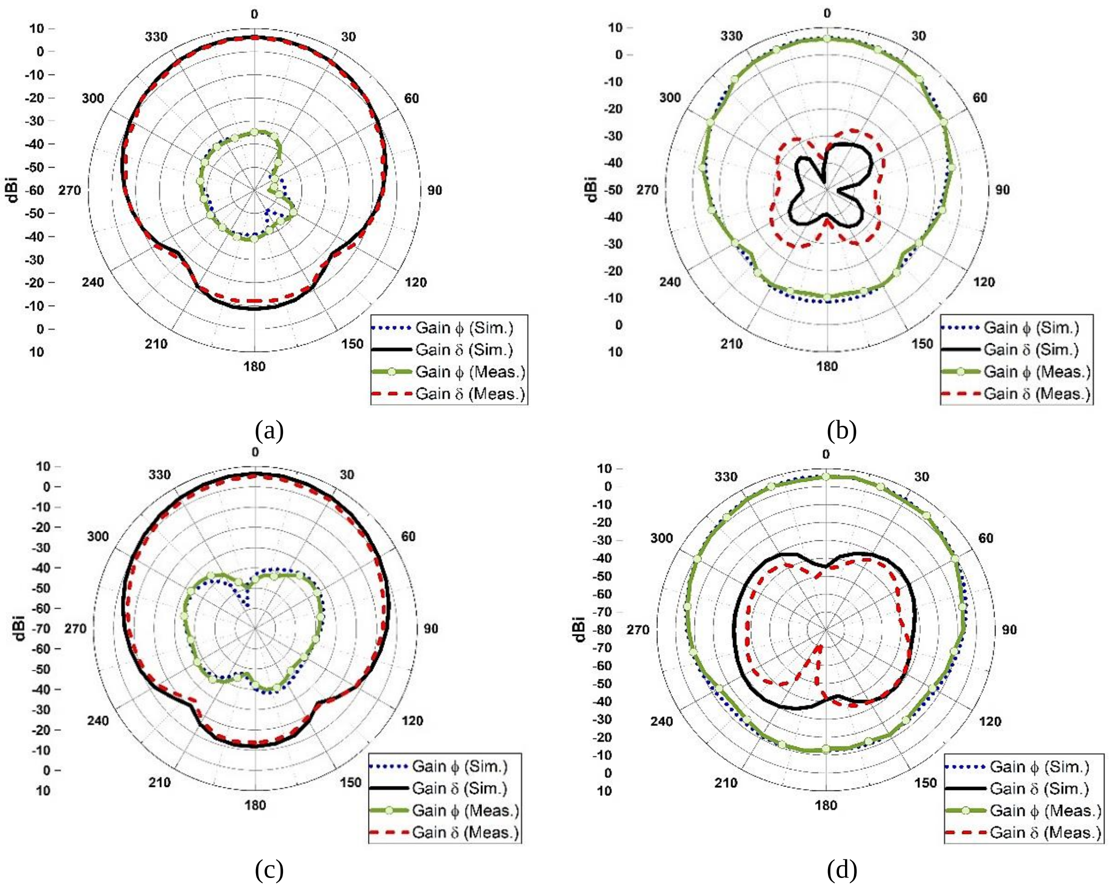

Figure 6. Simulated and measured Radiation patterns for proposed TVWS reconfigurable system (a) E plane at 622 MHz during OFF state, (b) H plane 622 MHz during OFF state, (c) E plane 635 MHz during ON state, and (d) H plane 635 MHz during ON state

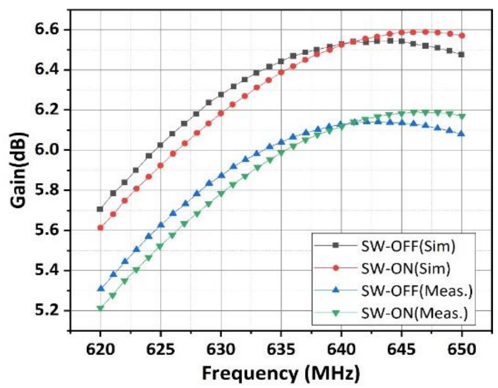

Figure 7. Gain of proposed reconfigurable aperture coupled antenna

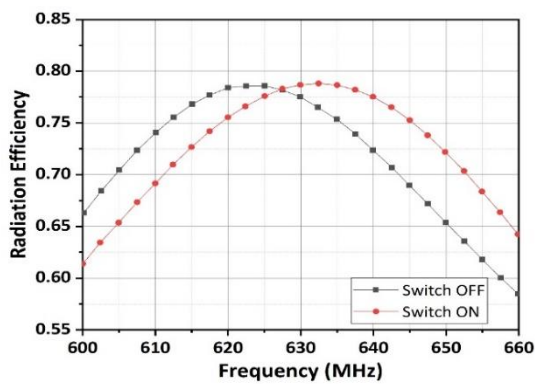

Figure 8. Radiation efficiency of proposed aperture coupled TVWS reconfigurable structure

4. CONCLUSION

The application areas for TV white space frequencies range from internet access to difficult-to-reach rural areas and urban connectivity to emergency and public safety, smart grid networks, internet of thing (IoT), and machine to machine (M2M) communication. The utilization of TVWS technology in smart applications has been on the rise. These smart solutions are expected to bring in a significant change in the existing electricity grid by allowing two-way communications, thereby improving the generation, transmission, and distribution of electric power. TVWS-based communication is used to provide connectivity to facilitate metering and other smart solutions. As the smart grid application is not very bandwidth-intensive, a limited number of TVWS channels are required for this application. Given the low bandwidth requirement, interest to adopt this communication network has been on the rise. For instance, Singapore is one of the first countries to deploy TVWS-based communication for various smart community projects. In this paper, an aperture coupled antenna with frequency reconfigurable feature has been realized for operation in TV white space band. The measured results are found suitable for TV white space band applications an example of which could be smart meters deployed at customer homes and control stations in smart grid solutions. The proposed reconfigurable antenna resonates at 633.5 and 622 MHz in the TV White space band with an impedance bandwidth of approximately 6 MHz. A measured peak gain of 6 dB and an efficiency of 78.5% are found encouraging and suitable for smart grid application.

As a future scope, the size of the antenna could be taken into consideration. Size reduction techniques could be employed to reduce antenna dimensions and design compact antennas. Suitable semiconductor diode switches could also be incorporated into these antennas to obtain frequency reconfigurability features.

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