Frequency Reconfigurable Antenna Array Using Defected Ground Structure for Outdoor Wireless Communication Systems

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***Abstract*—This paper proposes frequency reconfigurable antenna for outdoor wireless communication systems, the 4 x 4 array antenna has designed at two resonant frequencies 7.5 GHz and 8.85 GHz. The periodic dumbbell geometry etched on the ground layer newly proposed with dual functionality, to control desired frequency and to couple radiating patches at the top substrate with feeding line at the bottom substrate. The reconfigurability of the patch antenna is controlled by utilizing the copper pad of the feeding network with OPEN and SHORT states. The reconfigurable antenna has been simulated and optimized using Computer Simulation Technology (CST) to get the desired responds. The good agreement between simulation and measured results indicates that the frequency reconfigurable patch array antenna using Periodic Dumbbell Slotted Aperture Structure (FRPDSA) is feasible to support outdoor wireless communication systems.**

***Index Terms*— Reconfigurable antenna, Dumbbell aperture slot, Defected ground structure,**

I. INTRODUCTION

Recently, frequency reconfigurable patch antenna has been designed with numerous techniques, objectively to provide agile and versatile functionality in order to support different frequency standards in wireless communication systems [1], [2]. However, most of current reconfigurable antennas are designed with less than 10 dBi that only significant for indoor wireless communication systems. From our reviews, the complexity of the reconfigurable antenna is directly proportional with number element and switching network to control the desired frequency. Consequently, creates the limitation in effort to design reconfigurable antennas for outdoor wireless applications. With high demand of multifunction wireless communication systems, reconfigurable antenna for outdoor and satellite communication systems also has been discussed seriously [3]. However, by considering small size of satellite with optimum payload, the reconfigurable antenna should be designed with small size and low cost without power degradation.

In this paper, newly frequency reconfigurable antenna array using periodic dumbbell slotted aperture structure is proposed in order to miniaturize the size of proposed antenna and simultaneously improve the directivity of reconfigurable antenna for outdoor wireless communication systems. By introducing defected ground structure concept to control the desired frequency, constant radiating patch dimension is obtainable. To get high directivity, conceptually the antenna is designed so that produces directivity more than 10 dBi for outdoor wireless requirement. Consequently, antenna designers have freely remained the patch radiating dimension according to operating frequency. To make sure the antenna is significant for outdoor wireless communication systems and applicable for satellite band, the proposed antenna is conceptually designed at 7.5 GHz and 8.85 GHz operates at meteorology and radiolocation band, respectively.

The paper is organized into several sections. Basic concept of DGS technique is explained in section II, followed by full wave analysis technique used for simulation and optimization to obtain the required dimensions of DGS shape, corresponding to desired frequencies. Antenna design technique is explained in section III. Meanwhile, simulation and measurement results are elaborated in section IV. Conclusion of the research is explained in section V, respectively.

II. DEFECTED GROUND STRUCTURE (DGS)

Defected ground structures (DGS) is initiated by designing small size of RF low pass filter [4]. Basically, DGS structure is etched on the ground layer to alter the metal ground functionality based on required function [5] and normally placed under transmission line of patch structure. Fig. 1 shows

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the example of DGS geometries have been proposed for specific application mainly for antenna design.

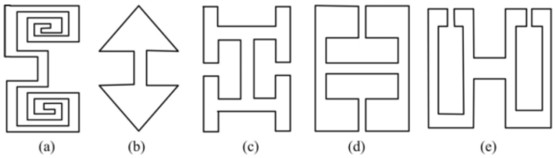

Fig. 1: (a) Spiral head, (b) arrowhead-slot, (c) "H" shape slot, (d) a square open-loop with a slot in middle section, (e) open-loop dumbbell

Based on unique background, DGS technique offers wide and deeper stop band, and very low insertion loss [6]. All those significant responses are referring to the two main characteristics of DGS, slow wave propagation in pass band that potentially provide desired resonant frequency due to specific dimension of geometries, band stop characteristics in microwave circuits provide frequency band rejection to eliminate specific frequency band [7]. Based on two basic background DGS concept has been widely used in antenna, purposely to reduce a few unwanted properties such as mutual coupling effect between array elements, harmonic signal, cross polarization and also for antenna size reduction [8], and by utilizing specific size of DGS elements, for example optimize the gap or symmetrical arrowhead-slot of the DGS geometry the desired resonant frequencies for specific applications are obtainable [9], [10]. Nevertheless, in getting appropriate dimension and better responses for designing patch antenna circuit using DGS structure, almost all process systemically have been conducted via full wave analysis and optimization, this is because of there is no significant relationship between numerical analysis for physical dimension of etched structure with LC circuit as reported by N. C. Karmakar et. al [9]. Consequently time consuming is considered in designing process. In order to achieve the desired specification for the proposed antenna, standard approaches conventionally introduced and performed as shown in Fig. 2 [11]. Basically, the initially step is by guessing the specific geometry of proposed DGS and continued with parametric analysis and this process will continuously performed to get better results and performance of antenna. Therefore, in this research the proposed antenna is designed through same processes; start from by determining DGS dimension, selecting desired frequency and performing optimization process.

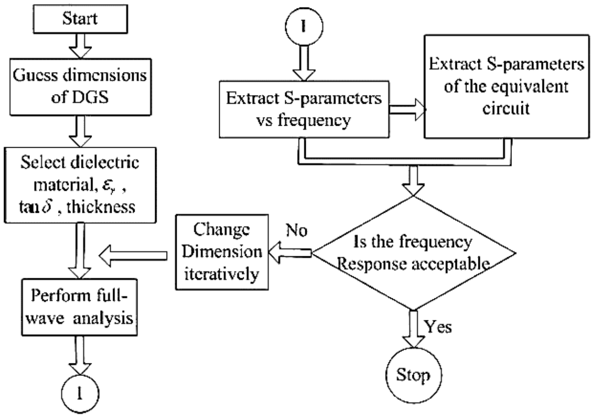

Fig. 2: Standard schematic diagram of designing and determining the required respond with DGS structure

III. ANTENNA DESIGN

A. *Single Element*

The proposed antenna starts with designing a single element of frequency reconfigurable antenna. Although the two resonant frequencies are dominantly determined from dumbbell dimension, the size of radiating patch is calculated by using equations (1) to (4) [12] as listed below for starting step to determine to appropriate antenna dimension, and the numerical analysis was considering center frequency (8.2125GHz) between 7.5 GHz and 8.85 GHz. Two substrate layers Rogers RO3006 with permittivity 6.15 and thickness 0.64 mm are stacked as shown in Fig. 3. Newly two alterable Dumbbell aperture structures with square arms are proposed to control the desired frequencies, and for initial design gap g1 and g2 maintained at 0.4 mm and 0.25 mm, respectively, while size of arm square initially designed at λ/8. The slot and square arms are etched on the ground plane as illustrated in Fig. 4.

$$w = \frac{1}{2f_r\sqrt{\mu_o\varepsilon_o}}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

$$l = \frac{1}{2f_r\sqrt{\varepsilon_{reff}}\sqrt{\mu_o\varepsilon_o}} - 2\Delta L \tag{2}$$

Where

$$\Delta L = \frac{0.412}{h}\frac{(\varepsilon_{reff}-0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W}{h}-0.8\right)} \tag{3}$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2} \tag{4}$$

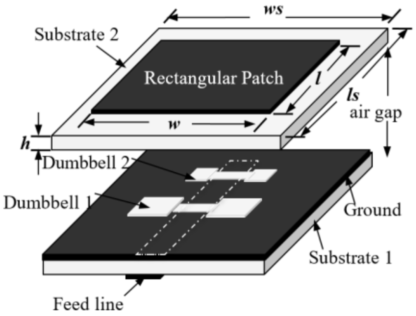

Fig. 3: Diagram for frequency reconfigurable microstrip patch antenna with periodic dumbbell aperture structure.

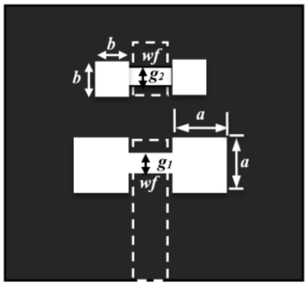

Fig. 4: Periodic Dumbbell aperture structures etched on the ground layer.

The reconfigurability of the proposed antenna is controlled by feeding line condition, OPEN and SHORT state of copper pad as shown in Fig. 5. Where the feeding line will alternately matched with the top and the bottom Dumbbell aperture structure, respectively. During "OPEN" state the feeding line is connected only with the bottom Dumbbell aperture. Inversely, in "SHORT" state the feeding line is connected to the top Dumbbell aperture. TABLE I shows the optimized values for the single element after well-tuned at 7.5 GHz and 8.85 GHz, respectively.

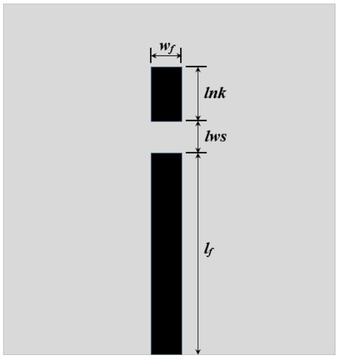

Fig. 5: Back view, feed line and position of switch for frequency reconfigurability

TABLE I DIMENSION OF DESIGNED ANTENNA SINGLE ELEMENT

Antenna parameters	Value (mm)
l	9.28
w	10
l_s	15
ws	15
h	0.64
w_f	0.995
a	2.36
b	0.84
g_1	0.4
g_2	0.25
air gap	1
lws	0.9
l_f	8.32

B. 4 x 4 Antenna Array

To ensure, the proposed antenna is workable for outdoor wireless application, the number of array elements is added by targeting the directivity from the antenna more than 10 dBi. Therefore, the 4 x 4 antenna array with size 80 x 80 mm is designed and fabricated by considering the switching activities in ideal condition, meaning that without real PIN diode. Radiating patches etched on the top substrate is shown in Fig. 6, and periodic dumbbell slot structure for the array is illustrated in Fig. 7. In order to eliminate the coupling effect between patch elements, the distance between elements is constantly kept at $\lambda/2$.

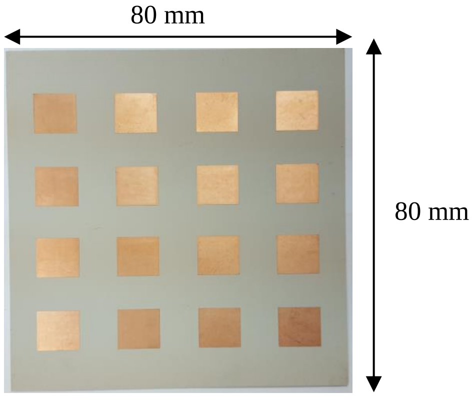

Fig. 6: Top layer with 4 x 4 rectangular patch antenna

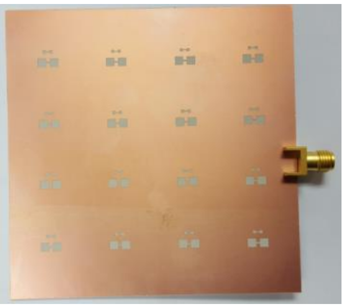

Fig. 7: Slot with equal square arms etched on the ground plane

A corporate feed network is used as a power divider between antenna elements. The 50 Ω transmission line consists of 70.7 Ω λ/4 transformer with 100 Ω power divider is designed with two conditions by referring to the ÖPEN" and "SHORT" condition of feeding network as shown in Fig. 8 and Fig. 9, respectively. Where the length of gap is equals to the physical length of PIN diode. Enlarged picture at the right side shows the different condition "OPEN" and "SHORT" condition of copper pad.

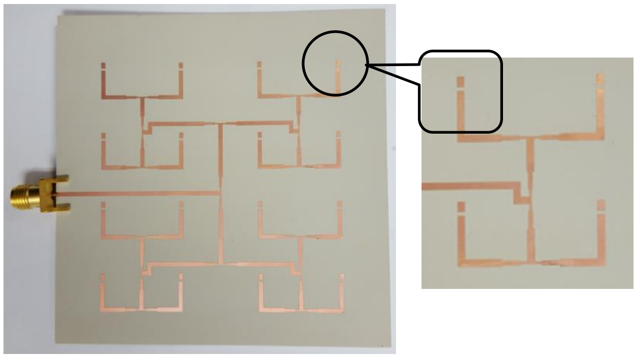

Fig.8: Feed line in "OPEN" condition.

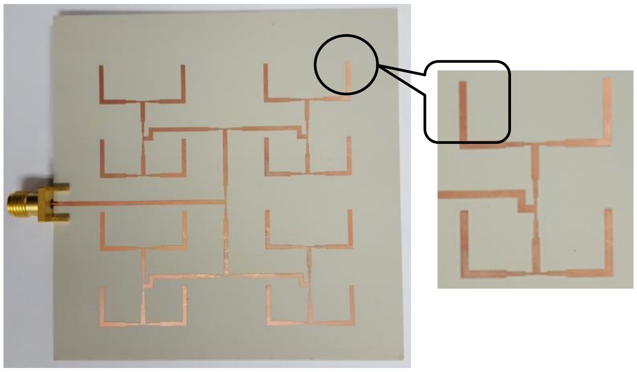

Fig. 9: Feed line in "SHORT" condition.

IV. SIMULATION AND MEASUREMENT RESULTS

A. Single element

Initially, the single element with calculated dimension is simulated and optimized to get optimum dimension with better output. Since the reconfigurability of the antenna is controlled by OPEN or SHORT condition, the simulation is performed at two separate conditions. The numerical analysis for the first element is performed and optimized. In this research the optimization processes are focused on square arm of both dumbbell slots on ground plane to determine the desired frequency. From the simulation and optimization process, two different sizes of dumbbell slots provides the better results, where the top dumbbell structure resonates at 8.85 GHz when the feeding line in "SHORT", while the bottom dumbbell structure resonates at 7.5 GHz if the feeding line in "OPEN" condition. Both responses of return loss for the respective simulation are illustrated in Fig. 10 and Fig. 11. In "OPEN" condition the return loss is -57.8 dB. While, in "SHORT" condition the return loss is -40.49 dB.

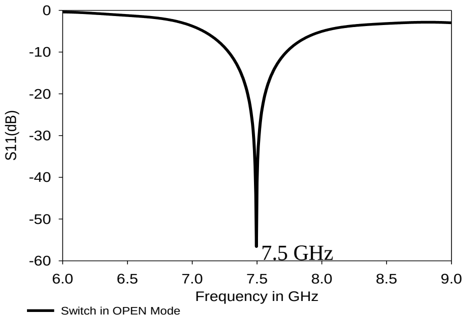

Fig. 10: Simulated result S_{11} when the feeding network in "ÖPEN" condition

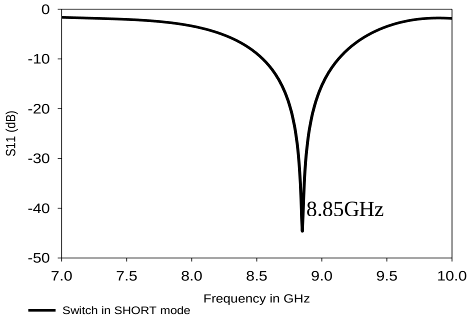

Fig.11: Simulated result S_{11} when the feeding network in "SHORT" condition

The effect of dumbbell dimension towards resonant frequency is observed through parametric analysis, and the analysis has been conducted to square arms of dumbbell slot. For the first analysis, the feeding line is default at "OPEN" condition. By decreasing the size of square arm the frequency is increasing which is agreed with the decrement of square arm size as illustrated in Fig. 12. Inversely, when in the "SHORT" condition, the size of square arm for the top dumbbell is varied by increasing the size. Consequently, the frequency is gradually decreased.

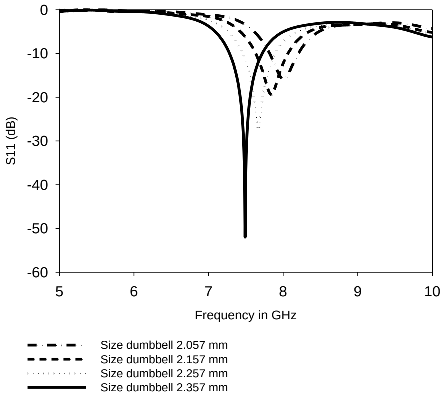

Fig. 12: Resonant frequency is changing with variation size of bottom structure during "OPEN" mode

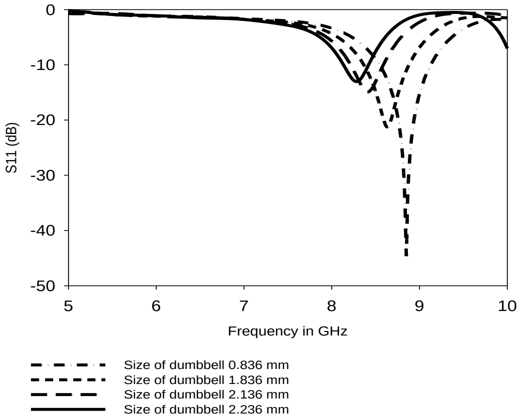

Fig. 13: Resonant frequency is changing with variation size of top structure during "SHORT" mode

B. Surface Current distribution

Since the frequency reconfigurable is working due to alteration of current distribution, effect of OPEN and SHORT condition of feeding line to select desired frequency is illustrated through current concentration around the activated dumbbell slot structure, and the concentration of the current distribution of the antenna is depicted in Fig. 14 and Fig. 15, respectively. If the feeding line is positioned in ÖPEN" condition, antenna current distribution is confined around the bottom dumbbell structure and indicate the antenna operates at 7.5 GHz in Fig. 14. Meanwhile, in "SHORT" condition, the antenna current distribution is confined around the top dumbbell slot to indicate that the antenna is operate at high frequency 8.85 GHz in Fig. 15.

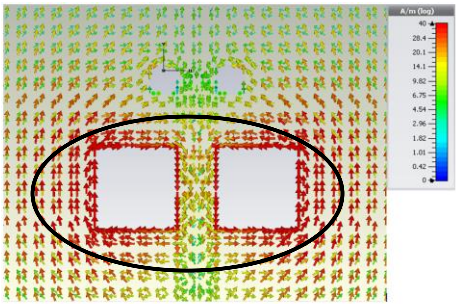

Fig. 14: The surface current more confined on the bottom structure during "OPEN" mode.

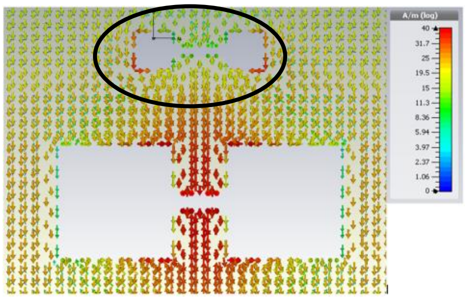

Fig. 15: The surface current more confined on the top structure during "SHORT" mode

C. 4 x 4 Array Antenna

Since, the antenna is proposed for outdoor applications, without fabrication process, the single element is expended to 4 x 4 array antenna in order to get directivity suitable for outdoor wireless applications. Simulation and optimization are performed to get better directivity and resonate at required frequencies. Further, S_{11} for the designed antenna is measured using microwave analyzer KEYSIGHT Model N9916A. After that, simulation and measurement results are composed and compared to observe the practicality of the proposed antenna. As shown in Fig. 16 and Fig. 17, the fabricated responses are slightly shifted compared with simulated response. Where, in "OPEN" feeding line the antenna resonates at 7.39 GHz, while in "SHORT" feeding line the fabricated antenna resonate at 8.76 GHz. These mismatch responses are due to several reasons, imperfect fabrication, substrate permittivity and real air gap approximation thickness.

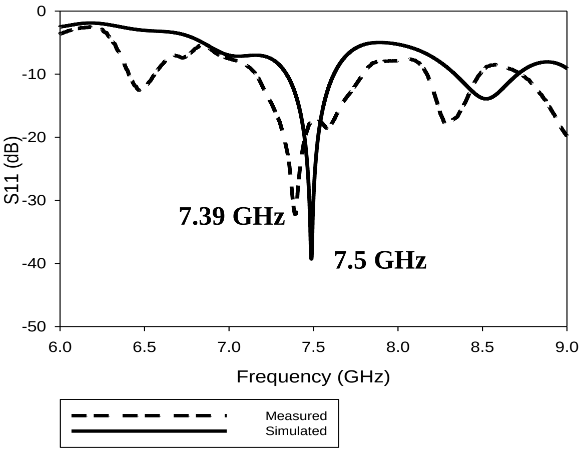

Fig. 16: Comparison between simulation and measurement in “OF” condition

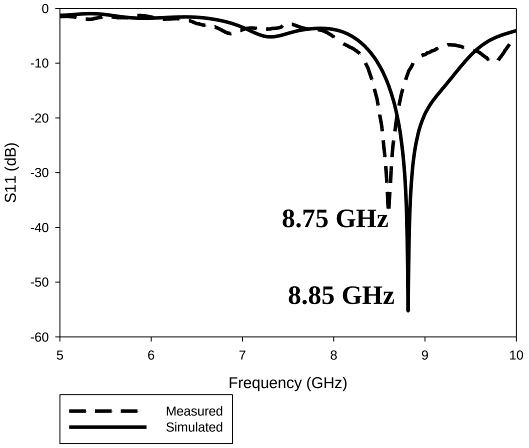

Fig.17: Comparison between simulation and measurement in “ON” condition

D. Radiation pattern and Antenna Gain

Radiation pattern of the proposed antenna is measured in ATENLAB model OTA-500 chamber with PNA KEYSIGHT model N5232A. Measured radiation patterns in “OPEN” and “SHORT” feeding line conditions, are compared with simulated radiation patterns. The normalized radiation patterns are shown in Fig. 18 and Fig. 19, respectively. It is observed that the radiation patterns are closely identical between simulation and measurement. However, the back lobe for 7.5 GHz is slightly bigger compared to 8.85 GHz. This big back lobe due to the big size of Dumbbell aperture slot etched on the ground plane for 7.5 GHz. Meanwhile, simulated gain and angle of the proposed antenna is depicted in Fig. 20 for 7.5 GHz and Fig. 21 for 8.85 GHz, respectively.

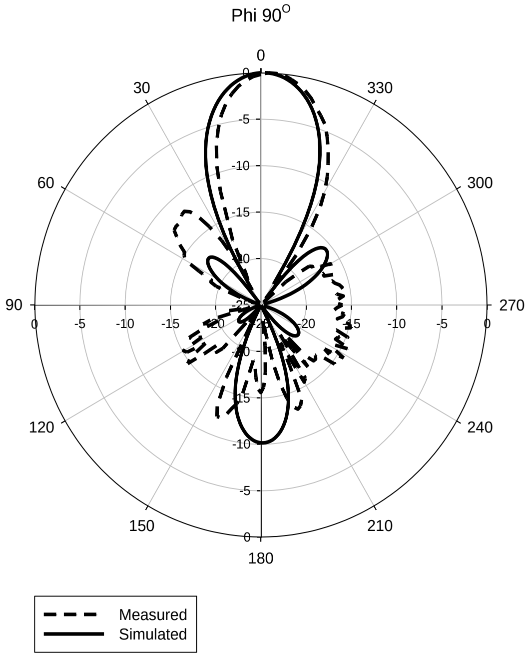

Fig. 18: Normalized radiation pattern feed line in “OPEN” condition

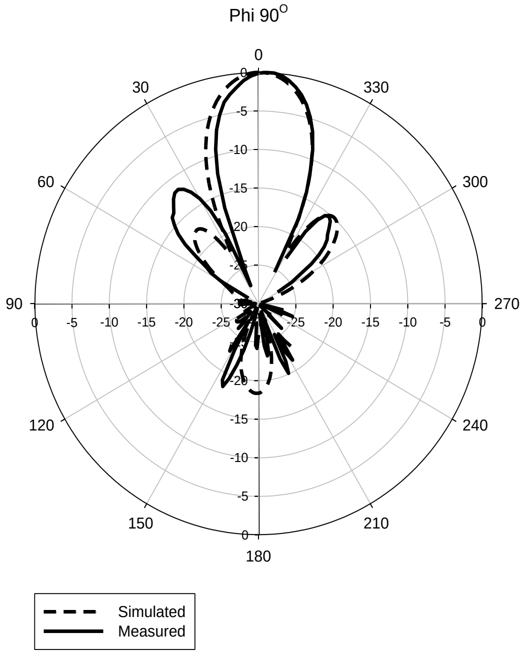

Fig. 19: Normalized radiation pattern feed line in “SHORT” condition

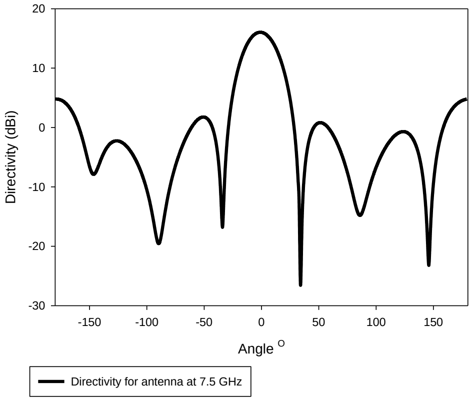

Fig. 20: Simulated directivity for 7.5 GHz

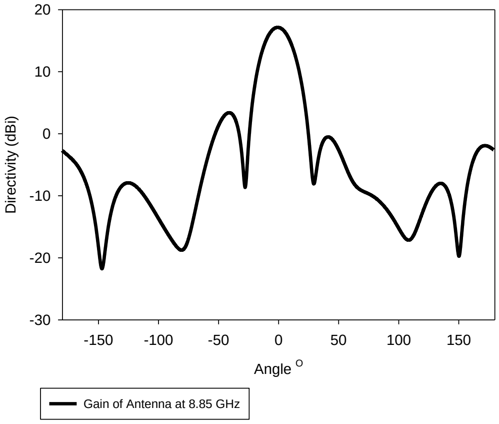

Fig. 21: Simulated directivity for 8.85 GHz

The output characteristics of the proposed array antenna are summarized in TABLE II. From the table we observe that the efficiency for 7.5 GHz drop from 91.88% to 79.62%, this reduction is expected effect from size of back lobe as shown in Fig. 18 and 19, respectively. Furthermore, we believe that all asymmetrical values are contributed by imperfect fabrication and effect of dielectric properties of substrate.

TABLE II: RESULT FOR FREQUENCY AND BANDWIDTH FOR DESIGNED AND FABRICATED ANTENNA.

	Switch Modes			
	Simulated		Measured	
	OFF	ON	OFF	ON
Centre Frequency (GHz)	7.5	8.85	7.39	8.75
Efficiency (%)	91.88	91.92	79.62	94.62
Directivity (dBi)	15.35	16.89	15.26	17.78
Bandwidth (MHz)	446.5	573.15	439.48	492.85
S_{11} (dB)	-38.77	-55.23	-53.20	-37.41

V. CONCLUSIONS

From the single element, frequency reconfigurable antenna using dumbbell slot structure is feasible and controllable based on the parametric analysis has been conducted on the dumbbell size. From the parametric analysis the frequency is decreased if the size of arm square increased, and the frequency is increased if the size of arm square decreased. The directivity of the proposed antenna for 4 x 4 array antenna seems consistent and provides very high values to support outdoor wireless communication systems.

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