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Fractal Resonator Based Frequency Reconfigurable Antenna with Varying Capacitive Effect for Wireless Applications

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Abstract: A frequency reconfigurable antenna for wireless applications using a fractal antenna structure is proposed. The fractal antenna is composed of a step resonator type which has a mirror image at the vertical axis in the top with a slit and a parallel mirror image at the vertical axis in the bottom without a slit. The resonating frequency of the fractal antenna is controlled by a Positive-Intrinsic-Negative (PIN) diode. Two PIN diodes are connected between the top and bottom of the fractal antenna. With the varying capacitance effect, the four possible modes of operation of the diode are obtained at the dual resonating frequency of 2.7 and 3.2 GHz. The proposed design holds significant potential for applications in Fifth Generation New Radio (5G NR) n1 band, and Wireless Fidelity (Wi-Fi) access points due to its small size and easy control mechanism. The Specific Absorption Rate (SAR) values were analyzed and are within the safety limits.

Keywords: Reconfigurable Antenna, Fractal, PIN diodes, Wireless, SAR

Frekvenčno nastavljiva antena s spreminjajočim se kapacitivnim učinkom za brezžične aplikacije, ki temelji na fraktalnem resonatorju

Izvleček: Predstavljena je frekvenčno nastavljiva antena za brezžične aplikacije, ki uporablja fraktalno strukturo antene. Fraktalna antena je sestavljena iz stopničastega resonatorja, ki ima zrcalno sliko na vrhu navpične osi z režo in vzporedno zrcalno sliko na dnu navpične osi brez reže. Resonančno frekvenco fraktalne antene nadzoruje dioda PIN (Positive-Intrinsic-Negative). Dve diodi PIN sta povezani med zgornjim in spodnjim delom fraktalne antene. S spreminjajočim se kapacitivnim učinkom se pri dvojni resonančni frekvenci 2,7 in 3,2 GHz dosežejo štirje možni načini delovanja diode. Predlagana zasnova ima zaradi svoje majhnosti in enostavnega mehanizma upravljanja velik potencial za uporabo v frekvenčnem pasu n1 nove radijske zveze pete generacije (5G NR) in dostopnih točkah brezžične povezave (Wi-Fi). Analizirane so bile vrednosti specifične absorpcijske hitrosti (SAR), ki so v mejah varnosti.

Ključne besede: Konfigurabilna antena, fraktali, diode PIN, brezžična povezava, SAR

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1 Introduction

The use of wireless technologies such as Wi-Fi, Wireless Gigabit Alliance (WiGig), Light fidelity (Li-Fi), Near-field communication technology, Fifth Generation (5G), Sixth Generation (6G), etc., in mobile phones has been increasing nowadays. The antenna for operating at the modes mentioned earlier is designed separately [1] and integrated into a single smartphone unit. As the space complexity is high, the heat liberated from the

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phones is increasing day to day. Also, there are some major considerations to be taken care of in the design of 5G smartphones, such as resonant frequency, antenna size, isolation, and SAR.

Reconfigurable Antenna finds applications where different frequencies are utilized in the same node like smartphones, Security, Radio Detection and Ranging (RADAR), and Automation etc.,. A frequency reconfigurable antenna [2] is a single antenna that switches to multiple frequencies, instead of using several antenna array elements for different frequencies. This reduces the antenna space, cost and also improves the compactness of the antenna size. The magneto-electric dipole [3] and Vivaldi antenna [4], [5] are large in size and have unidirectional beams. These characteristics are not suitable for portable devices, where a compact size is preferred. The proposed antenna is designed to reduce the size of the reconfigurable antenna and aims at reducing the SAR.

The switching in the reconfigurable antenna is achieved by electrical, mechanical, and optical modes. The electrical switching of frequencies is obtained by PIN diodes, Varactor diodes and Radio Frequency Microelectromechanical Systems (RF MEMS) switches. The mechanical switching is done by rotation in angular or linear motion, whereas the optical switching is done using Optical Fibre Cable (OFC), Light-emitting diode (LED) and Light amplification by stimulated emission of radiation (LASER). Of all the modes, electrical switching consumes power because an external supply is needed to bias the diodes. Despite huge power consumption, electrical switching is more advantageous due to its efficiency, reliability, and ease of integrating with microwave circuitry [6].

To switch the PIN diodes used in a reconfigurable antenna, some of the techniques used are external biasing circuit with a battery [7] and a remotely controlled Arduino unit [8]. Switching ON the PIN diode needs a high tuning speed, a high direct current (DC) bias current in the ON state, and a high power-handling capacity [6]. Owing to its reliability and cost-effectiveness, electrical switching using PIN diodes is more suitable for reconfigurable antenna.

The Electromagnetic (EM) radiation emitted from the antenna gets coupled to the human tissue and alters the biological functions of the body [9]. The EM absorption by humans is measured in terms of SAR. As per the Federal Communications Commission (FCC), American National Standards Institute / Institute of Electrical and Electronics Engineers (ANSI / IEEE), and Safety Code 6 standards the recommended SAR values are 0.08 W/kg for a Whole body and 1.6 W/kg for over any 1gram (g) of tissue [10].

A compact reconfigurable antenna of size 18 x 20 x 0.035 mm^3 has been designed. The top and bottom patches are connected through PIN diodes, and the frequency reconfigurable antenna switches at four different cases. The SAR analysis was done for the four cases of PIN diode switches and the results were analyzed.

2 Antenna design

The FR4 epoxy substrate of thickness 1.6 mm, and a loss tangent of 4.4 is constructed over the ground plane. To achieve the resonant frequency at the desired level, the defective ground is designed as an inverted E and C-shaped structure. The substrate has a cross-sectional area of 20 x 21 mm^2 and the patch has a cross-sectional area of 18 x 20 mm^2. The fractal antenna is composed of a step resonator type which has a mirror image at the vertical axis in the top with a slit and a parallel mirror image at the vertical axis in the bottom without a slit. The dimensions of the fractal antenna design are shown in Table 1. The top view and bottom view of the antenna are shown in Figure 1 (a) and (b).

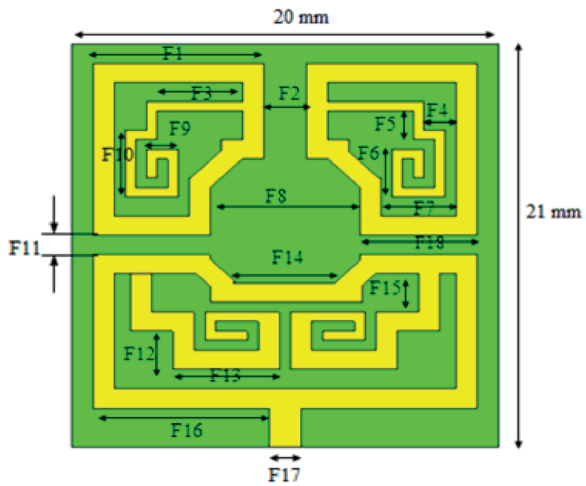

Figure 1: (a) Top view of antenna

The proposed antenna is designed and simulated using Computer Simulation Technology (CST) Microwave Studio software. The PIN diode is inserted between the antenna phases at two points and is shown in Figure 2. For different switching cases of PIN diodes, the return loss and resonant frequency are tabulated. For the four switching states of the diode, the value of the inductance and capacitance are chosen from the PIN diode datasheet. The diode ON state is formulated using an equivalent circuit consisting of 4.7 Ω resistor connected in series with 0.015 nH inductor. While the OFF state is formulated with an equivalent circuit of parallel combination of 4.7 Ω resistor and 0.017 pF capacitor connected in series with 0.015 nH inductor.

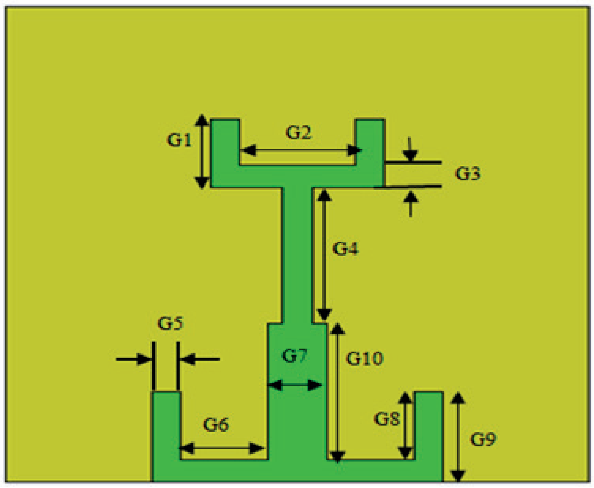

Figure 1: (b) Bottom View of Antenna

Table 1: Dimension of antenna structure

Parameters	Dimension (mm)	Parameters	Dimension (mm)	Parameters	Dimension (mm)
G1	1	F1	8	F11	1
G2	4	F2	2	F12	2
G3	1	F3	4.5	F13	5
G4	6	F4	1.5	F14	5
G5	1	F5	1.5	F15	2
G6	3	F6	2.5	F16	8.25
G7	2	F7	3.5	F17	1.5
G8	3	F8	7	F18	5.5
G9	4	F9	1.5		
G10	6	F10	3.5		

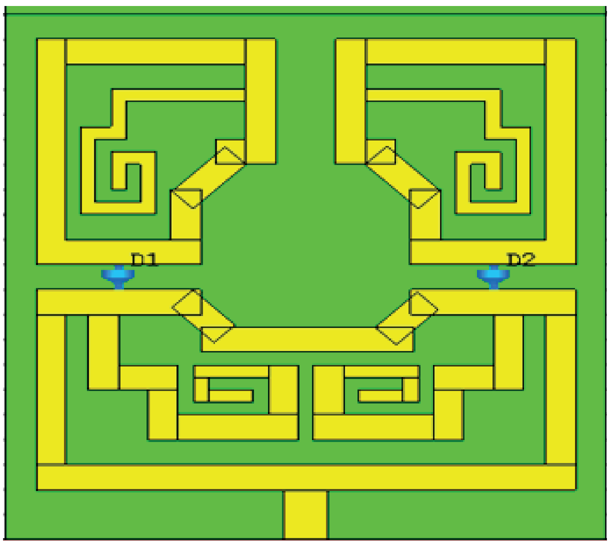

Figure 2: Antenna with PIN diode

2.1 Antenna working strategy

The substrate of the antenna was designed initially considering a conventional rectangular Microstrip patch antenna for the frequency of 3.5 GHz using the equation (1) and (2) by calculating the effective dielectric constant based on the height, dielectric constant & width of the patch antenna, and effective length [11], [12].

$$L_{eff} = \frac{c}{2 f_r \sqrt{\varepsilon_{eff}}} \tag{1}$$

$$\varepsilon_{eff} \approx \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\left(\frac{h}{w}\right)\right)^{-0.5} \tag{2}$$

The antenna design is then optimized to incorporate the fractal step resonator structure with a split in the middle. This creates a capacitive effect between the structures as shown in Figure 3 and shifts the frequency based on the diode switching condition. For case (i) when two diodes are off, the large area is utilized for the capacitance effect and the distance between the plates is increasing [13], thereby decreasing the capacitance as computed in the equation.(3). Due to this, the resonant frequency shifts lower to 2.878 GHz.

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{3}$$

where, ε_o – permittivity of air
ε_r – relative permittivity
A – Area of the plate
d – distance between the plates

For case (ii), when the diode D1 is inserted- Diode (10) case, the capacitance values are reduced by 3.09 x 10^{-15} F. This result in another resonant frequency shifted left at 3.175 GHz in addition to 2.729 GHz. Similar results were obtained for case (iii)-Diode (01). For case (iv), When the diodes D1 and D2 are inserted, both the diodes are ON, and the resonant frequency is shifted higher to 3.252 GHz.

At the bottom of the substrate, an inverted E- shaped structure is tilted towards the horizontal plane. In the middle of the E-structure, a small projection is connected to an inverted C-shaped structure. The inverted E and C-shaped structures together constitute the defective ground structure. The defects introduced in the ground plane alter the current distribution and result in variations of slot resistance, capacitance, and inductance.

3 Experimental results

The designed antenna is fabricated and tested using Vector Network Analyzer (VNA). The width and height of the antenna are 18 mm and 20 mm respectively and are depicted in Figure 4 (a) and (b). The antenna is provided with a port extension to check the output at the VNA connected. The bottom view of the antenna with defective ground inverted E and C-shaped structure is shown in Figure 5.

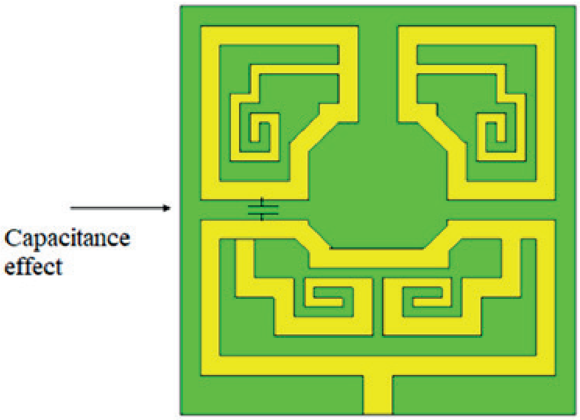

Figure 3: Illustration of capacitive effect

The PIN diode of type BAP65-03,115 is used as an RF switch for achieving frequency reconfigurability in the fractal antenna. The insertion of two PIN diodes in between the antenna elements results in four different switching cases such as 00, 01, 10 and 11 for OFF-OFF, OFF-ON, ON-OFF and ON-ON conditions. When one of the diodes is ON, the diode acts as a short circuit, and the inductive reactance dominates. As the diode is OFF, the diode acts as an open circuit, and capacitive reactance dominates. The inductive reactance shifts the resonant frequency (f_r) to a higher frequency (f_r +Δf) whereas capacitive reactance shifts it to a lower frequency (f_r -Δf).

Figure 4: (a) Width of antenna

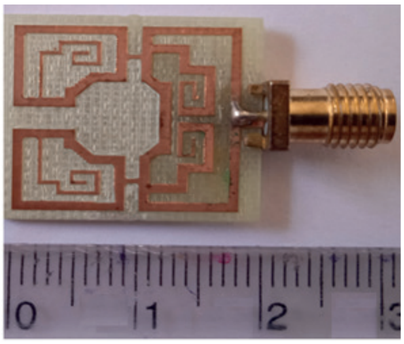

Figure 4: (b) Height of antenna

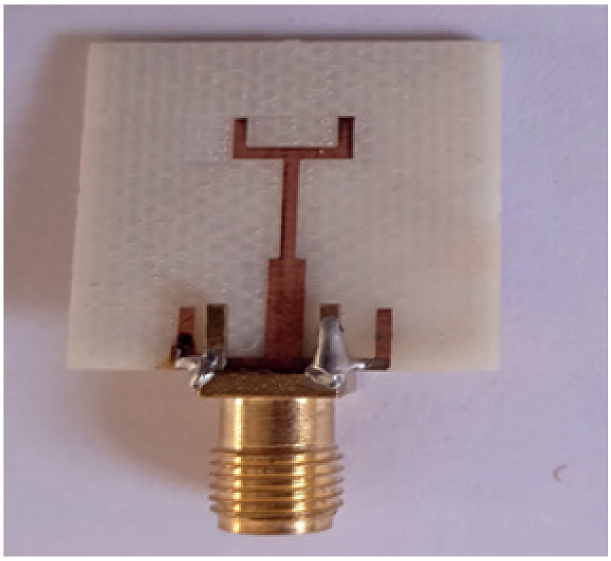

Figure 5: Fabricated antenna – bottom View

The experimental setup consisting of the fabricated fractal antenna with PIN diode and VNA is shown in Figure.6. To switch ON the diode, a 3V battery is connected across the PIN diodes through wires. The diode is said to be in OFF state when the battery is disconnected, as no current flows through the diode. The return loss values are tabulated in Table 4 where the switching of the diode results in antenna resonating between 2.713 GHz and 3.252 GHz frequencies. The experimental results obtained through VNA are depicted in Figure 7 for the diode 10 state.

The switching in the diode is considered to be a short circuit case for each of the diodes being set ON. The inductive reactance dominates when both the diodes are ON and resonate at a high frequency of 3.252 GHz. Similarly, when both the diodes are OFF, it acts as open-circuited capacitance. The fractal antenna resonating frequency is shifted to the lower frequency of 2.878 GHz. The average frequency, f_{av} is calculated by taking the mean of the highest and the lowest frequency values considering ON-ON and OFF-OFF cases of the diodes. From the results obtained the average frequency of

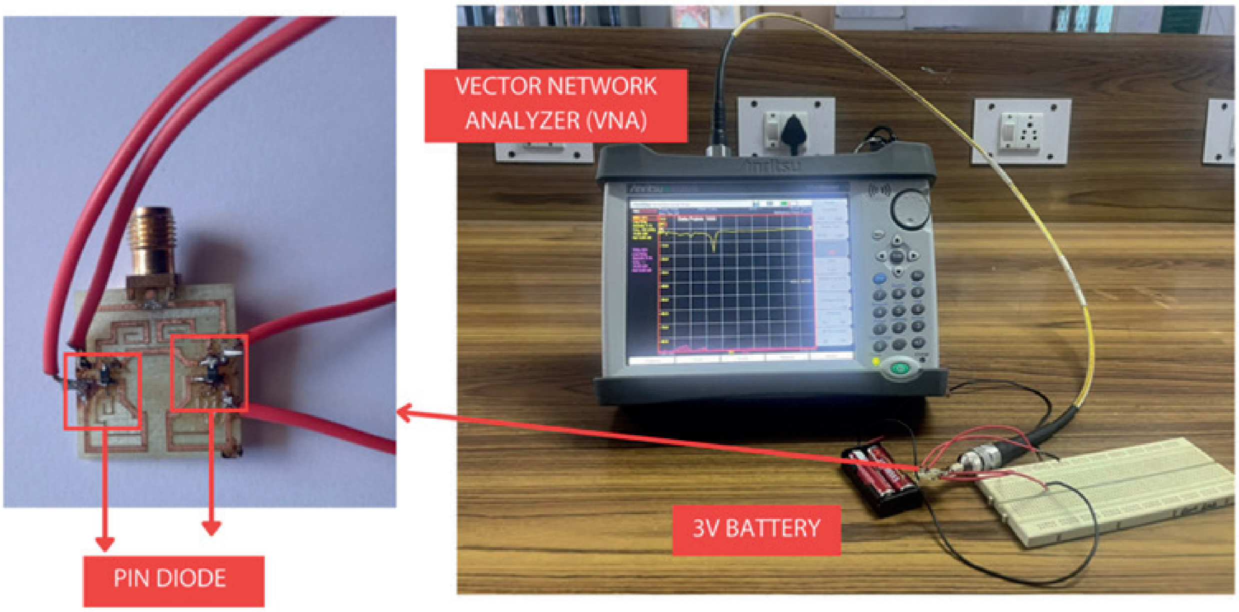

Figure 6: Antenna testing with VNA

3.065 GHz shifts higher to 3.252 GHz with a Δf of 0.187 GHz due to inductive effect, and shifts lower to 2.878 GHz due to capacitive effect.

The scattering parameter S11 depicts the return loss obtained for each case of the connected diode in the fractal antenna. From the obtained results given in Table 4, the antenna exhibits a return loss of less than -10 dB for all four combinations of diodes. The lowest return loss value of -31.57 dB is obtained for the antenna operating at 2.729 GHz when the diode is in ON-OFF (10) state.

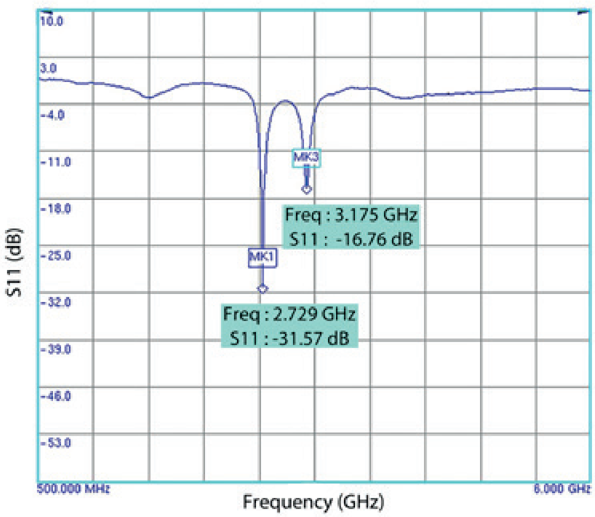

Figure 7: Return loss for diode – ON-OFF (10) state

4 SAR Measurement

The Electromagnetic absorption by humans is measured in terms of specific absorption rate (SAR). As per the FCC, ANSI/IEEE and Safety code 6 standards the recommended SAR values for smartphones are 0.08 W/kg for a Whole body and 1.6 W/kg for over any 1gram (g) of tissue. This maximum is set to 1.6 W/kg averaged over 1g of tissue, or 2 W/kg averaged over 10g of tissue [14].

The six-layer human head model (Figure 8) consisting of skin, fat, bone, Dura, Colony-Stimulating Factor (CSF), and brain is assumed to be a sphere and it is designed based on the properties of permittivity, conductivity, and thickness [15]. It acts as an absorbing surface for the radiations from the proposed antenna.

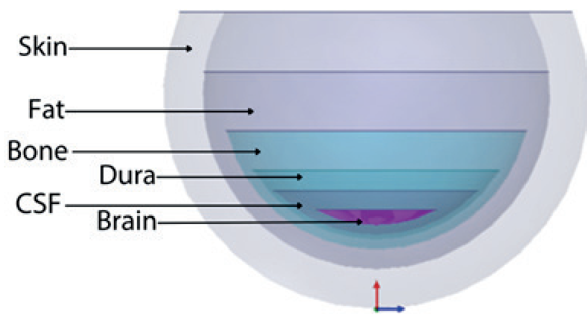

Figure 8: Six layer human head model

The tissue properties of these layers are taken into account to examine the amount of radiation. The tissue properties considered are permittivity, conductivity, and thickness, and the values corresponding to each layer are shown in Table 2 cited in [15]. The six-layer human head model is placed in the front of the antenna designed and the SAR is computed in CST Microwave studio as shown in Figure 9.

Table 2: Tissue properties of human head model

Tissue	Permittivity	Conductivity (S/m)	Thickness (mm)
Skin	40.7	0.65	1
Fat	10	0.17	0.14
Bone	20.9	0.33	0.41
Dura	40.7	0.65	0.5
CSF	79.1	2.14	0.2
Brain	41.1	0.86	81

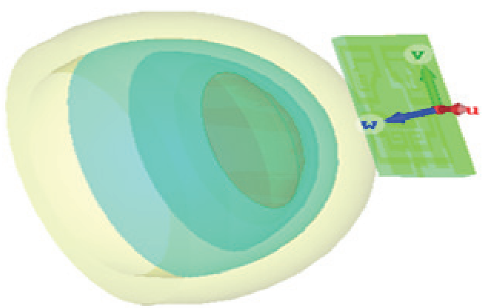

Figure 9: Head model with Antenna in CST

The computed SAR value for diode 00 state at 2.878 GHz is shown in Figure. 10 and is well within the standard safety limits. The SAR value for diode 10 state operating at 2.729 GHz is 0.648 which is higher as compared with other cases of diode switching (Table 4). The comparison of State-of-the-art antennas is given in Table 3. The proposed antenna is compact as compared to other state-of-the-art antennas. As the space occupied is lesser, it can be used in 5G smartphones to be operated at 2.713 GHz, 2.729 GHz, 2.878 GHz, 3.175 GHz, 3.183 GHz and 3.252 GHz frequencies.

Table 4: Return loss and SAR values

Diode Switching States D1D2	Resonant frequencies (GHz)	Return loss (dB)	SAR (W/kg)
00	2.878	-18.44	0.294
01	2.713	-30.52	0.334
	3.183	-17.71	0.149
10	2.729	-31.57	0.648
	3.175	-16.76	0.173
11	3.252	-37.52	0.174

In the proposed work, SAR analysis is performed in the human head model considering 10 g of tissue to test the electromagnetic absorption from the antenna. The simulation results infer that the SAR value holds within the safety limit of 2 W/kg averaged over 10g of tissue.

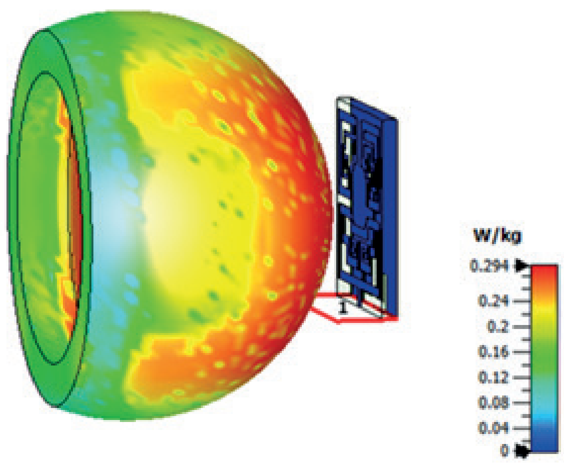

Figure 10: SAR Analysis- diode 00 state-2.878 GHz

Table 3: Comparison with the state-of-the-art antennas

Ref	Antenna size (mm^2)	Substrate (ε_r , h in mm)	Resonant Frequencies (GHz)	Reconfigurable	SAR Analysis
[16]	33×21	FR4-ε_r =4.3, h =1.6	3.3-3.7, 5-5.30	Yes	No
[17]	30×40	Rogers (RO4350B) – ε_r =3.66, h =0.76	3, 6.8	Yes	No
[18]	46×52	FR4-ε_r =4.4, h =1.6	3.42 – 3.82, 5.17- 6.07, 6.89 -7.48 (OFF-OFF State)	Yes	No
[19]	24×30.5	RO4003C-εr =3.38, h =1.5	3.5 and in between 5.45-5.9	Yes	No
[20]	82.77x83.53	Taconic RF-30 – ε_r=4.4, h= 1.6 mm	1.8,2.7,3.1,3.3,4.1,5.1,5.4	Yes	No
This Work	18 x 20	FR4-ε_r =4.3, h =1.6	2.713, 2.729, 2.878, 3.175, 3.183 and 3.252	Yes	Yes

5 Conclusion

The fractal-based reconfigurable antenna is designed and analyzed for wireless applications. The S parameter results show better agreement for the numerical calculations obtained by substituting the capacitance value. The capacitance effect shifts the resonant frequency to a higher level and an average increase of return loss in dB to 50%. The SAR values are also analyzed for different diode-switching cases. The low SAR (0.149) is obtained for the diode 01 case operating at 3.183 GHz and the high SAR (0.648) for the diode 10 case operating at 2.729 GHz. The SAR values are well within the safety limits.

6 Conflict of interest

We, the authors, declare no conflict of interest

The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results

7 References

1. T. Alam, M. R. I. Faruque, M. T. Islam, Printed Circular Patch Wideband Antenna for Wireless Communication, Journal of Microelectronics, Electronic Components and Materials, Vol. 44, No. 3, 2014, 212 – 217.
2. Karthika K, Kavitha K (2021) Reconfigurable Antennas for Advanced Wireless Communications: a review. Wirel Pers Commun 120(4):2711–2771. https://doi.org/10.1007/s11277-021-08555-4
3. Ge, L.; Luk, K.M. Band-reconfigurable unidirectional antenna: A simple, efficient magneto-electric antenna for cognitive radio applications. IEEE Antennas Propag. Mag. 2016, 58, 18–27.
4. Chagharvand, S.; Hamid, M.R.; Kamarudin, M.R.; Kelly, J.R. Wide-to-narrowband reconfigurable Vivaldi antenna using switched-feed technique. Telecommun. Syst. 2016, 63, 711–717.
5. Chagharvand, S.; Hamid, M.R.; Kamarudin, M.R.; Kelly, J.R. Wide and multi-band reconfigurable Vivaldi antenna with slot-line feed. Telecommun. Syst. 2017, 65, 79–85.
6. Ojaroudi Parchin, N.; Jahanbakhsh Basherlou, H.; Al-Yasir, Y.I.A.; M. Abdulkhaleq, A.; A. Abd-Alhameed, R., "Reconfigurable Antennas: Switching Techniques—A Survey", Electronics 2020, 9, 336. https://doi.org/10.3390/ electronics9020336
7. Awan, W.A.; Naqvi, S.I.; Ali, W.A.E.; Hussain, N.; Iqbal, A.; Tran, H.H.; Alibakhshikenari, M.; Limiti, E. "Design and Realization of a Frequency Reconfigurable Antenna with Wide, Dual, and Single-Band Operations for Compact Sized Wireless Applications", Electronics 2021, 10, 1321. https://doi.org/ 10.3390/electronics10111321
8. Genço ˘glan, D.N.; Çolak, ¸S.; Palandöken, M." Spiral-ResonatorBased Frequency Reconfigurable Antenna Design for Sub-6 GHz Applications", Appl. Sci. 2023, 13, 8719. https://doi.org/10.3390/ app13158719.
9. ICNIRP, "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)", 1998, Health Physiol. 74, pp. 494–552.
10. IEEE C95.1-1999, "Safety levels with respect to human exposure to radiofrequency electromagnetic fields: 3 kHz to 300 GHz", IEEE standard,1999.
11. Bahl, I.J, "A designer's guide to microstrip line. Microwaves", 1977, 16, 174–182.
12. Derneryd, "A Design of Microstrip Patch Antenna Elements", 1978.
13. H. Nishiyama and M. Nakamura, "Form and capacitance of parallel-plate capacitors," in IEEE Transactions on Components, Packaging, and Manufacturing Technology: Part A, vol. 17, no. 3, pp. 477-484, Sept. 1994, https://doi.org/10.1109/95.311759
14. Lin, J. C., "A new IEEE standard for safety levels with respect to human exposure to radio-frequency radiation," IEEE Antennas and Propagation Magazine, Vol. 48, No. 1,pp. 157-159, Feb. 2006.
15. Asmalak, "Evaluation of SAR Distribution in Six-Layer Human Head Model", International Journal of Antennas and Propagation, 2015, vol.58, pp.40-47
16. H. Medkour, M. Cheniti, A. Narbudowicz, S. Das, E. Vandelle, and T. Vuong, "Coplanar waveguide-based ultra-wide band antenna with switchable filtering of WIMAX 3.5GHz and WLAN 5GHz signals," Microw. Opt. Technol. Lett., vol. 62, pp. 2398– 2404, Feb. 2020.
17. H. Ayadi, J. Machac, S. Beld, and L. Latrach, "Planar hexagonal antenna with dual reconfigurable notched bands for wireless communication devices," Radioengineering, vol. 30, no. 1, pp. 25-32, Apr. 2021.
18. R. Orugu and N. Moses, "Triangular fractal loaded reconfigurable antenna with notch band characteristics," Int. Journal of Numerical Modelling Electronic Networks Devices and Fields, vol. 34, no. 1, pp. 1-11, Sep. 2020.
19. A. Haider, M. Rahman, H. Ahmad, M. N. Jahromi, M. T. Niaz, and H. S. Kim, "Frequency-agile WLAN notch UWB antenna for URLLC applications," Computers, Materials & Continua, vol. 67, no. 2, pp. 2243-2254, 2021.

20. M. M. Ismail et al., “Multi-Beam Metasurface Control Based on Frequency Reconfigurable Antenna“, Inf. Midem-J. Microelectron. Electron. Compon. Mater., Vol. 54, No. 2,2024, pp. 77–85.

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