A CPW Fed T-shaped Frequency Reconfigurable Antenna for Multi Radio Applications

Sulakshana Chilukuri [1], Keshav Dahal [1], Anjaneyulu Lokam [2], and Wenbing Chen [3]

[1] School of Engineering and Computing
University of West of Scotland, Paisley, PA12LJ, United Kingdom
sulakshana312ster@gmail.com, Keshav.Dahal@uws.ac.uk

[2] Department of Electronics and Communication Engineering
National Institute of Technology, Warangal, 506004, India
anjan.lokam@nitw.ac.in

[3] School of Mathematics and Statistics
Nanjing University of Information Science and Technology, Nanjing, Jiangsu, 210044, China
chenwb@nuist.edu.cn

Abstract ─ This paper deals with design, simulation and experimental analysis of a compact, Coplanar Waveguide (CPW) fed T-shaped reconfigurable antenna with frequency diversity. The antenna mainly comprises of four strips placed in T-shape fed by coplanar waveguide feed which operates at 5.8GHz. The reconfigurability in frequency is achieved by connecting four strips through three switches in main antenna structure by the use of Positive-Intrinsic-Negative (PIN) diodes. By operating the switches in a controlled manner, the antenna is able to operate at seven frequencies namely 5.82GHz, 5.46GHz, 5.26GHz, 5.15GHz, 4.69GHz, 3.93GHz, and 3.21GHz which are suitable for Wi-Fi, WiMAX, WLAN, other C-band, and S-band applications. The antenna aperture area is 35mm × 30mm and it is designed on a FR4 epoxy substrate whose dielectric constant $\varepsilon_r=4.3$, thickness h=0.8mm. A parametric study has been carried to analyze the characteristics of the proposed antenna. The measured results are in good agreement with simulation results and show that the antenna exhibits good radiation behavior in the specified application bands.

Index Terms ─ Antenna gain, CPW feed, frequency diversity, PIN diodes, radiation pattern, reconfigurable antennas.

I. INTRODUCTION

A frequency reconfigurable antenna comprises of elements of the antenna which can be reconfigured to a different physical structure that in turn alters frequency properties of the antenna while maintaining constant radiation behavior. Nevertheless, reconfiguration of one parameter of the antenna affects the rest of the parameters. For example, altering frequency response may affect radiation pattern and vice versa. This inter dependency is one of the main challenges in the area of reconfigurable antennas. This type of reconfiguration includes switching or shifting a resonant frequency, matched impedance bandwidth, or providing multiband and/or stop band characteristics. The most common method of obtaining frequency reconfigurability is by implementing conductor modification reconfiguration mechanism to the microstrip antennas in order to change the effective electrical length which in turn results in change of operating frequency. The operating frequency of the antenna is mainly determined by the antenna's electrical length.

The advantage of the frequency reconfigurable antennas is that by reusing the total antenna volume to function in different operational modes, the size of the antenna can be reduced. The fundamental operating frequency of the antenna depends on its electrical length which can be altered through electronic, mechanical or optical switching. However, electronic tuning is most widely used because of its efficiency and reliability in allocation of bandwidth dynamically. This is achieved by employing switching components such as Positive-Intrinsic-Negative (PIN) diodes, Field Effect Transistors (FETs), Radio Frequency Micro-Electro-Mechanical Systems (RF MEMS) and optical switches. All types of switches have their own advantages and disadvantages and can be used according to the application suitability. For example, in the applications where low power consumption, high linearity and high isolation are needed RF MEMS switches are used [1]. Recently, Wu et al. [2] used reed switch other than the above mentioned switches for the reconfigurable antenna application to eliminate the use of bias and control lines

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near the radiating patch area thus avoiding its impact on antenna radiation performance. So far frequency reconfigurable antennas that alter the physical structure of the antenna through electrical means have been discussed widely. A larger frequency shifts whether used for switched or continuous frequency bands can also be obtained by mechanical means [3]. Reconfigurable antennas that use RF switches like PIN diodes have been extensively researched in the past wherein a folded slot antenna employing two switches operating at two frequencies is proposed in [4], three PIN diodes on a meandered tuning stub which is placed on a half circular patch operating in four modes is presented in [5]. In [6] a multiband antenna with wide band characteristics by employing two switches on feed network of dual patch C-slot patch elements is discussed, a T-shaped switchable slot antenna employing five PIN diodes on ground plane operating at nine different frequencies is proposed in [7]. A CPW fed slot antenna with four PIN diodes is reported in [8]. A MEMS based optimized E shaped patch antenna for cognitive radio is presented in [9]. Also, latest researches [10-12] use different forms of reconfiguration mechanisms. A few antennas based on frequency, polarization and semi compound reconfigurability using PIN diodes with four operating modes are reported in [13-15].

This research proposes a novel and compact T-shaped antenna with frequency reconfigurable capability integrating with three switches functioning in eight different operating bands. The designed antenna finds few applications in wireless communications such as Wi-Fi, WiMAX, and WLAN. The prototype of the antenna is fabricated and tested. The principal aim of designing this frequency reconfigurable antenna is to achieve a wide-bandwidth with a compact size antenna while maintaining the integrity of the radiation pattern when the antenna reconfigures among eight different bands unlike aforementioned reconfigurable antennas with complex structure, use of large number of switches, large dimensions, low impedance bandwidth, feed radiation and low efficiency due to microstrip mechanism. The antenna is carefully designed to meet specific applications in all most all the operating modes. To get enhanced operating bandwidth, the coplanar waveguide (CPW) feeding technique is employed in this study and the experimental results are compared with simulated ones. The structural design aspects are discussed in Section II. The effect of few geometrical parameters on the performance of the antenna is reported in Section III. The simulated and experimental results are presented in Section IV and Section V. Finally, conclusion is presented in the last section.

II. ANTENNA DESIGN AND OPTIMISATION

The structural configuration of the proposed frequency reconfigurable slot antenna is shown in Fig. 1. The antenna is designed on a single layer of FR4 (Flame Retardant epoxy substrate) substrate whose dielectric constant $\varepsilon_r = 4.4$, loss tangent $\tan \delta = 0.027$ and thickness h = 0.8mm with single Coplanar feed. The antenna dimensions are 35 mm × 30 mm. It is longitudinally symmetrical and consists of four unfolded strips creating three slots separated by a distance of 0.5mm attached to CPW feed line. These three slot gaps are connected through three switches S_1, S_2 and S_3 to allow current flow through the metal strips. The optimized antenna parameters after several simulation runs are: L=35mm, W=30mm, the length of one arm of CPW ground L_1=15.3mm, and width W_1=5mm, the width of the feed line L_2=3.6mm, W_2=3.5mm, the length of the radiating strip L_3=8mm, and width W_3=1mm, W_4=0.5mm. The spacing between the ground and feed line, g=0.4mm.

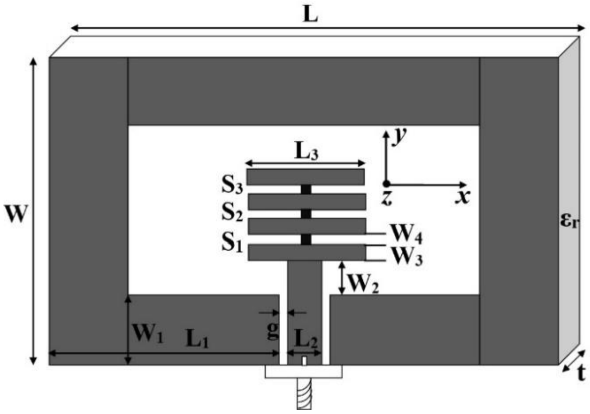


Fig. 1. Geometrical design of the proposed T shaped slot antenna with frequency diversity.

The conductor modification frequency reconfiguration mechanism is obtained by changing the electrical length of the slot and hence its resonant modes by implementing the switching technique using PIN diodes, operated in their ON/OFF condition. Several switches can be employed in the gaps between the strips for generating many resonant mode excitations. We use only three RF switches for the basic proof of concept. The operating conditions of switches are realized by forward (ON state) and reverse (OFF state) biasing of PIN diodes. When the diode is forward biased, the switch acts as short circuit with low impedance allowing current to flow through the switch. This increases the effective electrical length. When it is reverse biased (OFF state), the switch acts as open circuit, exhibiting high impedance and hence there is no connection between the slots. The PIN diodes are realized as short copper paths in the simulation. The ON state of the switch is realized by a small metallic patch of dimensions 0.1mm × 0.5mm and absence of the patch is considered as OFF. In order to obtain frequency reconfiguration, the three diodes are switched ON and OFF in eight (2^n where n=3 is the number of switches) different configurations as shown in Table 1.

Table 1: Eight cases of switch configurations

Case	Switch 1	Switch 2	Switch 3
1	OFF	OFF	OFF
2	OFF	OFF	ON
3	OFF	ON	OFF
4	OFF	ON	ON
5	ON	OFF	OFF
6	ON	OFF	ON
7	ON	ON	OFF
8	ON	ON	ON

In order to check the changes in the frequency shift or bandwidth, sensitivity studies for each parameter have been carried out. The parameters that show the considerable effect are slot length L_3, slot width W_3 and height of the slots above the center strip, i.e., W_2.

Figure 2 shows the S-parameter curves depicting the variations observed in reflection coefficient (S_{11} in dB) based on variation in the parameter L_3 for all the eight cases keeping W_3 (=1.0mm) and W_2 (=3.5mm) as constant. As the length is increased from 5.0mm to 10.0mm, it is observed that the operating frequency decreases, the bandwidth increases and the gain of the antenna decreases. This is due to the decrease in the frequency with increase in electrical length switching from Case 1 to Case 8. A better characteristic for S_{11} and the bandwidth is obtained when (L_3) is 8.0mm with other parameters fixed, i.e., W_3 = 1.0mm and W_2 = 3.5mm.

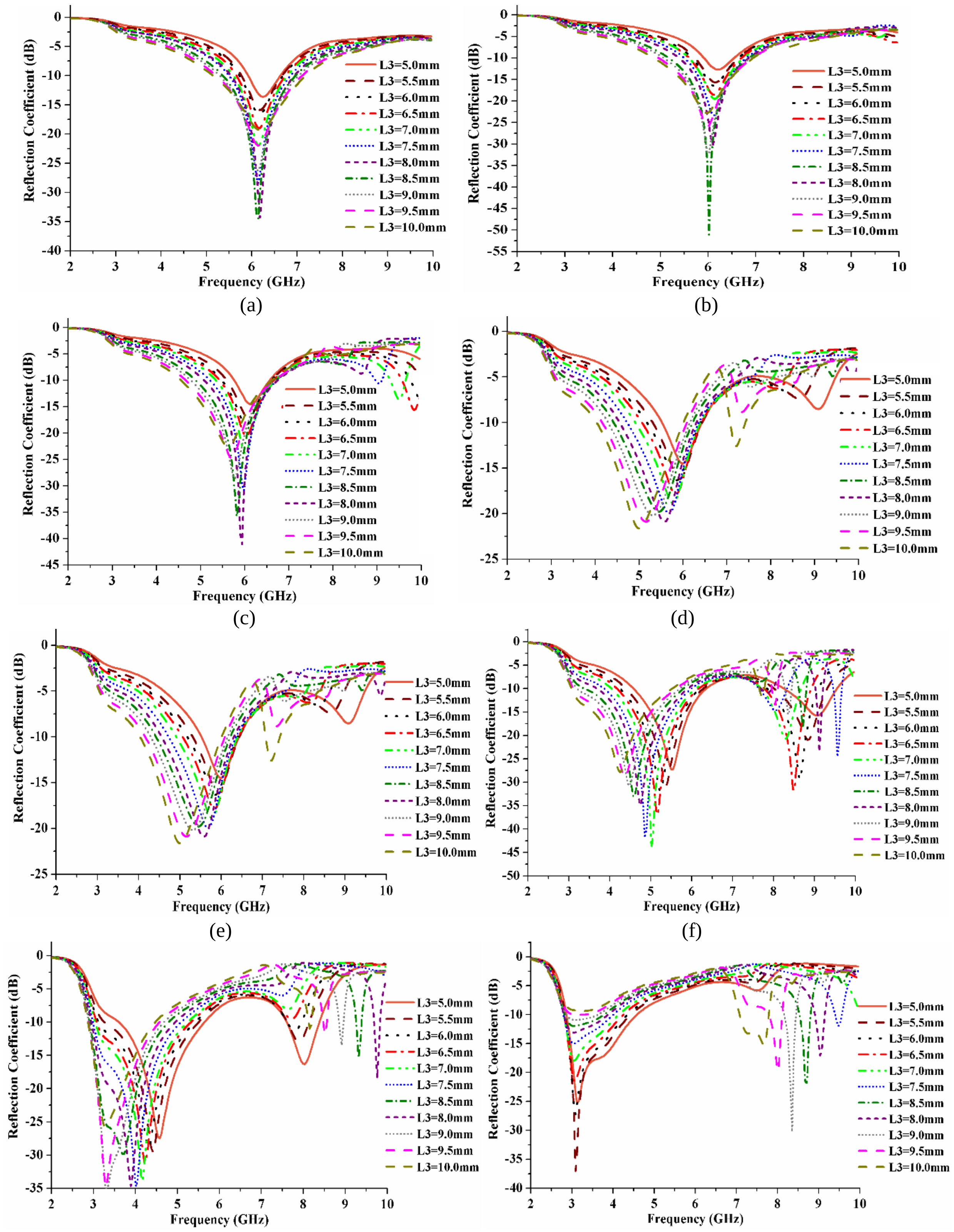
By keeping the slot length and height fixed and by varying the slot width W_3, different S_{11} curves are observed for all the eight cases. As the slot width is increased from 0.3mm to 1.5mm, the resonant frequency is decreasing while increasing the bandwidth. The value W_3=1.0mm is found to be the best compromised value for optimized return loss, bandwidth, gain and application frequency among all the cases.

Also, the height at which the patch is positioned above the ground plane is also varied to achieve the best performance of the antenna. The variations to the height are made from 0.5mm to 3.5mm while keeping L_3 (=8mm) and W_3 (=1.0mm) fixed. A better characteristic for S_{11} and the bandwidth is obtained when (W_2) is 3.5mm. Moreover with this value of W_2, in most of the cases, the operating frequency falls in the appropriate application band.

III. SIMULATION RESULTS

A commercially available Method of Moments (MoM) based CAD tool-IE3D, has been used to analyse the performance of the proposed antenna configurations. It uses adaptive symmetric matrix solver for solving Maxwell's boundary equations. The meshing frequency for the solution setup is chosen to be 5.8GHz with 20 number of cells/wavelength. The meshing alignment parameters such as maximum layer distance, regular size and refined size of the cell and refined ratio are set to be 0.0005mm, 2.05357, 0.410713 and 0.2 respectively to obtain more accurate results. The design of the antenna has been simulated with the proper geometrical parameters as shown in Fig. 1 for required numerical analysis.

The simulated S-parameter curves (S_{11} in dB) versus frequency of the proposed reconfigurable antenna in its eight operating modes are shown in Fig. 3. When any two of the switches are made ON, the antenna has single operating band and has low return loss which is desirable. In Case 4, when switches S_2 and S_3 are made ON, the antenna operates at 5.34GHz. The electrical length of the T-shaped patch at this frequency with two strips connected via two switches is about one half of the wavelength ($\approx 0.49\lambda_g$) where $\lambda_g = \frac{\lambda}{\sqrt{\varepsilon_{eff}}}$ and $\varepsilon_{\mathrm{eff}} = \frac{\varepsilon_r+1}{2} = 2.7$ and the current flowing in the top two strips is due to the mutual coupling between the first strip and the remaining three strips. In Case 6, when S_1 and S_3 are made ON, it operates at 4.6GHz with electrical length nearly equal to half wavelength ($\approx 0.54\lambda_g$) whereas in Case 7, when S_1 and S_2 are made ON, the antenna resonates at 4.0GHz with electrical length is $\approx 0.53\lambda_g$. It is observed that, when any single switch is made ON, the antenna resonates at two frequencies and exhibits dual band characteristics except in Case 2, switch S_3 is made ON where the antenna operates at single frequency 5.75GHz. In this case, second resonant frequency is not suitable mode of operation because of high return loss, high cross polarization and low gain obtained. In Case 3, when only S_2 is made ON, the antenna resonates at two frequencies namely 5.6GHz and 9.2GHz. The electrical length at 5.6GHz with current flowing in second and third strip is $\approx 0.46\lambda_g$ and at 9.2GHz with current flowing in all three strips is $\approx 0.55\ \lambda_g$. Likewise, in Case 5, when switch S_1 is ON, it operates at two different frequencies namely 4.85GHz and 8.3GHz. It is also observed that the -10dB impedance bandwidth obtained at the first resonant frequency when a single switch is made ON is low compared with the bandwidth obtained when two switches were made ON. Lastly, when all switches are made OFF, the antenna operates at 5.85GHz with electrical length equal to quarter wavelength ($\approx 0.26\lambda_g$) and when all switches are made ON, it resonates at 3GHz with an electrical length of $0.55\ \lambda_g$.



(a) (b)

(c) (d)

(e) (f)

(g) (h)

Fig. 2. Simulated S_{11} of proposed reconfigurable antenna for varying slot lengths (L_3) operating in: (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4, (e) Case 5, (f) Case 6, (g) Case 7, and (h) Case 8.

The operating frequency of the antenna when switched from Case 1 to Case 8 decreases as the electrical length of the antenna from Case 1 to Case 8 is increased.

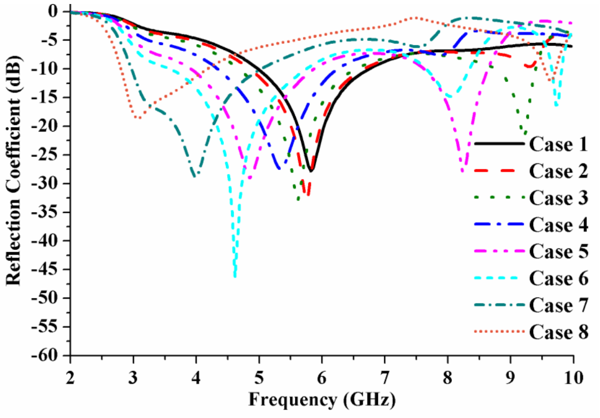


Fig. 3. Simulated reflection coefficients (S_{11}) of proposed reconfigurable antenna.

IV. ANTENNA PROTOTYPE AND EXPERIMENTAL RESULTS

In order to validate the simulated results, the proposed reconfigurable antenna was tested with the optimized geometrical parameters L_3=8.0mm, W_3=1.0mm and W_2=3.5mm. It is fabricated on a FR4 substrate with dielectric constant 4.4 and thickness 0.8mm. In this design, the PIN diode selected is a MADP-008120-12790T from M/A-COM Technology Inc. In ON state it has a very low forward resistance $R_S = 2.5\Omega$ and in OFF state it has total capacitance of C_T = 0.15pF and L_S = 0.7nH. Figure 4 shows the DC bias network (on the reverse side of the antenna board) for the practical PIN diodes that are incorporated on the patch. It is biased with forward voltage V_F = 0.73 V.

Two DC blocking capacitors (C_1, C_2), (C_3, C_4), (C_5, C_6) for each diode with 64pF are used to prevent the DC signal but allow RF current to pass through. The inductors L_1, L_2, L_3, L_4, L_5 and L_6 with 56nH are used as RF chokes to provide low impedance for DC signal and high impedance for RF signals. The resistors R_1, R_2, R_3, R_4, R_5 and R_6 are used to control the biasing current to the PIN diodes. The fabricated prototype of the antenna used for the measurement is shown in Fig. 5. An Agilent E8363C PNA Series Microwave Network Analyzer that operates in the frequency range 10 MHz to 40 GHz was used to measure all the return loss parameters.

The measured and simulated return loss graphs are depicted in Figs. 6 (a)-(h) for Case 1 to Case 8. The practical antenna results are in good match with the simulated ones. A very wide bandwidth of around 30%-40% is achieved in all the useful applications and in other cases it is around 50%.

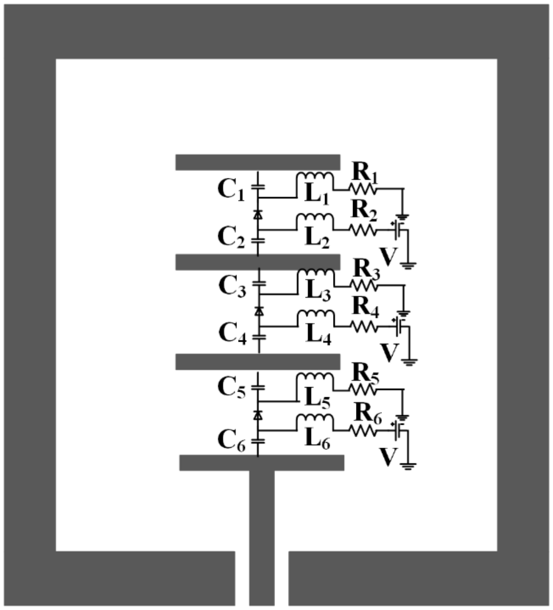


Fig. 4. DC bias network for the PIN diodes.

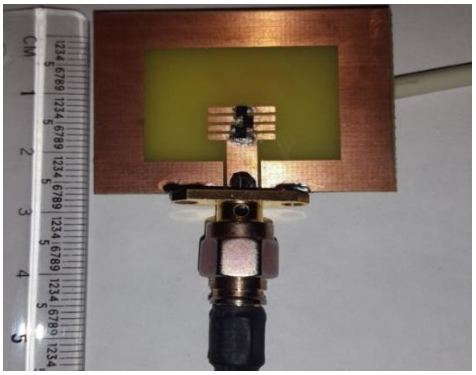
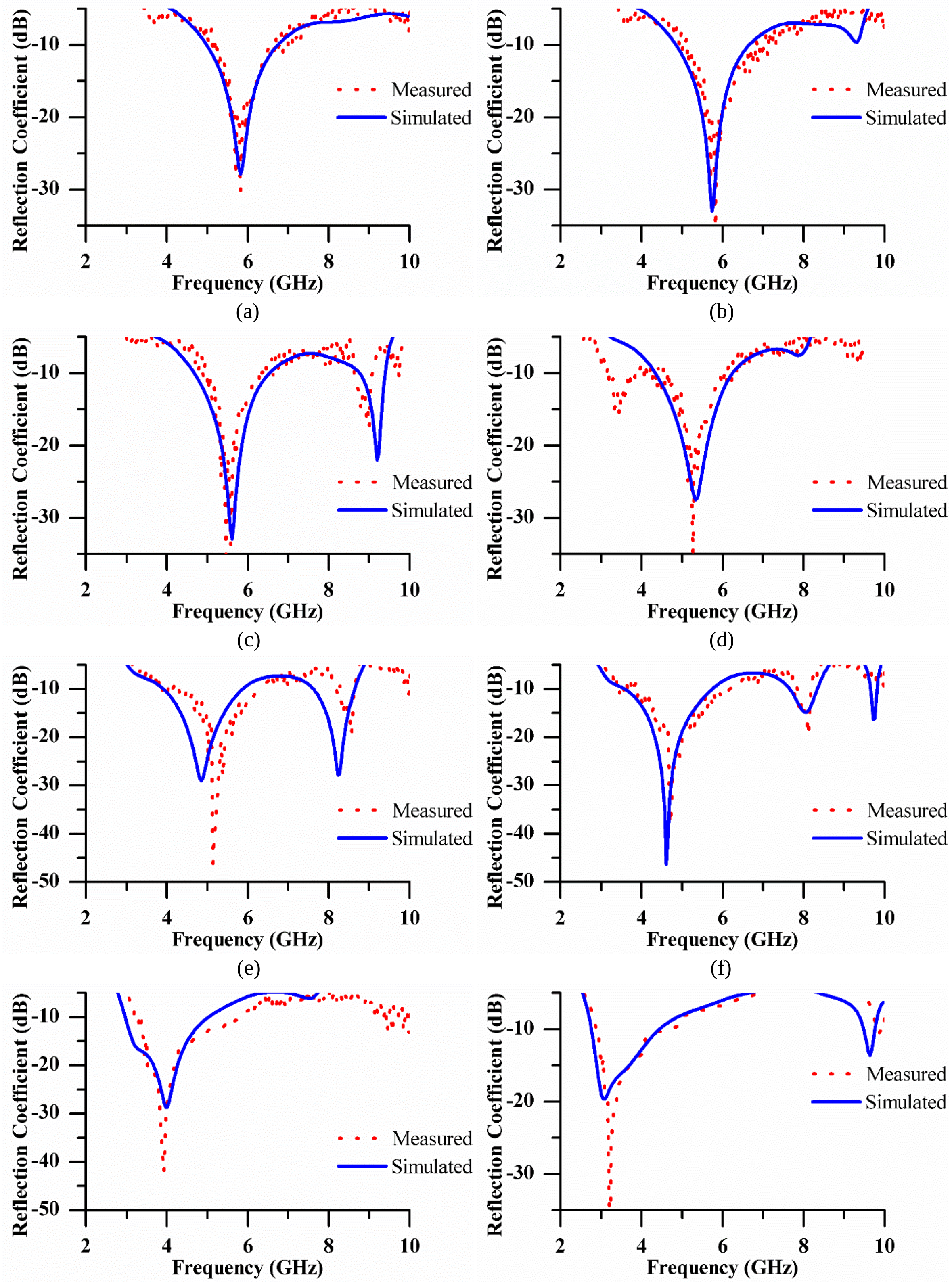


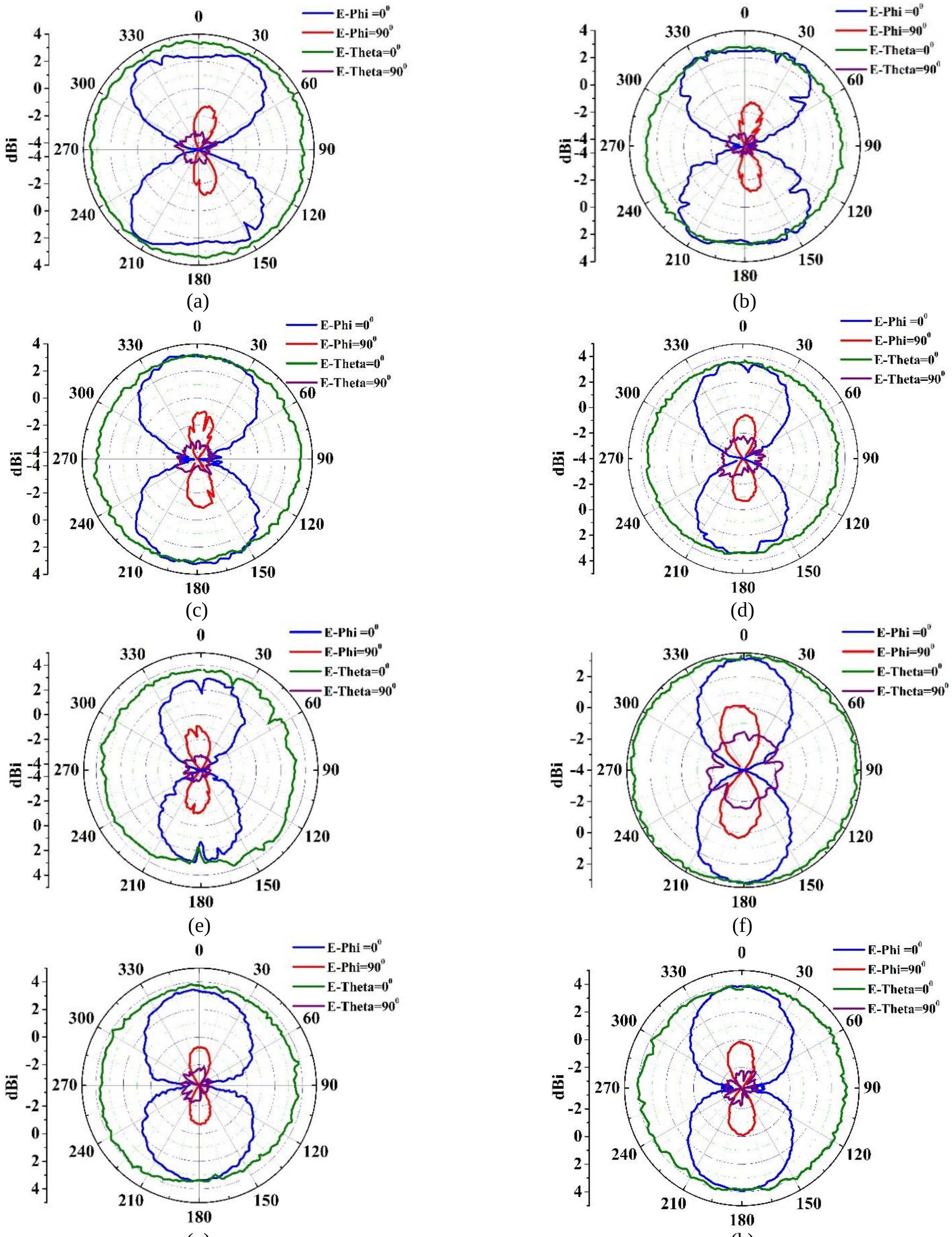
Fig. 5. Prototype of the fabricated T-shaped reconfigurable antenna.

Figure 7 depicts the measured 2D gain radiation patterns in dBi. The figure shows E-total field of the proposed antenna in eight different operating modes in the elevation (E_θ) and azimuth (E_ϕ) planes with $\phi=0^0$ and $\theta=0^0$ referring co-polarization and $\phi=90^0$ and $\theta=90^0$ referring cross-polarization. In all the operating modes, the antenna maintains almost similar and stable (Figure of '8') radiation pattern which satisfies the frequency reconfigurability condition where only frequency has to be changed, not patterns and polarization. It is also observed from the figure that the cross-polarization response is very much below the co-polarization response.



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 6. Simulated and measured reflection coefficients (S_{11}) of proposed reconfigurable antenna operating in: (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4, (e) Case 5, (f) Case 6, (g) Case 7, and (h) Case 8.



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 7. Measured gain patterns of proposed reconfigurable antenna operating at: (a) 5.78GHz (Case 1), (b) 5.82GHz (Case 2), (c) 5.42GHz (Case 3), (d) 5.24GHz (Case 4), (e) 5.15GHz (Case 5), (f) 4.72GHz (Case 6), (g) 3.95GHz (Case 7), and (h) 3.09GHz (Case 8).

Table 2: Characteristics of reconfigurable antenna in eight operating modes

Antenna Parameters	**Mode 1**	**Mode 2**	**Mode 3**	**Mode 4**	**Mode 5**	**Mode 6**	**Mode 7**	**Mode 8**
Operating Frequency (GHz)	5.82 (5.82)	5.75 (5.82)	5.61 (5.46)	5.34 (5.26)	4.85 (5.15)	4.61 (4.69)	4.0 (3.93)	3.07 (3.21)
Return Loss (dB)	27.8 (30.2)	32.83 (36.4)	32.86 (31.9)	27.5 (34.9)	29.0 (46.1)	46.1 (37.9)	28.7 (42.1)	18.63 (41.9)
Measured Operating band (GHz)	5.2-6.7	4.9-6.7	4.8-6.6	4.4-6.2	4.0-6.3	3.6-5.9	3.2-5.7	2.9-4.6
Bandwidth (%)	30.24 (25.61)	31.13 (36.4)	32.97 (31.9)	35.58 (33.8)	40.21 (43.69)	46.63 (51.39)	51.5 (64.12)	44.63 (53.89)
Gain (dBi)	3.22 (3.0)	3.12 (2.9)	3.15 (3.0)	3.44 (3.0)	3.5 (2.4)	3.25 (2.6)	3.35 (3.0)	3.82 (2.9)
VSWR	1.08	1.04	1.04	1.08	1.07	1.009	1.07	1.26
Application	Wireless LAN				Wi-Fi (IEEE 802.11)	C-Band	S-band	WiMAX (IEEE 802.16)

*The values in the braces indicates measured results.

Table 3: Comparison of frequency reconfigurable antennas in literature

Reference Antenna	**No. of Switches**	**Dimensions**	**Modes**	**Operating Frequency (GHz)**	**Bandwidth (%)**
Proposed Antenna	3	$0.676\lambda_0 \times 0.58\lambda_0 \times 0.0155\lambda_0$	8	3.21 to 5.82	25 to 64
[6]	2	$0.77\lambda_0 \times 0.58\lambda_0 \times 0.0155\lambda_0$	2	5.25, 5.78	15.5, 13.9
[7]	3	$0.73\lambda_0 \times 0.73\lambda_0 \times 0.023\lambda_0$	4	2.5, 2.9, 3.5, 4.4	5.4, 9.8, 16, 13.7
[8]	2	$1.167\lambda_0 \times 1.167\lambda_0 \times 0.037\lambda_0$	3	(5.55, 5.65) and 5-7	33.5 (wideband)
[9]	5	$0.213\lambda_0 \times 0.337\lambda_0 \times 0.034\lambda_0$	9	1.98 to 3.59	4.6 to 7.7
[13]	4	$0.77\lambda_0 \times - \times 0.018\lambda_0$	3	1.51, 3.27, 3.55	6.0

The average difference between the co-pol and x-pol levels in the main plane (Elevation, x-y plane) direction for most of the frequencies is higher than co-pol and x-pol levels in the Azimuth plane (x-z and y-z plane) direction because of the symmetric shaped strips as the main patch and ground plane that mainly excited all the eight frequencies. In Azimuth plane, a high degree of x-pol is observed for most of the resonant frequencies because of the coupling influences between the T-shaped strips. This is due to the dual mode excitation caused mainly by the nearby four coupled strips which then affected the x-pol levels of these operating frequencies in this plane.

The measured gain of the antenna operating in eight different modes is shown in Fig. 8. The maximum gain of the antenna in all the operating modes is around 3dBi. The detailed simulated and measured values of return loss, bandwidth and other antenna parameters are given in Table 2.

Table 3 compares the results of proposed antenna with conventional frequency reconfigurable antennas in the available literature. It is apparent that the proposed antenna is able to generate all possible modes with the use of limited number of switches when compared to others. The presented antenna provides wider -10dB return loss bandwidth (%) than the existing ones. Also, the total volume occupied by the proposed antenna is less compared to the antennas in the literature. Even though the reconfigurable antenna in [9] occupies less volume and can generate more number of operating modes than the proposed antenna, it has more number of switching elements and less bandwidth when compared to the nominated antenna. The presented antenna provides almost double the -10dB return loss bandwidth when compared to [8].

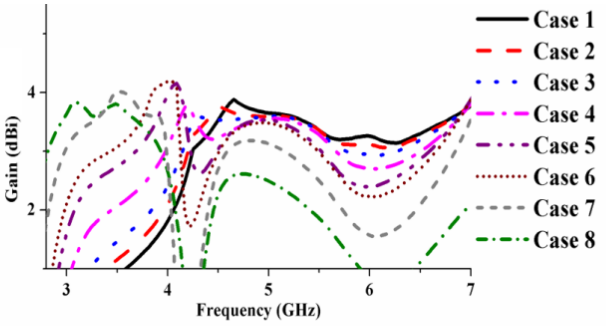


Fig. 8. Measured gain of proposed reconfigurable antenna.

V. CONCLUSION

A frequency reconfigurable slot antenna is designed and evaluated in this paper that operates in eight different operating bands. The coplanar waveguide feeding technique is used to attain wide bandwidths up to 65%. The measured results of the fabricated antenna prototype are found in good agreement with simulated ones with acceptable small deviations which are due to inaccuracies in fabrication process, SMA connector solder losses which causes impedance mismatch at the CPW feed and some imperfections in the dielectric material. The fabricated antenna has found applications in wireless communications such as Wi-Fi, WiMAX and WLAN.

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Sulakshana Chilukuri received the Bachelor's degree in Electronics and Communication Engineering from G. Narayanamma Institute of Technology and Science, Hyderabad, India, in 2007, the Master's degree in Electronics and Communication Engineering with Communication Systems specialization from National Institute of Technology, Tiruchirappalli, Tamilnadu, India in 2010 and received her Ph.D. degree in Electronics and Communication Engineering from national Institute of Technology Warangal, Telengana, India in 2016.

She is presently working as Post-Doctoral Research Fellow at University of West of Scotland. Her field of study is Reconfigurable Antennas and other areas of interest are Microwave Engineering, Electromagnetics and Transmission lines, Wireless Communication Systems and MIMO antennas. She has published her work in 8 peer reviewed International Journals, 10 International conferences.

Keshav P. Dahal is a Professor of Intelligent Systems and the leader of the Artificial Intelligence, Visual Communication and Network (AVCN) Research Centre at the University of the West of Scotland (UWS), UK. He is also affiliated with Nanjing University of Information Science and Technology (NUIST) China. Before joining UWS he was with Bradford and Strathclyde Universities in UK. He obtained his Ph.D. and Master from Strathclyde. His research interests lie in the areas of applied AI to intelligent systems, trust and security modelling in distributed systems, and scheduling/ optimization problems. He has published extensively with award winning papers, and has sat on organizing/ program committees of over 55 international conferences including as the General Chair and Programme Chair. He is a Senior Member of the IEEE.

Lokam Anjaneyulu was born in 1967 in India. He obtained his B.Tech (ECE) in 1989, M.Tech in 1991 and Ph.D. in 2010 from National Institute of Technology, Warangal, India. He worked as Project Officer at Institute of Armament Technology, Pune, India for 5 years from 1991 and involved in the design of Surface borne and Airborne Radar systems for clutter measurement application. Later, he worked as Staff Scientist at Helios Systems, Madras, India for 2 years and engaged in the development of Radio Wave propagation assessment software modules for ship-borne radars. He has been with the Department of Electronics and Communications Engineering at National Institute of Technology, Warangal, India since 1997. His areas of interest include Computer Networks, Electromagnetic Field Theory, Microwave & Radar Engineering, and Neural Networks & Fuzzy Logic Systems. He has completed few Defense R&D Projects and has 31 papers to his credit in National and International Conferences and Journals.

Wenbing Chen is a Senior Engineer and the Head of Department of Information and Computing Science at Nanjing University of Information Science and Technology. He received M.Sc. degree in Applied Mathematics from Nanjing University of Science Information and Technology. He has been regularly visiting the Artificial intelligence, Visual Communications & Networks (AVCN) Research Centre at the University of the West of Scotland. His research interests lie in the areas of machine learning, image processing and pattern recognition, artificial neural network. He has published over 30 peer-reviewed journal/conference papers.