Progress In Electromagnetics Research C, Vol. 113, 59–68, 2021

A Compact Dual Asymmetric L-Slot Frequency Reconfigurable Microstrip Patch Antenna

Bhaben Saikia, Pulin Dutta, and Kunal Borah*

Abstract—A frequency reconfigurable microstrip patch antenna with two asymmetric L-slots is proposed in this article. Two RF pin diodes inserted on the asymmetric L-slots are used to switch the operating frequency over the C band. Design and optimization of different physical parameters of the antenna viz. slot dimensions, feed location, notch size, and pin diode positions are carried out using High Frequency Structure Simulator Version 13.0. The design is implemented on an FR4 substrate ($\varepsilon_r = 4.4$) of dimension $(35 \times 40 \times 1.6)\,\mathrm{mm}^3$. DC bias circuitry for RF PIN diode activation is also integrated with the antenna. Switching combinations of two PIN diodes offer four reconfiguration modes of operation at 4.75, 5.05, 5.11, and 5.18 GHz. In all the states, the -10 dB bandwidth shows minimal changes with average variations of 15.8% with respect to the state when both PIN diodes are OFF. The gains of the antenna for different modes of operation are found almost stable with an average of 6.64 dBi.

1. INTRODUCTION

The rapid development in multiband and multifunction wireless communication platforms demands antennas with dynamic and adaptive operating characteristics. Reconfigurable antenna (RA) has the potential to fulfil the diverse communication requirements with its frequency agility, steerable radiation pattern, and polarization diversity. Besides, RAs can reduce the size and complexity of wireless systems by performing the functions of multiple conventional antennas. RAs can be classified according to the dynamically adjustable characteristics viz. frequency reconfigurability, pattern reconfigurability, and polarization reconfigurability. The reconfiguration of two or more antenna characteristics leads to compound reconfigurable antennas [1, 2]. Because of the attractive features such as low profile, low cost, and light weight, microstrip patch antennas are mostly preferred by antenna researchers to design reconfigurable antennas [3]. Frequency reconfigurable patch antennas (FRPAs) offer many advantages over traditional broadband antennas such as compact size, similar far-field radiation pattern, and almost constant gain for all the switchable operating frequencies, and above all, frequency selectivity that minimizes the adverse effects of co-site interference and jamming. They also eliminate the needs of complex filter circuits used in most of the broadband antennas [4].

The reconfiguration techniques are categorized as electrical, photoconductive or optical, mechanical or physical reconfiguration and reconfiguration using tunable smart materials [5, 6]. In electrical reconfiguration method, solid state switching devices such as PIN diode, RF-MEMS, and varactors are integrated in the antenna structure to alter the current distribution or field arrangement in the radiating element. Among these devices, low cost, extremely fast switching operation, and high-power handling ability make RF PIN diode most preferable [7, 8]. Slot loaded frequency reconfigurable patch antennas offer a wide reconfigurable frequency span by placing different types of switches in it [9–14].

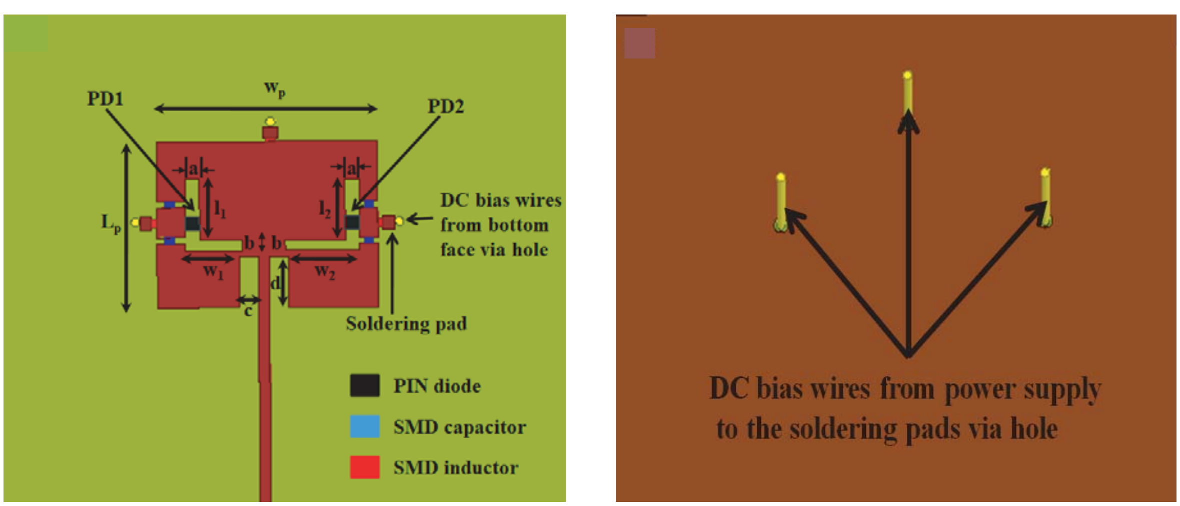
Received 10 April 2021, Accepted 7 June 2021, Scheduled 10 June 2021
* Corresponding author: Kunal Borah (kbnerist@gmail.com).
The authors are with the Department of Physics, North Eastern Regional Institute of Science and Technology (Deemed to-be-University), Nirjuli, Itanagar, Arunachal Pradesh 791109, India.

An FRPA loaded with slot and slit geometry to cover a reconfigurable frequency range of 0.6 GHz is presented in [15]. However, a large number of switches employed in the structure increase its complexity. In [16], a frequency reconfigurable U slot antenna employing two varactors is proposed which offers 1 GHz tunability range. Requirement of large biasing voltage for varactor reactance tuning reduces its utility for low power handheld and wearable devices. The reconfigurable U slot antenna presented in [17] covers 1 GHz continuous frequency adjustment using four PIN diodes. In [18], a tunable slotted patch antenna is investigated which uses shorting posts between patch edge and ground plane via PIN diode switches. Three PIN diode switches are employed in the design which produces resonances at 620 MHz, 837 MHz, 924 MHz, and 1150 MHz with different combinations of short-circuited posts. Poor radiation efficiency ranging from 20% to 58% for its different modes is the major concern with this design.

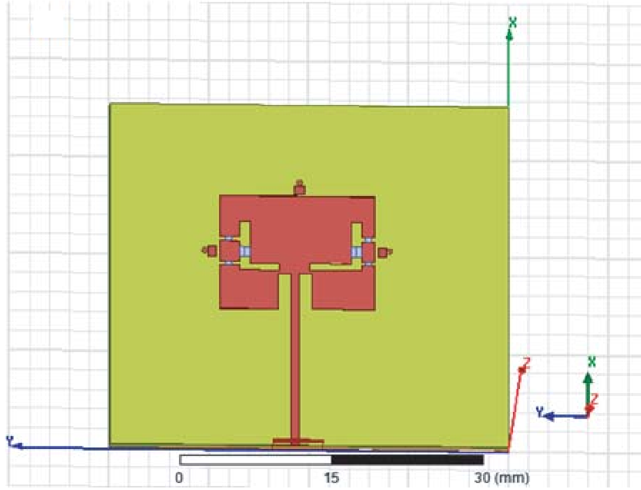
A single fed FRPA loaded with two asymmetric L-slots is included over a rectangular patch and is discussed in this article. Two RF PIN diodes are inserted in the slots to achieve the desired frequency reconfigurability. As the position of the RF switch and slot dimensions are crucial in reconfigurable antenna design, they are optimized for the best possible antenna performance. An integrated simple DC bias circuit consisting of RF block inductors and DC block capacitors is also designed for the activation of PIN diodes. Main features of the proposed design include a small number of PIN diode switches, simple integrated biasing circuitry, almost constant gain for different modes, and low DC voltage (1 volt) needed for frequency switching. The proposed design offers a simple and efficient way to achieve frequency reconfiguration at four discrete frequencies viz. 4.75 GHz, 5.05 GHz, 5.11 GHz, and 5.18 GHz. The C-band frequencies of 5.4 GHz band (5.15 to 5.35 GHz, 5.47 to 5.725 GHz, or 5.725 to 5.875 GHz, depending on the region of the world) are used for IEEE 802.11a Wi-Fi wireless computer networks, and several antenna designs are found in the literature working in this band [19, 20]. In [21], 4.8 GHz band is used for wireless implantable body area network (WiBAN), and in [22], it is reported to be used for future 5G applications.

2. ANTENNA DESIGN AND CONFIGURATION

The top and bottom views of the proposed FRPA are shown in Figures 1(a) and (b), respectively, and Figure 1(c) shows the snapshot of the proposed structure from HFSS. The FRPA is fabricated on an FR4 substrate ($\varepsilon_r = 4.4$ and $\tan\delta \sim 10^{-2}$) with dimensions $(35 \times 40 \times 1.6)\,\text{mm}^3$. The dimension of the base patch is calculated using transmission line model (TLM) of patch antenna [23] and is chosen as $L_p = 11.59$ mm and $W_p = 15.49$ mm to resonate at 6 GHz. For excitation, microstrip line feeding technique is used with a $50\,\Omega$ inset feed line of length 17.6 mm and width 0.8 mm. Length and width of the notch in inset feed is optimized for the best impedance matching at the desired resonant frequency. Then two nonidentical L-shaped slots are etched on the patch. Two RF PIN diodes (SMP 1345-079LF from Skyworks Solutions) are inserted in these slots to adjust the slot configuration. These



(a) (b)



(c)

Figure 1. (a) Top view. (b) Bottom view of the proposed FRPA. (c) Snapshot of the proposed structure from HFSS work plane.

PIN diodes work as switches, change surface current densities across the slots, and alter electrical length of the radiator to provide the desired frequency reconfigurability. The slots dimensions and PIN diode positions are also optimized for maximization of -10 dB reconfigurable frequency range using HFSS ver.13.0. Four rectangular slots are etched near the L-slots to accommodate four DC block capacitors of bias circuitry. Length and width of the rectangular slots adjacent to left L-slot are 2 mm and 0.4 mm, respectively, and 1.3 mm and 0.4 mm for the right L-slot. Ground plane contains three circular etching islands of radius 0.7 mm to accommodate DC bias wires to RF PIN diode switches via hole through the substrates. Optimized physical dimensions of L-shaped slots and notch are listed in Table 1.

Table 1. Dimensions of slot and notch of the proposed FRPA.

Design parameter dimension
$l_1 = l_2 = 5\,\text{mm}$
$w_1 = 3\,\text{mm}$
$w_2 = 4.2\,\text{mm}$
$a = 1\,\text{mm}$
$b = 0.7\,\text{mm}$
$c = 1.3\,\text{mm}$
$d = 3.6\,\text{mm}$

The PIN diodes inserted into the left and right-side L-slots are named as PD1 and PD2, respectively. For simulation, ON and OFF state RLC equivalent of PIN diode is considered, which is shown in Figure 2(a). The diode offers a very low resistance of 1.5 Ω with a series inductance of 0.7 nH in forward biased condition. In reverse biased condition, the equivalent circuit of the PIN diode contains a parallel combination of resistance 5 kΩ and capacitance of 0.15 pF in series with an inductance of 0.7 nH.

In order to switch the PIN diodes between ON and OFF states, a DC biasing network is incorporated in the antenna structure as shown in Figure 2(b). The interference of DC with RF signal flowing in the patch largely affects the antenna performance while passing RF signal towards the power supply creates disturbance. Hence, in the proposed FRPA, DC biasing network contains four DC block capacitors of 3.3 pF (Murata Electronics), three RF block inductors of 3.9 nH (Murata Electronics), and three DC bias wires passing via holes drilled from the islands of ground plane to the top of the substrate. These wires are terminated at the soldering pads of dimension $(1 \times 0.8)\,\text{mm}^2$ as shown in Figures 1(a) and (b). RF block inductors are placed between these soldering pads and the patch while DC block capacitors are inserted in the rectangular slots adjacent to L-slots. These capacitors maintain the continuity of RF current across these slots, however prevent DC interference with RF. The anode of each diode is connected to one of the two bias wires from a 1 V power supply, while the third DC bias wire serves as common ground for the cathodes of both PIN diodes. To control the bias current, resistor $R = 100\,\Omega$ is connected in series with each bias wire as shown in Figure 2(b). Each PIN diode can be individually set to ON state by applying positive DC voltage at its anode.

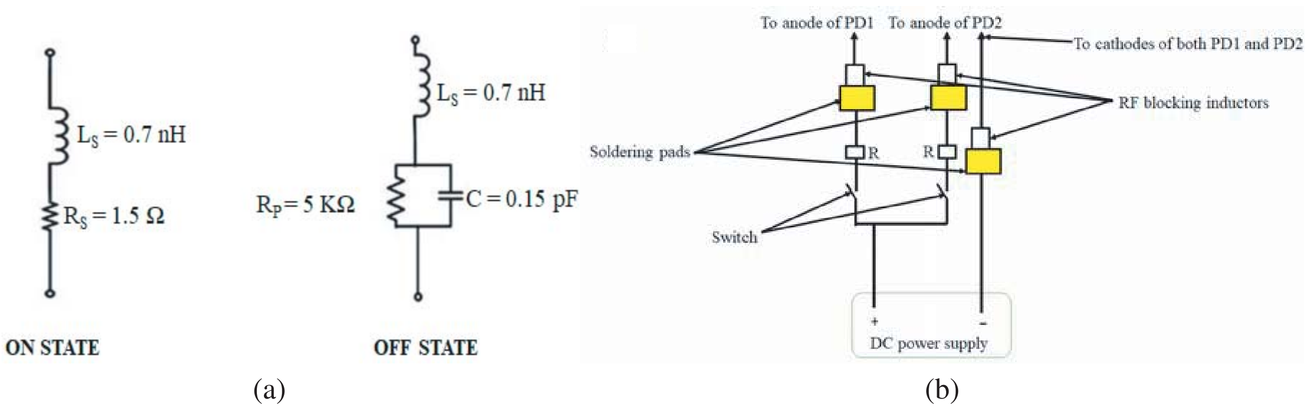


Figure 2. (a) RLC equivalent circuit of PIN diode switch. (b) DC biasing circuit for PIN diode activation.

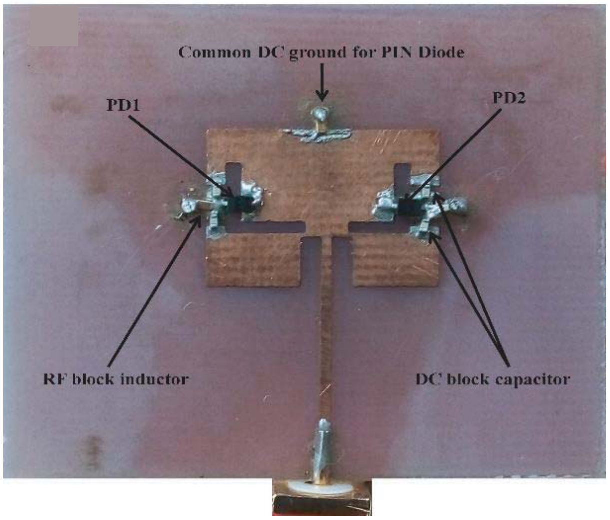
3. RESULTS AND DISCUSSION

The proposed FRPA is fabricated as shown in Figures 3(a) and (b), and Figure 3(c) is a snapshot of measurement of the fabricated antenna. Two PIN diodes inserted across the slots offer four possible switching combinations which lead to four different reconfigurable modes of operation, i.e., mode 1 (OFF-OFF), mode 2 (ON-OFF), mode 3 (OFF-ON), and mode 4 (ON-ON). To measure the return loss and radiation pattern of the antenna at these reconfigurable modes, Agilent N5222 vector network analyzer and antenna measurement systems are used. The simulated and measured return losses (S_{11} parameters) of the FRPA under investigation for different modes of operation are presented in Figures 4(a), (b), (c), and (d).

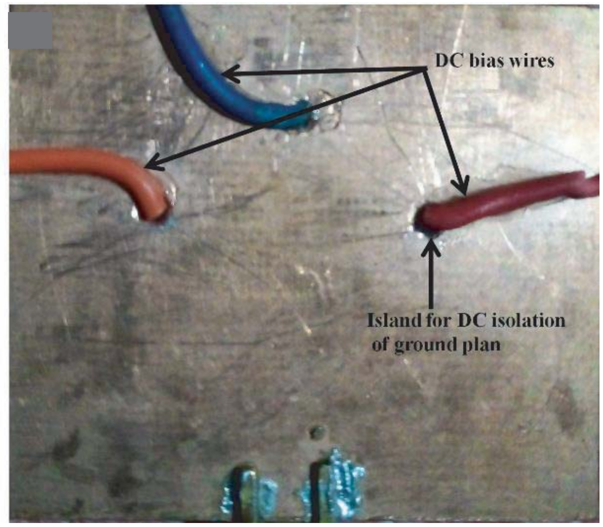
In mode 1, both PD1 and PD2 are OFF, and the antenna resonates at 4.75 GHz. For mode 2 operation, PD1 is turned ON while PD2 remains OFF, and the resonance occurs at 5.05 GHz. The resonant frequency measured is 5.18 GHz for mode 3 operation in which PD1 is OFF and PD2 ON. In mode 4 operation, both PD1 and PD2 are turned ON which shifts the resonant frequency to 5.11 GHz. Resonant frequency, -10 dB bandwidth, S_{11} parameter, and gain for all reconfigurable modes of operation are listed in Table 2. The simulated gains of the FRPA for mode 1, mode 2, mode 3, and mode 4 are 6.45 dB, 5.96 dB, 6.08 dB, and 6.02 dB, respectively. It is noted from Table 2 that all the reconfigurable modes offer resonant frequency with return loss parameter $S_{11} < -10$ dB. The measured S_{11} values are higher than the simulated ones. This may be due to soldering or fabrication tolerances [24]. The measured S_{11} values range from -15 dB to -21 dB which falls under a generous range for a radiating patch antenna, according to various literatures [3, 14, 19].

The resonant frequency of patch antenna is controlled by the effective electric length and surface current distribution of the radiator. When PIN diode is OFF, the current path elongates, due to the absence of any electrical connection across the slot. As a result, surface current concentrates along the slot edges and lowers the resonant frequency of the FRPA.

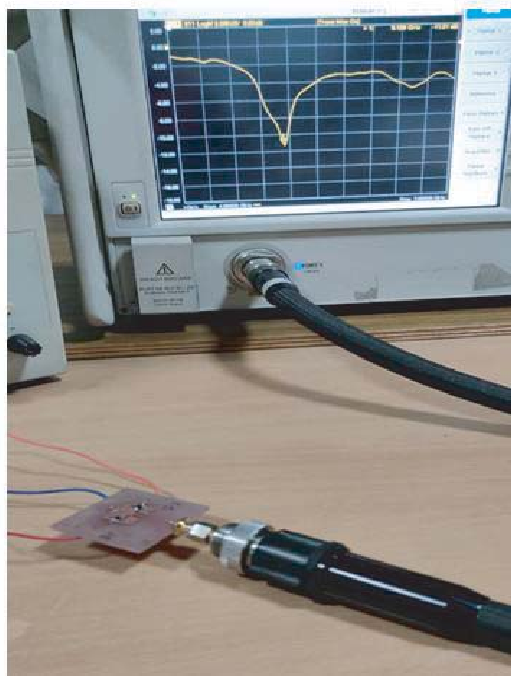
For ON state of PIN diode, the presence of electrical connection across the slot decreases the current path, and surface current concentration falls down along the slot edges. Instead, current concentration



(a)



(b)



(c)

Figure 3. (a) Top face. (b) Bottom face of the fabricated prototype. (c) Snapshot of measurement.

increases along the PIN diode to result in a higher resonant frequency of the FRPA [14, 25, 26]. To validate this explanation for the proposed FRPA, surface current distributions at respective resonant frequencies for different modes of the operation are depicted in Figure 5.

In Figure 5(a), increase in the surface current concentration along the slot is observed for mode 1 operation of the FRPA (both PD1 and PD2 OFF). Figure 5(b) shows the decrease of current density across the perimeter of the left slot when PD1 is ON (mode 2). Decrease in current density along the right slot is depicted in Figure 5(c) for mode 3 operation (PD2 ON) while Figure 5(d) indicates the fall in surface current concentration across the perimeter of both slots for mode 4 operation (Both PD1 and PD2 ON).

It is observed from measurements that the proposed FRPA is capable to resonate at 4.75 GHz

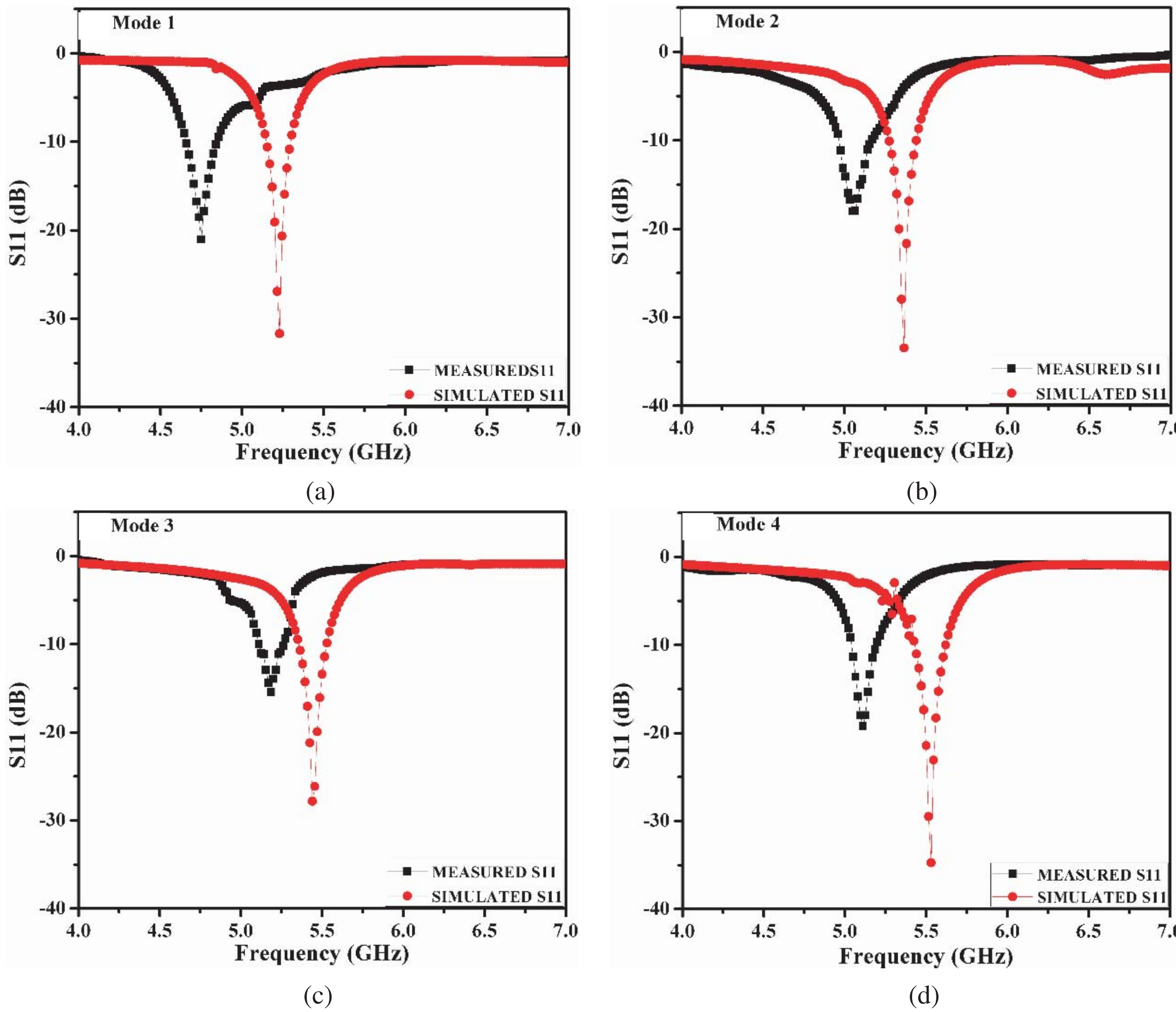


Figure 4. Simulated and measured S_{11} for different modes.

Table 2. Resonant frequency, bandwidth, S_{11} and gain for different modes of the proposed FRPA.

Mode	PIN diode state		Resonant frequency (GHz)		-10 dB % BW	Measured S_{11} (dB)	Measured Gain (dBi)
	PD1	PD2	Simulated	Measured			
1	OFF	OFF	5.23	4.75	4%	−21.03	6.82
2	ON	OFF	5.36	5.05	3.76%	−18	6.78
3	OFF	ON	5.44	5.18	2.7%	−15.41	6.39
4	ON	ON	5.53	5.11	2.94%	−19.21	6.58

with a relatively smaller patch dimension $L_p = 11.59$ mm and $W_p = 15.49$ mm than a conventional rectangular patch antenna designed to resonate at the same frequency (i.e. 4.75 GHz). Hence compared to traditional patch, a size reduction of 35.7% is achieved at the lowest resonant frequency of the proposed FRPA. Moreover, the proposed FRPA has overall smaller size of only $(35 \times 40)\,\text{mm}^2$ than the

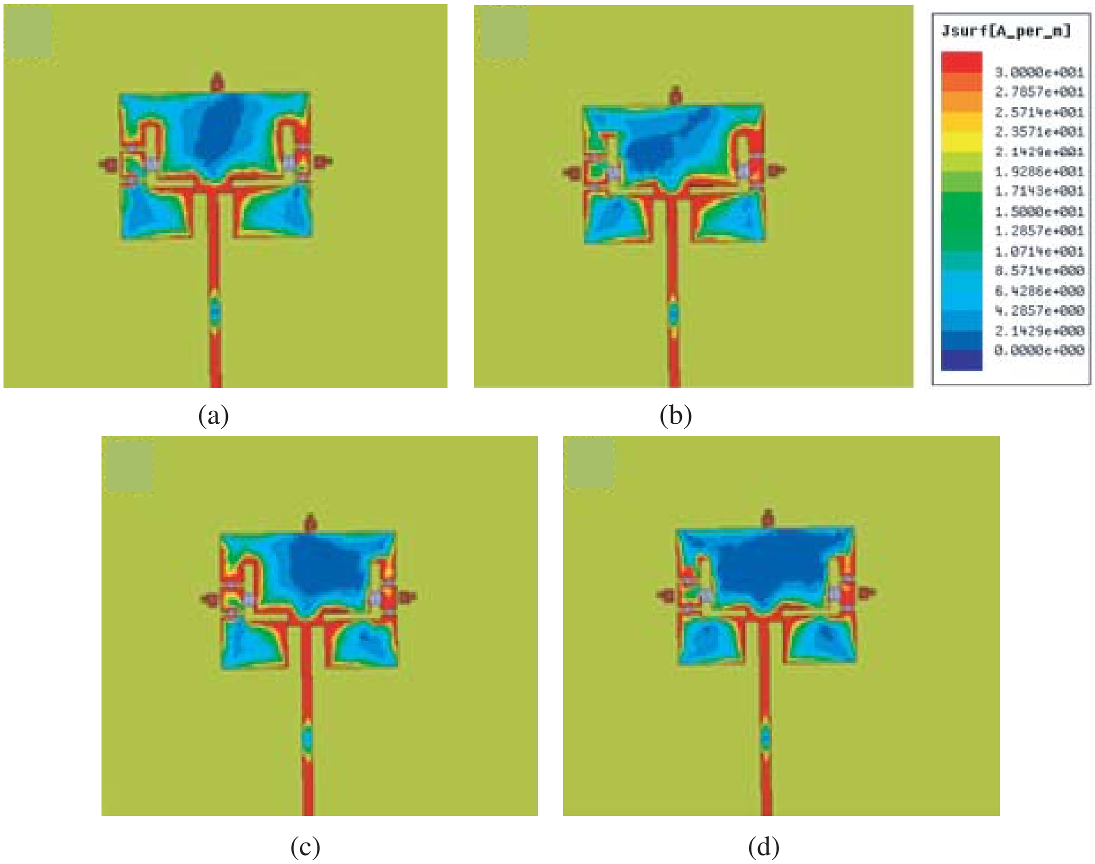


Figure 5. Surface current distribution for different modes of operation.

reconfigurable patch antennas reported in [3, 27–30].

The E and H plane radiation patterns for different modes are simulated, and no visible changes are observed as shown in Figures 6(a), (b), (c), and (d).

The gains for different reconfiguration modes are measured, and it is found that the proposed FRPA

Table 3. Comparison of the proposed design with previously reported frequency reconfigurable antenna.

Ref. No.	Switch Type and Quantity		Max. Bias voltage	Operating frequencies (GHz)	Integrated DC biasing circuit	Peak Gain (dBi)	Radiation pattern
[16]	Varactor	2	14 V	2.56, 2.88, 3, 3.1, 3.15, 3.46	Yes	5	Stable
[17]	PIN diode	4	5 V	1.637, 1.75, 1.79, 2.08, 2.454	Yes	2.5	Unstable
[18]	PIN diode	3	3 V	0.62, 0.837, 0.924, 1.15	Yes	Not reported	No details found
[31]	PIN diode	2	15 V	5.14, 5.75	No	5.6	Stable
[32]	PIN diode	4	3 V	2.337, 5.54	No	7	Stable
Proposed design	PIN diode	2	1 V	4.75, 5.05, 5.11, 5.18	Yes	6.82	Stable

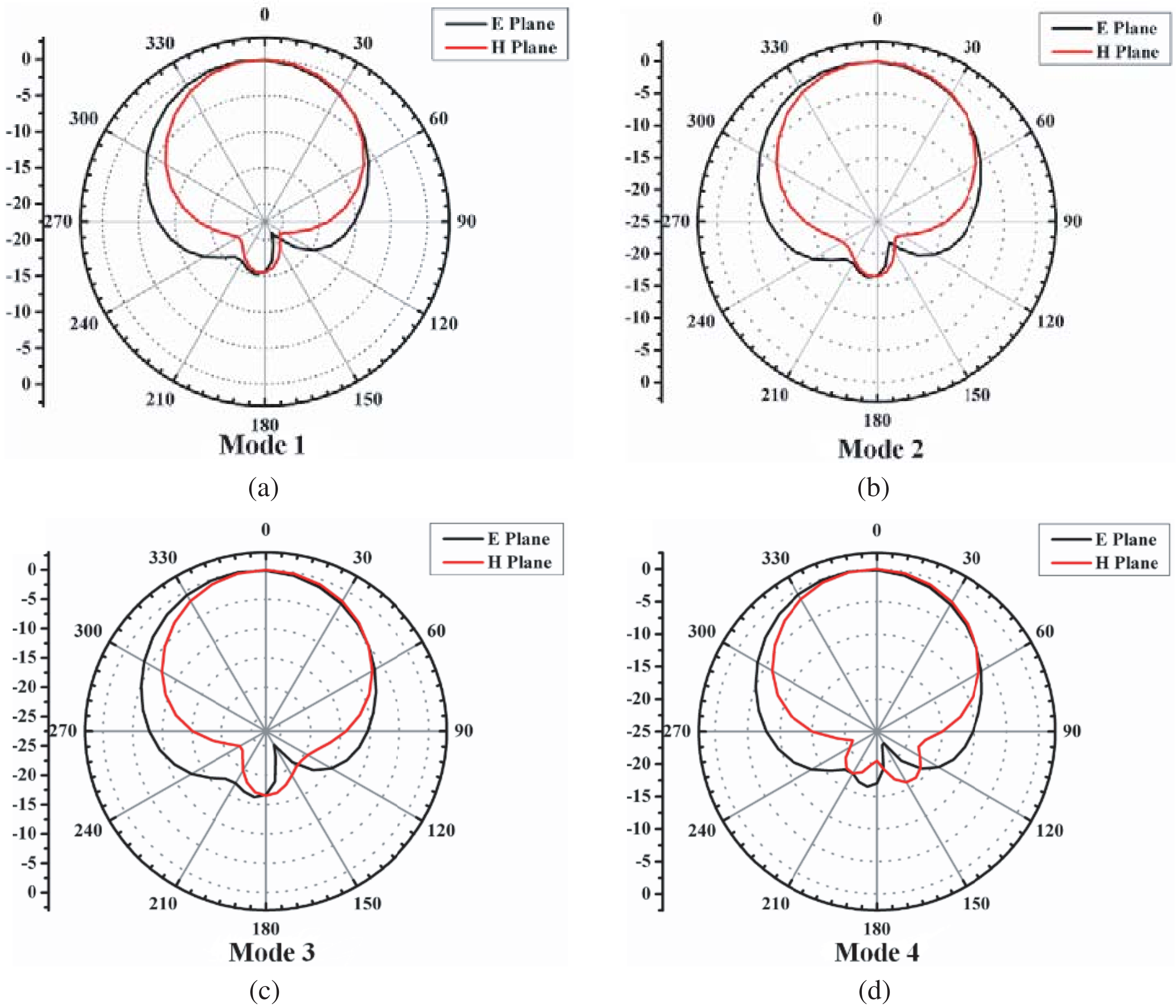


Figure 6. E and H-plane pattern for different modes (Simulated).

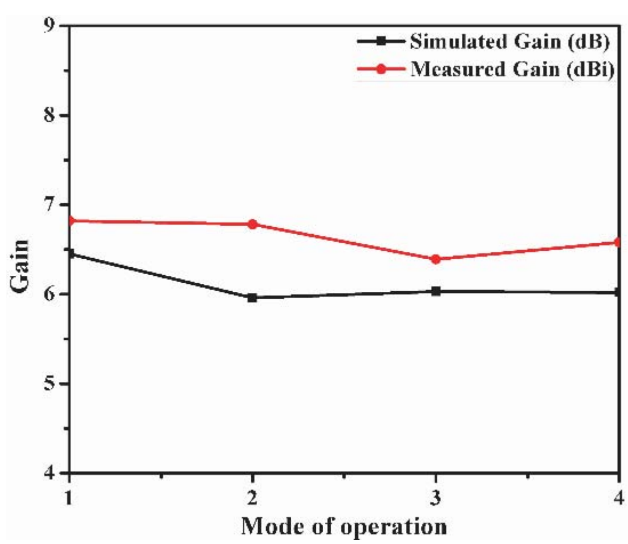


Figure 7. Gain of the proposed antenna for different modes of operation.

produces almost constant gain for its different modes of operation as shown in Figure 7. The average gain of the fabricated antenna for its four modes of operation is found as 6.64 dBi. A comparison of design and performance parameters of the proposed FRPA with other relevant works is stated in Table 3.

4. CONCLUSION

A simple and compact FRPA loaded with a pair of asymmetric and inimitable L-slots is designed and analyzed. The antenna achieves frequency reconfigurability by surface current redistribution mechanism across the slots upon the activation of two inserted PIN diode switches. Resonant frequencies for its four operating modes are measured as 4.75 GHz, 5.05 GHz, 5.18 GHz, and 5.11 GHz with stable radiation characteristics throughout all reconfigurable bands. The average gain of the FRPA for different modes of operation is found to be 6.64 dBi. The achieved operating modes will be useful for applications in C band. Enhancement of reconfigurable frequency range is the scope for further investigations.

ACKNOWLEDGMENT

This research did not receive any financial grant from public or commercial funding agencies.

REFERENCES

1. Aberle, J. T., S. H. Oh, D. T. Auckland, et al., "Reconfigurable antennas for wireless devices," *IEEE Antennas and Propagation Magazine*, Vol. 45, No. 6, 148–154, 2003.
2. Christodoulou, C. G., Y. Tawk, S. A. Lane, et al., "Reconfigurable antennas for wireless and space applications," *Proceedings of the IEEE*, Vol. 100, No. 7, 2250–2261, 2012.
3. Nazir, I., I. E. Rana, N. U. A. Mir, and K. Afreen, "Design and analysis of a frequency reconfigurable microstrip patch antenna switching between four frequency bands," *Progress In Electromagnetics Research C*, Vol. 68, 179–191, 2016.
4. Hinsz, L. and B. D. Braaten, "A frequency reconfigurable transmitter antenna with autonomous switching capabilities," *IEEE Transactions on Antennas and Propagation*, Vol. 62, No. 7, 3809–3813, 2014.
5. Costantine, J., Y. Tawk, S. E. Barbin, et al., "Reconfigurable antennas: Design and applications," *Proceedings of the IEEE*, Vol. 103, No. 3, 424–437, 2015.
6. Ojaroudi Parchin, N., H. Jahanbakhsh Basherlou, Y. I. Al-Yasir, et al., "Reconfigurable antennas: Switching techniques — A survey," *Electronics*, Vol. 9, No. 2, 336, 2020.
7. Ismail, M. F., M. K. Rahim, and H. A. Majid, "Wideband to narrowband frequency reconfiguration using PIN diode," *Microwave and Optical Technology Letters*, Vol. 54, No. 6, 1407–1412, 2012.
8. Yu, Y., J. Xiong, H. Li, et al., "An electrically small frequency reconfigurable antenna with a wide tuning range," *IEEE Antennas and Wireless Propagation Letters*, Vol. 10, 103–106, 2011.
9. Li, H., J. Xiong, Y. Yu, et al., "A simple compact reconfigurable slot antenna with a very wide tuning range," *IEEE Transactions on Antennas and Propagation*, Vol. 58, No. 11, 3725–3728, 2010.
10. Kalteh, A. A., G. R. Dadash Zadeh, M. Naser-Moghadasi, et al., "Ultra-wideband circular slot antenna with reconfigurable notch band function," *IET Microwaves, Antennas & Propagation*, Vol. 6, No. 1, 108–112, 2012.
11. Majid, H. A., M. K. Rahim, M. R. Hamid, et al., "Frequency-reconfigurable microstrip patch-slot antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 12, 218–220, 2013.
12. Pazin, L. and Y. Leviatan, "Reconfigurable slot antenna for switchable multiband operation in a wide frequency range," *IEEE Antennas and Wireless Propagation Letters*, Vol. 12, 329–332, 2013.
13. Borakhade, D. K. and S. B. Pokle, "Pentagon slot resonator frequency reconfigurable antenna for wideband reconfiguration," *AEU — International Journal of Electronics and Communications*, Vol. 69, No. 10, 1562–1568, 2015.

14. Baruah, R. and N. S. Bhattacharyya, "A frequency reconfigurable meandered slot cut rectangular patch antenna using PIN diodes," *Progress In Electromagnetics Research C*, Vol. 77, 81–89, 2017.
15. Xiao, S., B. Z. Wang, and X. S. Yang, "A novel frequency-reconfigurable patch antenna," *Microwave and Optical Technology Letters*, Vol. 36, No. 4, 295–297, 2003.
16. Ren, Z., W. T. Li, L. Xu, et al., "A compact frequency reconfigurable unequal U-slot antenna with a wide tunability range," *Progress In Electromagnetics Research Letters*, Vol. 39, 9–16, 2013.
17. Sharma, S. and C. C. Tripathi, "Frequency reconfigurable U-slot antenna for SDR application," *Progress In Electromagnetics Research Letters*, Vol. 55, 129–136, 2015.
18. Sheta, A. F. and S. F. Mahmoud, "A widely tunable compact patch antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 7, 40–42, 2008.
19. Fertas, F., M. Challal, and K. Fertas, "A compact slot-antenna with tunable-frequency for WLAN, WiMAX, LTE, and X-band applications," *Progress In Electromagnetics Research C*, Vol. 102, 203–212, 2020.
20. Braham Chaouche, Y., F. Bouttout, M. Nedil, I. Messaoudene, and I. B. Mabrouk, "A frequency reconfigurable U-shaped antenna for dual-band WIMAX/WLAN systems," *Progress In Electromagnetics Research C*, Vol. 87, 63–71, 2018.
21. Ramli, N. H., M. R. Kamarudin, N. A. Samsuri, E. N. Ahyat, and N. H. Khamis, "A 4.8 GHz implantable small printed antenna for wireless implantable body area network applications," *IEEE International RF and Microwave Conference (RFM)*, 210–213, IEEE, Dec. 9, 2013.
22. Chen, W. S. and Y. L. Chang, "Small-size 5G C-band/WLAN 5.2/5.8 GHz MIMO antennas for laptop computer applications," *IEEE International Workshop on Electromagnetics: Applications and Student Innovation Competition (iWEM)*, 1–2, IEEE, Aug. 29, 2018.
23. Balanis, C. A., *Antenna Theory: Analysis and Design*, 816–826, Wiley, Hoboken, New Jersey, USA, 2005.
24. Tian, W., H. Cui, and W. Yu, "Analysis and experimental test of electrical characteristics on bonding wire," *Electronics*, Vol. 8, No. 3, 365, Mar. 2019.
25. Singh, P. P., S. K. Sharma, and P. K. Goswami, "A compact frequency reconfigurable printed antenna for WLAN, WiMax multiple applications," *Progress In Electromagnetics Research C*, Vol. 106, 151–161, 2020.
26. Ullah, S., A. Shaheen, B. A. Khan, and J. A. Flint, "A multi-band switchable antenna for Wi-Fi, 3G advanced, WiMAX, and WLAN wireless applications," *International Journal of Microwave and Wireless Technologies*, Vol. 10, No. 8, 991–997, 2018.
27. Chattha, H. T., M. Hanif, X. Yang, I. E. Rana, and Q. H. Abbasi, "Frequency reconfigurable patch antenna for 4G LTE applications," *Progress In Electromagnetics Research M*, Vol. 69, 1–13, 2018.
28. Sahu, N. K. and A. K. Sharma, "An investigation of pattern and frequency reconfigurable microstrip slot antenna using PIN diodes," *2017 Progress In Electromagnetics Research Symposium — Spring (PIERS)*, St. Petersburg, Russia, May 22–25, 2017.
29. Mansoul, A., F. Ghanem, M. R. Hamid, and M. Trabelsi, "A selective frequency-reconfigurable antenna for cognitive radio applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 13, 515–518, 2014.
30. Yang, S. L., A. A. Kishk, and K. F. Lee, "Frequency reconfigurable U-slot microstrip patch antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 7, 127–129, 2008.
31. Anagnostou, D. E. and A. A. Gheethan, "A coplanar reconfigurable folded slot antenna without bias network for WLAN applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 8, 1057–1060, 2009.
32. Tekin, I. and M. Knox, "Reconfigurable microstrip patch antenna for WLAN software defined radio applications," *Microwave and Optical Technology Letters*, Vol. 54, No. 3, 644–649, 2012.