(Received 27 November 2023, Accepted 5 April 2024, Scheduled 12 April 2024)

Frequency Reconfigurable Antenna Design and Analysis with White LED Lamp, Red and Infrared LEDs

V. Reji[1,*] and C. T. Manimegalai[2]

[1]*Department of Electronics and Communication Engineering*
SRM Institute of Science and Technology, Ramapuram, Chennai, India
[2]*Department of Electronics and Communication Engineering*
SRM Institute of Science and Technology, Kattankulathur, Chennai, India

ABSTRACT: This research presents a frequency reconfigurable antenna analysis for wireless applications using multiple light sources. The antenna is constructed on a Roger substrate with $(44 \times 28)\,\text{mm}^2$ dimensions. The antenna comprises two parallel tuner arrangements in addition to a V-shaped radiating section. Two optical PIN photodiodes are connected to the two parallel monopole tuners, which serve as the antenna's switching component and are utilized to adjust the resonant frequency. These two PIN photodiode switches work in the 600–1050 nm wavelength range. To analyze the antenna performance, four different optical sources are used. They are white colour LED lamp, 650 nm optical fiber, red LEDs, and IR LEDs. In every case, the antenna performance analysis is carried out for all the four logic states of the switches (00, 01, 10, 11). Under white lamp test conditions, the antenna's maximum gain is 6 dBi, and when red LEDs are employed as the optical source, its maximum bandwidth is 21%. The antenna reconfigurable frequencies are 3.5 GHz and 5–5.8 GHz (5, 5.2, 5.5, 5.8 GHz).

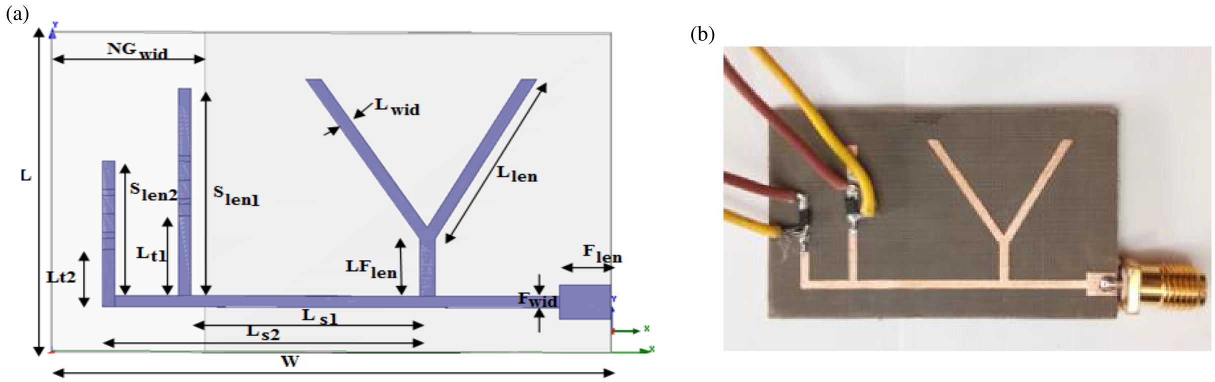
1. INTRODUCTION

The most recent advancement in microstrip antenna technology is reconfigurable antennas. Reconfigurable antennas are fewer antennas that cause less interference throughout the frequency bands. Additionally, the reconfigurable antennas change the frequency, radiation pattern, and polarization directions. The characteristics of the antennas can be changed by combining switches with the printed antenna. Varactor diodes, PIN photodiodes, micro-electromechanical system (MEMS) switches, and photoconductive switches are examples of frequently used switches. Optical signals are also used to control reconfigurable antennas. These optical signals may be in the visible or infrared spectrum. The selection of the optical source purely depends upon the type of photo receiver connected to the antenna. A photodiode, phototransistor, or photoconductive switch could be one of these optical receivers. Only the wavelength of the optical source and optical receiver determines the antenna's reconfigurable frequency. The conventional multiband antennas and the reconfiguration antennas using PIN, varactor diodes, and passive elements have been discussed in [1–4]. For wireless and visible light applications, a multiband optical receiver antenna has been created with a radio frequency transceiver [5, 6]. For reconfigurable applications, a low-power optical switch and an antenna were utilized in [7]. A photoconductive switch was introduced as a switching element for frequency reconfiguration in [8]. A photoconductive switch was introduced as a switching element for frequency reconfiguration in [8]. This antenna shifts frequencies by a minimum of 0.3 GHz. Two silicon switches were activated via an 850 nm fibre optic cable, which changed the frequency from 28 GHz to 38 GHz and modulated the signal [9, 10]. A photoconductive method of frequency reconfiguration is introduced in [11, 12]. For high-power applications, an optical antenna has been developed with time-delay components and high-power photodiodes [13, 14]. Some frequency diversity antennas have been developed for cognitive radio and impedance tuning applications. In these cases, one or more silicon die switches are used. The silicon dies are activated by laser or LED coupled to a 980 nm optical fiber cable [15–17]. Two optically controlled reconfigurable antennas were demonstrated with 2 commercially available PIN photodiodes and phototransistors, as discussed in [18, 19]. A novel optically controlled frequency reconfigurable antenna for future wireless applications is demonstrated in the proposed work. The proposed optically controlled antenna is a compact, high gain, and multiband antenna. In the current design, only optical fiber cables are used to control the optical receiver switches. However, in this work, an LED bulb, small LEDs, and LED-mounted optical fiber cables are used to activate two commercially available 600 nm to 1010 nm photodiodes. These reconfigurable antennas are suitable for radio over fiber, smart TVs, and Internet of Things devices.

2. ANTENNA DESIGN

The antenna's construction is done on a Roger RO3003(tm) substrate. The antenna's substrate has a thickness of 1.52 mm, a permittivity of 3.3, and a loss tangent of 0.0013. This antenna is a long-wire, resonant V-shaped antenna [20]. Two parallel tuners that are $(18.15 \times 1.2)\,\text{mm}^2$ and $(12.75 \times 1.2)\,\text{mm}^2$ in size are connected side by side with the feeding stubs. Figures 1(a)

* Corresponding author: V. Reji (rejiv@srmist.edu.in).



($W=44, L=28, LF_{len}=4, NG_{wid}=12, S_{len1}=20, S_{len2}=25, L_{t1}=7, L_{t2}=5$, $F_{wid}=1.5, LF_{len}=4, L_{len}=8, S_{len1}=18.15, S_{len2}=12.75$)

FIGURE 1. (a) Proposed antenna with dimensions in mm. (b) Antenna prototype.

and (b) show the antenna design and how the optical switches are connected to the parallel monopole tuners. The lengths of the legs are calculated within the value of $\lambda/4$ and $\lambda/2$.

3. PROPOSED ANTENNA EQUIVALENT CIRCUIT

To switch the frequency bands, two photodiodes are incorporated with dimensions of 4 mm in length and 1.2 mm in width. These photodiodes function as switches, and their switching conditions are simulated using light signals with and without a DC bias voltage. The equivalent impedance circuit of the photodiode switch, combined with the monopole tuners, is depicted in Figure 2. Equation (1) represents the equivalent admittance of the V-shaped radiator. These experiments allow us to study the impact of different internal resistance and capacitance values on the performance of the antenna, enabling us to optimize its frequency reconfiguration capabilities. By adjusting the internal resistance (R) and capacitance (C) values of the photodiode switches, the admittance values of the antenna can be varied. Equations (2) and (3) provide a mathematical representation of the relationship between the internal admittance and the resonant frequency of the tuners. Equation (4) provides the resonant frequency of the antenna. Equation (5) shows the relationship between the photocurrent, incident optical power, the responsivity of the photodiode, and the quantum efficiency of the photodiode. By manipulating these parameters, the performance of the photodiode in RF applications can be optimized for specific requirements.

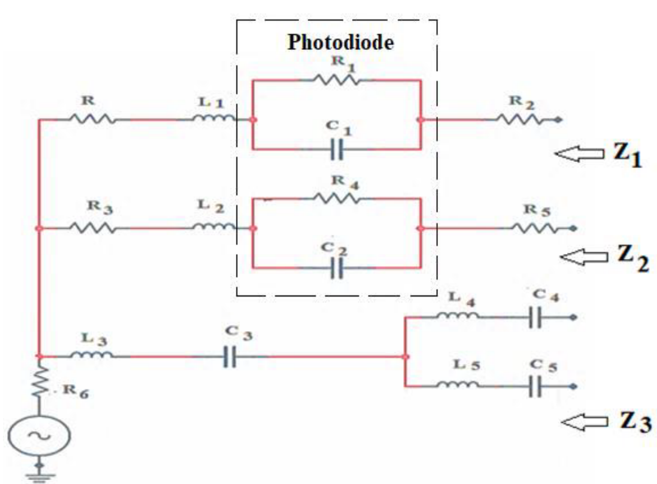


FIGURE 2. Equivalent circuit of the proposed optically controlled antenna.

$$Y = Y_1 + Y_2 - JY_3 \tan \beta l \quad (1)$$

$$f_1 = \frac{1}{2\sqrt{\varepsilon}}(Y_1 + Y_2) \quad (2)$$

$$f_2 = -\frac{1}{2\sqrt{\varepsilon}} JY_3 \tan \beta l \quad (3)$$

$$f_r = f_1 + f_2 \quad (4)$$

$$I = P * R_s * \eta * G * A * \lambda * f_1 \quad (5)$$

Z_1, Z_2, Z_3 — Branch impedances
f_1 — frequency of monopole tuners
f — frequency of the V-shaped radiator
f_r — resonant frequency of the antenna
Y — Load Admittance, β — phase constant
λ — wavelength, I — Photo current, R_s — Responsivity
G — gain, P — the incident optical power

4. SWITCH DESIGN

Two photodiodes are chosen with dimensions of 4×1.2 mm and a thickness of 0.85 mm to serve as switches for simulation. Two PIN photodiodes are mounted on the parallel tuners, to control the resonant conditions of the V-shaped radiator. These PIN photodiode switches are activated by a DC bias voltage and an optical signal. When it is activated, the admittance of the photodiodes changes, leading to alterations in the resonant conditions of the antenna. The simulation of the switches involves adjusting their internal capacitance and resistance values. In this proposed work, two TEMD71001TX01 PIN photodiodes

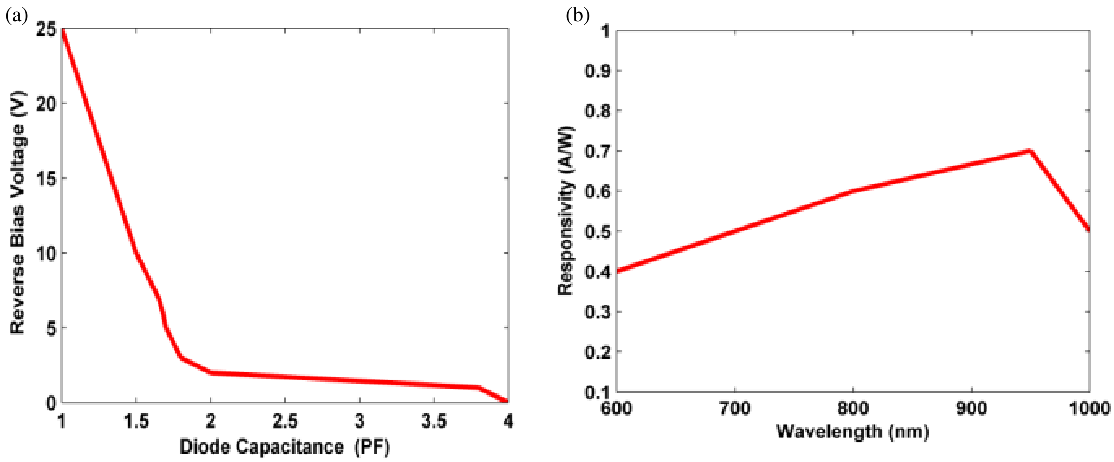


FIGURE 3. (a) Photodiode capacitance verses reverse voltage. (b) Photodiode wavelength verses responsivity.

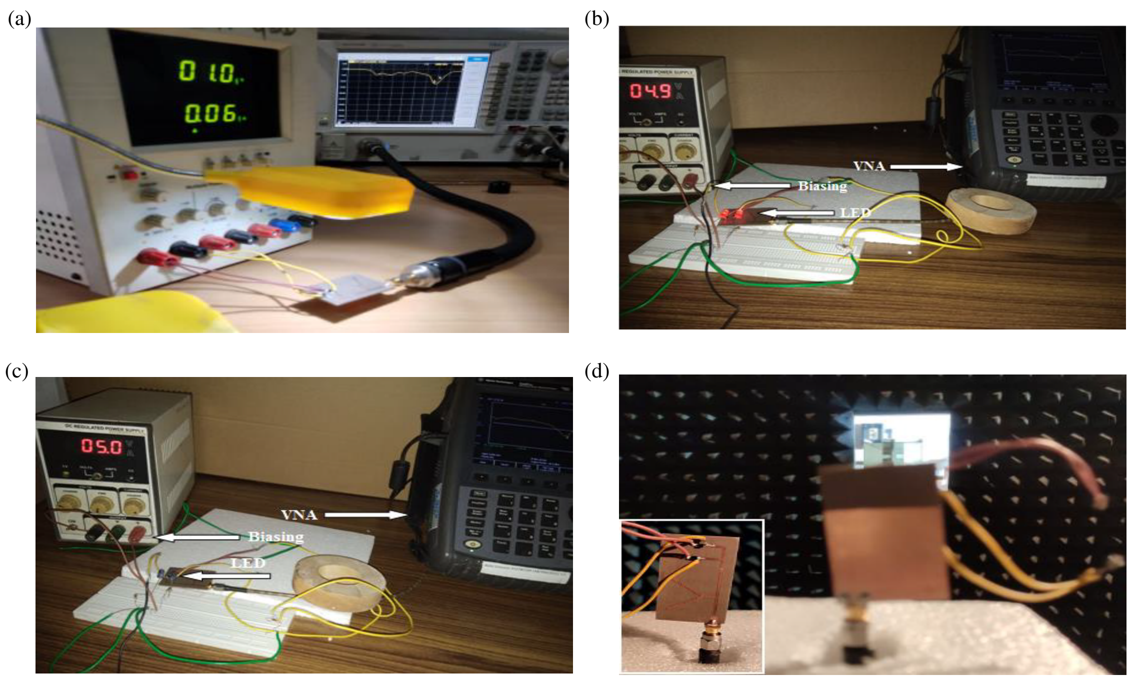


FIGURE 4. Antenna under measurement condition. (a) White LED lamp. (b) Red LED. (c) IR LED. (d) Radiation pattern measurement.

are employed for frequency reconfiguration. These miniature surface mount devices have a sensitive area of 0.23 mm^2. Figure 3(a) illustrates the capacitance variation with respect to the bias voltage, while Figure 3(b) shows the responsivity variations corresponding to wavelength. A 4 pF capacitance value is selected at the OFF condition of the switch, and 1.8 pF is selected at the ON condition of the switch at -5 V DC. The peak wavelength of the photodiode is 950 nm. The maximum current of 100 μA of the photodiode is drawn at 5 mW power.

5. RESULT AND DISCUSSION

Figures 4(a), (b), (c), and (d) illustrate the different kinds of light sources that can be used to analyze antenna performance and radiation pattern measurement. The sources are white LED lamp, LED coupled fibers (650 nm), two RED LEDs, and two IR LEDs. For all measurements, the DC bias voltage is set at 3 volts. (The monitor indicates 5 volts, but a breadboard connection of two resistors lowers the voltage.) DC bias voltage and optical signals from various sources activate both photodiodes. Without using any light signal or DC bias voltage, the fabricated antenna radiates at 4.3 GHz. Four different switching states, S_00, S_01, S_10, and S_11, are produced by the two photodiode switches. The antenna radiates at 3.5 GHz when a 3 V DC bias voltage is applied to the photodiode switches without any light signal. This state is considered as S_00 state of the switches at all the measurement conditions.

When an LED lamp is used to measure the antenna, the antenna radiates at 3.5 GHz in the switch's S_00 state. At the S_01, S_10, and S_11 switching stages, the antenna changes its

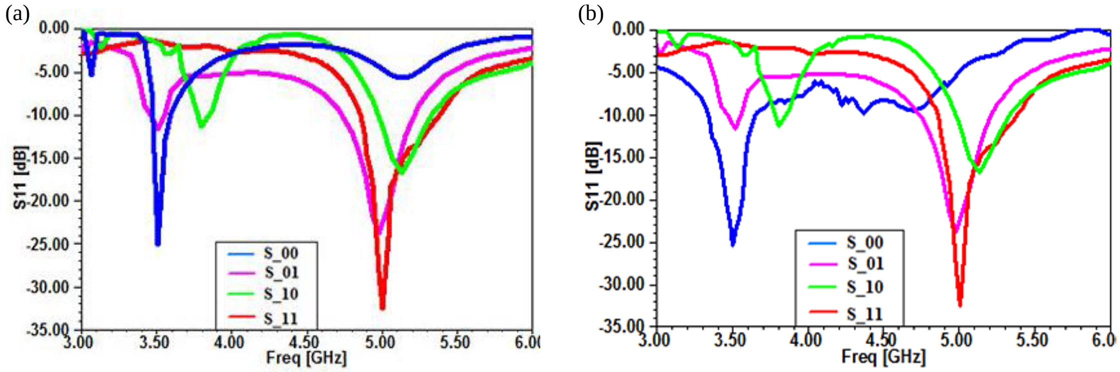


FIGURE 5. Reflection co-efficient of the antenna using white LED lamp. (a) Simulation. (b) Measurement.

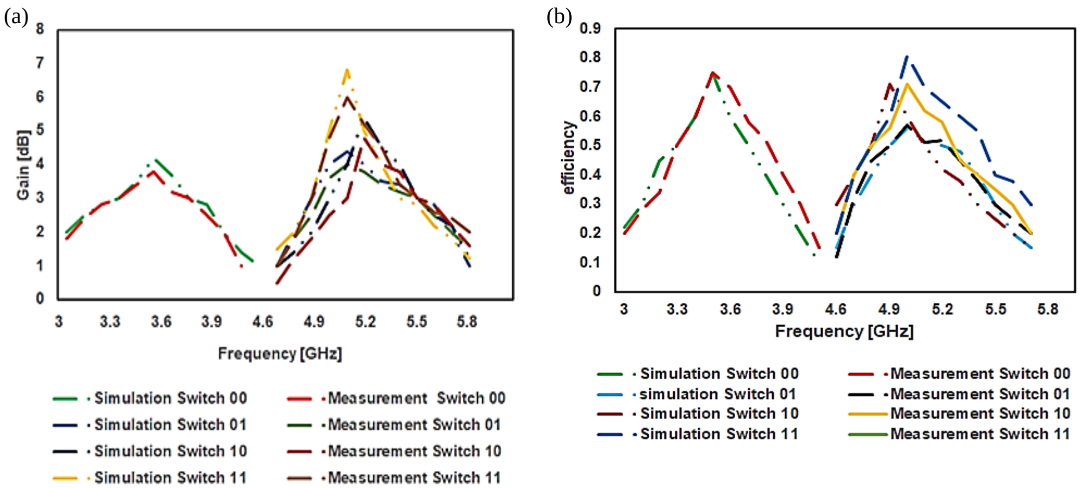


FIGURE 6. Light source — White LED lamp. (a) Gain. (b) Efficiency.

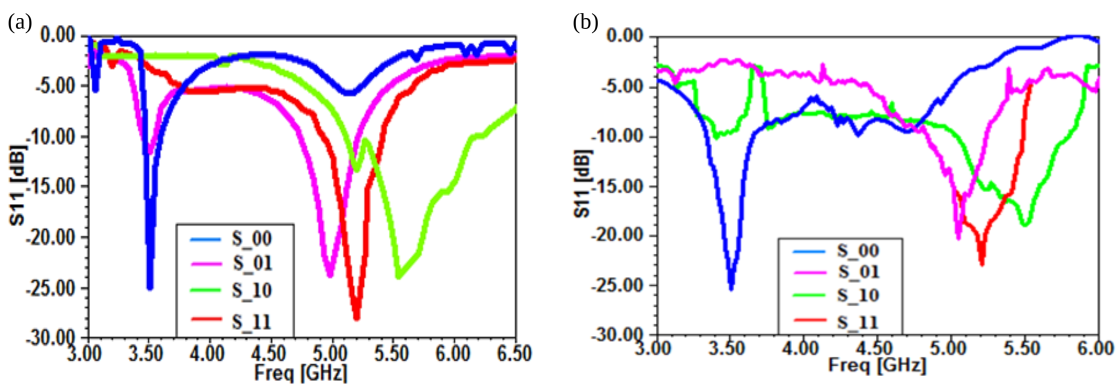


FIGURE 7. Reflection co-efficient of the antenna using red LED. (a) Simulation. (b) Measurement.

frequency to 5 GHz and 5.1 GHz, respectively. The comparison of return loss values for simulation and measurement conditions is shown in Figures 5(a) and (b). The measured reflection coefficient value at S_00 switching condition is −25.35 dB; at S_01 switching state, the value is −23 dB; and at S_10 and S_11 switching conditions, they are −17 dB and −32 dB, respectively. The antenna provides maximum measured gain of 6 dBi at the S_11 switching condition and an average gain of 4 dBi in the other three switching states of the antenna.

Maximum of 81% measured efficiency is achieved in S_11 switching condition. The gain and efficiency comparisons of the antenna are given in Figures 6(a) and (b).

When 650 nm-red LEDs are used as a source for photodiodes, the antenna reconfigures its frequencies from 3.5 GHz to 5 GHz, 5.5 GHz and 5.2 GHz in the switching conditions

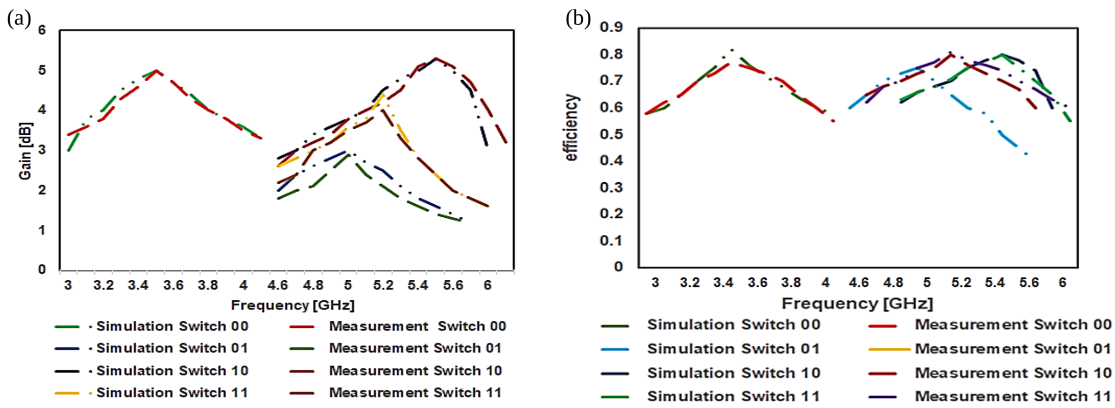


FIGURE 8. Light source — Red LED. (a) Gain. (b) Efficiency.

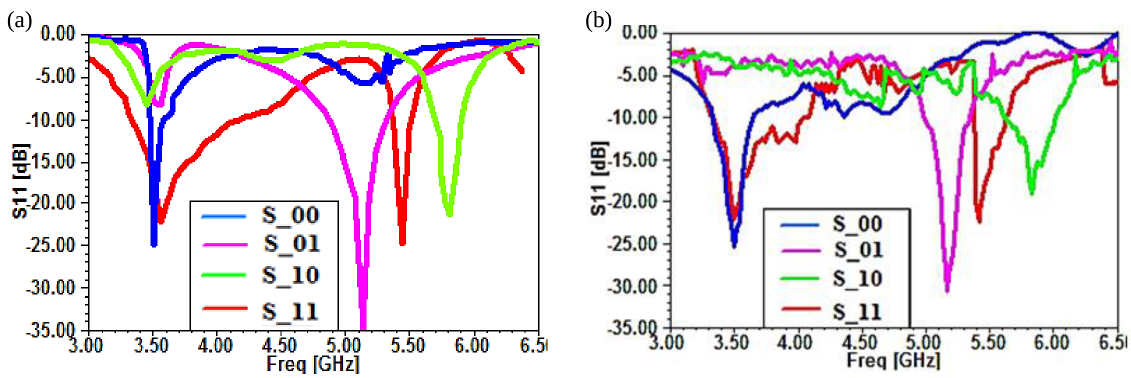


FIGURE 9. Reflection co-efficient of the antenna using IR LED. (a) Simulation. (b) Measurement.

TABLE 1. Simulated antenna parameters comparison with various optical sources.

Antenna Parameters	White LED lamp				RED LED				IR LED				LED coupled Optical fiber			
Switching state	00	01	10	11	00	01	10	11	00	01	10	11	00	01	10	11
Frequency (GHz)	3.5	5	5.1	5	3.5	5	5.5	5.2	3.5	5.2	5.8	5.5, 3.5	3.5	5	5.5	5.2
Return Loss (dB)	−25	−23	−17	−32	−25	−24	−24	−28	−28	−35.96	−23	−22, −23	−26	−24	−24	−28
Gain (dBi)	4.2	4.4	5.4	6.8	5	3	5.3	4	5	3.5	5.3	2.8, 6	5	3	5.3	4
Bandwidth (%)	8	10	8	12	8	11.5	21	10	8	12	8	10, 14	11.5	21	10	8
Efficiency (%)	75	56	71	81	82	85	80	80	83	83	80	80, 79	82	85	80	80

of S_01, S_10, and S_11, respectively, as illustrated in Figures 7(a) and (b). The maximum measured gain of the antenna is 5.3 dBi in S_00 and S_01 switching states; the average gain is 4 dBi in S_10 switching conditions; and the minimum gain of 2.9 dBi in S_01 conditions are noted down from Figures 8(a) and (b). The maximum efficiency of 81% is achieved in the S_11 switching condition. When a red LED connected fiber is used to measure the antenna parameters, it produces results that are nearly identical to those of red LEDs under all conditions. However, the antenna produces the same parameter values up to 2 meters when the source distance is varied.

When 950 nm IR LEDs are used for measurement the antenna reconfigures its frequencies from 3.5 GHz to 5.2 GHz, 5.8 GHz and 5.5 and 3.5 GHz in S_01, S_10 and S_11 switch-

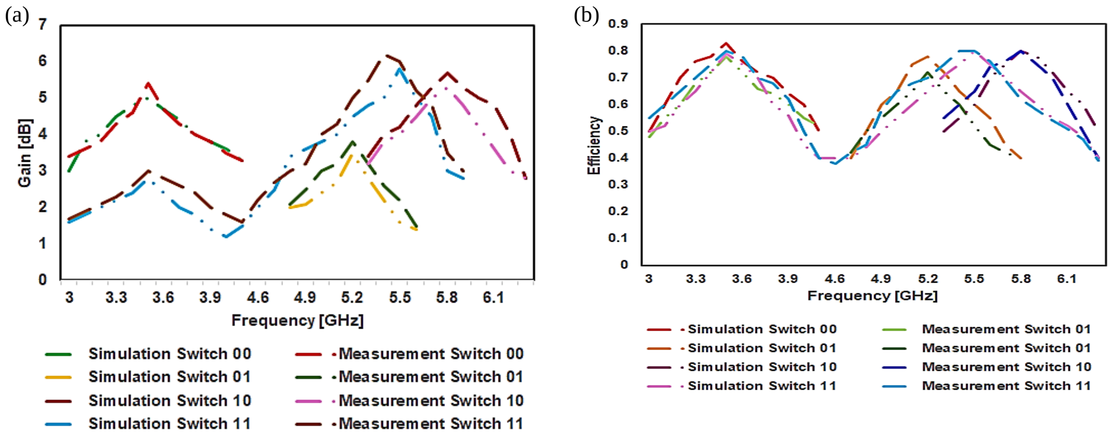


FIGURE 10. Light source — IR LED. (a) Gain. (b) Efficiency.

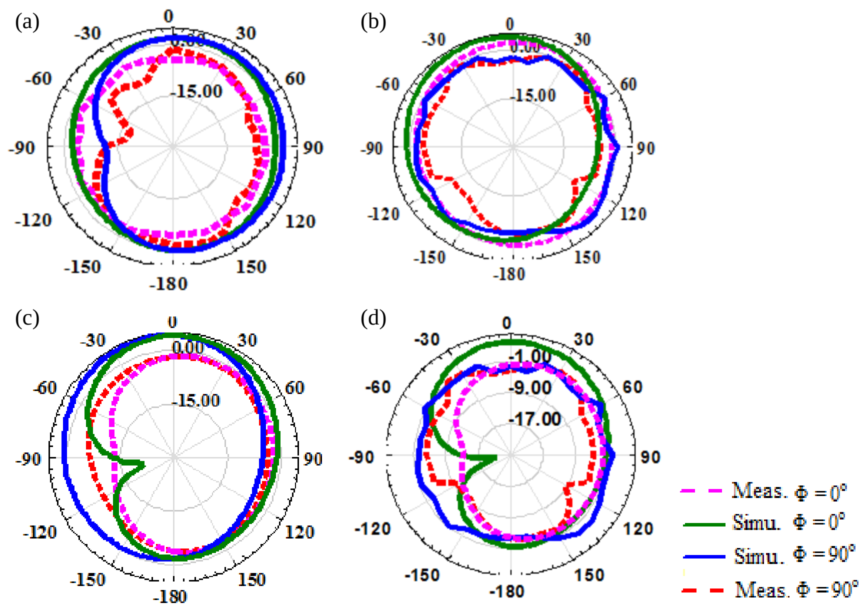


FIGURE 11. E-plane radiation pattern, (a) 3.5 GHz, (b) 5.2 GHz, (c) 5.5 GHz, (d) 5.8 GHz.

TABLE 2. Measured antenna parameters comparison with various optical sources.

Antenna Parameters	White LED lamp				RED LED				IR LED				LED coupled Optical fiber			
Switching state	00	01	10	11	00	01	10	11	00	01	10	11	00	01	10	11
Frequency (GHz)	3.5	5	5.1	5	3.5	5	5.5	5.2	3.5	5.2	5.8	5.5, 3.5	3.5	5	5.5	5.2
Return Loss (dB)	−25.3	−23	−17	−32	−25.3	−20.3	−19	−25.48	−25.3	−32	−22	−23, −22	−25.3	−20.3	−19	−23
Gain (dBi)	3.8	4	4.8	6	5	2.9	5.3	4	5	3.5	5.3	2.8, 6	5	2.9	5.3	4
Bandwidth (%)	11.4	10	8	12	8	11.4	21	10	11.4	9	11.6	14, 19	11.4	10	14.5	15
Efficiency (%)	77	57	71	81	77	73	80	81	78	72	80	80, 80	77	73	80	81

TABLE 3. Proposed antenna parameter comparison with reference antennas.

References		Number of bands	Maximum gain	Antenna size	Number of diodes	Applications
[2]		2.89–4.07, 5.1–6.19	2.6	$0.66 \times 0.66 \times 0.021$	4-PIN diode	5G, WLAN
[14]		2.81–3.73, 1.94–2.14 3.17–3.91, 2.34–2.94	2.2	$0.37 \times 0.37 \times 0.016$	2-PIN Diodes	5G, LTE, Wi-Fi, Wi-Max
[17]		2.5 5.2	3	$0.53 \times 0.66 \times 0.02$	2-Silicon Dies	Wi-Max, WLAN
[18]		1.8–2.37 2.1–2.35	5.8	$1.10 \times 1.47 \times 0.011$	2-PIN photo diodes	Wireless applications
Proposed antenna	White LED lamp	3.5, 5, 5.1, 5	3.8 6	$0.58 \times 0.37 \times 0.02$	2-Photo diodes	5G, 5 GHz band, 5.8 GHz ISM band applications
	Red LEDs and Fiber	3.5, 5, 5.2, 5.5	2.9 5.3			
	IR LEDs	3.5, 5.2, 5.8, 5.5, 3.5	2.8 6			

ing state of the antenna. The simulated and measured return loss comparison is given in Figures 9(a) and (b). The measured return loss values in S_00, S_01, S_10, S_11 conditions are -28 dB, -32 dB, -23 dB, and -23 dB, respectively. The maximum measured gain of the antenna at this condition is 5.3 dBi, and minimum gain is 2.3 dBi at S_10 and S_11 condition of the switch. As seen in Figures 10(a) and (b), a maximum efficiency of 80% is achieved under S_01 and S_11 switching conditions.

6. RADIATION PATTERN

Figure 11 shows the radiation pattern of the antennas in $\varphi = 0°$ and $\varphi = 90°$. The proposed antenna's maximum radiation is along $90°$. For the radiation pattern measurement, a reference horn antenna is used. The measured radiation pattern is slightly changed from the simulated radiation pattern. The radiation patterns of 5 and 5.2 GHz are the same.

The simulated and measured antenna parameters with various light sources are displayed in Tables 1 and 2. From these tests, the antenna provides extremely distinct bands that emerge at 3.5 GHz and 5.2 GHz when the S-parameter is measured with infrared LEDs. When IR LEDs and white LED lamps are used as photo-diode sources, a high measured gain is observed. In every circumstance, the antenna's measured bandwidth is larger than the simulated values. The proposed antenna parameter comparison with reference antennas is displayed in Table 3.

7. CONCLUSION

In this paper, parameters of the fabricated optically controlled frequency reconfigurable antenna are experimentally measured for S_00, S_01, S_10, S_11 switching conditions. The proposed antenna radiates at 3.5 GHz without applying a light signal, and it reconfigures its frequency to 5 GHz, 5.2 GHz, 5.5 GHz, and 5.8 GHz at various wavelength conditions. When 950 nm LEDs are used as a source, the antenna performs well in terms of reconfiguration, gain, and bandwidth compared to other LED sources. When red LEDs are utilized as the optical source of the antenna, a maximum bandwidth of 21% is provided. This antenna is mostly suitable for 5G application at 3.5 GHz and 5 GHz band WLAN and Wi-Fi applications at 5 GHz, 5.2 GHz, 5.5 GHz, and 5.8 GHz.

ACKNOWLEDGEMENT

This research work was funded by "Visvesvaraya Ph.D Scheme for Electronics & IT" Ministry of Electronics and Information Technology, the Government of India.

REFERENCES

[1] Cui, J., A. Zhang, and X. Chen, "An omnidirectional multiband antenna for railway application," *IEEE Antennas and Wireless Propagation Letters*, Vol. 19, No. 1, 54–58, Jan. 2020.

[2] Jin, G., C. Deng, Y. Xu, J. Yang, and S. Liao, "Differential frequency-reconfigurable antenna based on dipoles for sub-6 GHz 5G and WLAN applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 19, No. 3, 472–476, Mar. 2020.

[3] Jose, M. C., R. Sankararajan, B. S. Sreeja, M. G. N. Alsath, and P. Kumar, "A compact omnidirectional to directional frequency reconfigurable antenna for wireless sensor network applications," *International Journal of Microwave and Wireless Technologies*, Vol. 14, No. 7, 859–870, 2022.

[4] Li, L., J. Nan, J. Liu, and C. Tao, "A compact UWB antenna with triple band notch reconfigurability," *International Journal of Microwave and Wireless Technologies*, Vol. 13, No. 8, 826–832, Oct. 2021.

[5] Peng, X. and L. Kong, "Design and optimization of optical receiving antenna based on compound parabolic concentrator for indoor visible light communication," *Optics Communications*, Vol. 464, 125447, Jun. 2020.

[6] Borges, R. M., T. N. Rodovalho, and A. C. Sodré Jr., "Reconfigurable multi-band radio-frequency transceiver based on photonics technology for future optical wireless communications," *IET*

Optoelectronics, Vol. 9, No. 5, 257–262, 2015.

[7] Vian, J. and Z. Popovic, "A transmit/receive active antenna with fast low-power optical switching," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 48, No. 12, 2686–2691, Dec. 2000.

[8] Pendharker, S., R. K. Shevgaonkar, and A. N. Chandorkar, "Optically controlled frequency-reconfigurable microstrip antenna with low photoconductivity," *IEEE Antennas and Wireless Propagation Letters*, Vol. 13, 99–102, 2014.

[9] Da Costa, I. F., D. H. Spadoti, A. C. Sodré Jr., L. G. d. Silva, S. Rodriguez, R. Puerta, J. J. V. Olmos, and T. Monroy, "Optically controlled reconfigurable antenna for 5G future broadband cellular communication networks," *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, Vol. 16, No. 1, 208–217, 2017.

[10] Da Costa, I. F., A. C. Sodré Jr., D. H. Spadoti, L. G. d. Silva, J. A. J. Ribeiro, and S. E. Barbin, "Optically controlled reconfigurable antenna array for mm-Wave applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, 2142–2145, 2017.

[11] Konkol, M. R., D. D. Ross, S. Shi, C. E. Harrity, A. A. Wright, C. A. Schuetz, and D. W. Prather, "High-power photodiode-integrated-connected array antenna," *Journal of Lightwave Technology*, Vol. 35, No. 10, 2010–2016, 2017.

[12] Yegnanarayanan, S. and B. Jalali, "Wavelength-selective true time delay for optical control of phased-array antenna," *IEEE Photonics Technology Letters*, Vol. 12, No. 8, 1049–1051, Aug. 2000.

[13] Da Costa, I. F., A. C. Sodré Jr., E. Reis, D. H. Spadoti, and J. R. M. Neto, "Optically controlled reconfigurable antenna array based on a slotted circular waveguide," in *2015 9th European Conference on Antennas and Propagation (EuCAP)*, 1–4, Aug. 2015.

[14] Ullah, S., S. Ullah, I. Ahmad, W. U. R. Khan, T. Ahmad, U. Habib, M. A. Albreem, M. H. Alsharif, and P. Uthansakul, "Frequency reconfigurable antenna for portable wireless applications," *Computers, Materials & Continua*, Vol. 68, No. 3, 3015–3027, 2021.

[15] Zhang, Y., S. Lin, S. Yu, G. J. Liu, and A. Denisov, "Design and analysis of optically controlled pattern reconfigurable planar Yagi-Uda antenna," *IET Microwaves, Antennas & Propagation*, Vol. 12, No. 13, 2053–2059, 2018.

[16] Xu, B., Z. Liu, and C. P. Yue, "An AC-powered smart LED bulb for 3D indoor localization using VLC," in *2019 IEEE 8th Global Conference on Consumer Electronics (GCCE)*, 236–237, Feb. 2020.

[17] Zhao, D., L. Lan, Y. Han, F. Liang, Q. Zhang, and B.-Z. Wang, "Optically controlled reconfigurable band-notched UWB antenna for cognitive radio applications," *IEEE Photonics Technology Letters*, Vol. 26, No. 21, 2173–2176, Nov. 2014.

[18] Panagamuwa, C. J., A. Chauraya, and J. C. Vardaxoglou, "Frequency and beam reconfigurable antenna using photoconducting switches," *IEEE Transactions on Antennas and Propagation*, Vol. 54, No. 2, 449–454, Feb. 2006.

[19] Patron, D., A. S. Daryoush, and K. R. Dandekar, "Optical control of reconfigurable antennas and application to a novel pattern-reconfigurable planar design," *Journal of Lightwave Technology*, Vol. 32, No. 20, 3394–3402, Oct. 2014.

[20] Reji, V. and C. T. Manimegalai, "Light controlled frequency reconfigurable antenna for wireless applications," *International Journal of Microwave and Wireless Technologies*, Vol. 15, No. 1, 143–149, 2023.