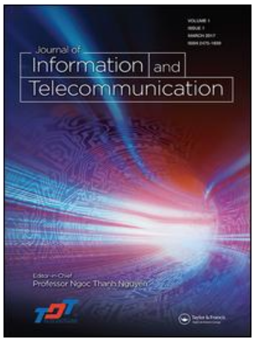

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Improved performance for antenna based on a combination of fractal geometry with CSRR

Thanh Nghia Cao [a], Thi Quynh Hoa Nguyen [a], Thi Nha Nguyen [a], Ngoc Hieu Nguyen [b] and Dac Tuyen Le [c]

[a] School of Engineering and Technology, Vinh University, Vinh city, Vietnam; [b] Nghe An University of Economics, Vinh city, Vietnam; [c] Department of Physics, Hanoi University of Mining and Geology, Hanoi, Vietnam

ABSTRACT

In this paper, an antenna design method operating at 3.5 GHz for 5G system is presented to improve its performance. The antenna is designed using fractal geometry combined with an imperfectly structured ground plane. In which, the radiation surface has the form of a Minkowski island fractal geometry, and the removed part of the ground is a complementary split ring resonator unit cell. In this design, the substrate material is FR4-epoxy microwave laminates with dielectric constant $\epsilon = 4.4$, loss tangent (tan δ) of 0.02, and h = 1.6 mm thickness used to design the antennas. HFSS software is used in the simulation with the feeding method with a microstrip line. The proposed antenna has a significant performance increase compared to the original microstrip antenna such as reduced about 56% reduction in total size, enhanced 207% bandwidth, increased peak gain to 4.66 dB, and improved radiated efficiency to 89.3%. The physical model of the antenna has been fabricated and measured to verify the correctness of the design.

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KEYWORDS
Fractal antenna; metamaterials; CSRR; 5G application; microstrip antenna

1. Introduction

Today, with the great development of science and technology, the need to increase the performance of telecommunications equipment is very urgent. They not only need to integrate many new features, but also tend to reduce the size to be more flexible in use. Especially, for 5G systems, the data transmission rate is much faster than in other systems. Therefore, the issue of improving the performance of devices for 5G applications is of more significant concern to designers.

There are many factors that directly affect the performance of a radio transceiver system, one of them is the performance of the antennas in these devices. Therefore, improving the antenna's performance also determines the system's overall performance. In antenna design, performance is often evaluated through critical parameters such as

CONTACT Thanh Nghia Cao caothanhnghia@vinhuni.edu.vn School of Engineering and Technology, Vinh University, 182 Le Duan, Vinh city, Vietnam

size, bandwidth, gain, and radiation efficiency, etc. Currently, there have been many types of research and technical solutions to increase antenna performance such as antenna microstrip design, shorting pin, and shorting walls, … . Using fractal geometry and metamaterial structures in the designed antenna is one of the solutions being considered and selected (MogharIya et al., 2013).

Fractal geometry is understood as a rough fragment that can be separated into similar parts but at a smaller scale. Fractal geometry can be found in nature such as branches of rivers, branches of a tree, mountains, thunders, etc., or they could be generated by mathematical equations, such as the Sierpinski carpet, Minkowski island, Hilbert curve … Fractal geometry is applied in many fields of life such as information technology, medicine, art, etc. In addition, the study of electromagnetic theory based on fractal geometry has created new radiation devices. Self-similarity and space-filling are the two most important properties of fractal geometry, especially in antenna design. The fractal geometries are used in planar antenna design as the radiation surface of the antenna. Where the self-similarity property is used in the design to create multi-band antennas and space-filling is often used to reduce the dimension of antennas (Cao & Krzysztofik, 2016; Cohen, 1997; Krzysztofik & Cao, 2017; Parmar & Singh, 2017).

Metamaterials are understood as a type of material, which has properties that do not exist in nature. They are created by the arrangement of microstructures to create the desired macro-physical properties. Therefore, metamaterials are also called artificial materials, their properties depend on the structure more than their composition. Microstructures can be made of electromagnetic materials, no electromagnetism or dielectric and are called 'atoms'. The structure of 'atoms' can be symmetrical, isotropic or anisotropic. The arrangement of 'atoms' can be chaotic or in a certain order, so that they are having simultaneously negative permittivity (ε) and permeability (μ), leading to a negative refractive index. Therefore, metamaterials structures can support backflows, i.e. the phase velocity of metamaterials and group velocities are parallel. Metamaterials have properties that no natural material can have, such as disobey to Snell's law, Doppler effect, Vavilov – Cerenkov radiation, … so, it can change the nature of the electromagnetic wave as it passes through it (Caloz & Itoh, 2006; Dong & Itoh, 2012).

In antenna engineering, metamaterials are used for the purpose of improving the parameters or reducing the size. To satisfy that, they can be applied as an antenna environment or as part of an antenna. Depending on the design objective of the antenna, the metamaterial application method is chosen differently. In the case of wanting to improve the performance of an antenna, metamaterials are applied as its environment by arranging the unit cells of the metamaterials around the radiation surface or placing them on one or more other substrates (that also called superstrate) (Krzysztofik & Cao, 2018; Sarkar, 2015). In addition, these metamaterials can also be used as part of the antenna, the unit cell can be loaded into the radiation surface, and the ground plane can also be partially removed by the ground plane (it is called defected ground structure – DGS). This case can be applied to reduce the size or increase the bandwidth of the planar antenna (Chkraborty et al., 2017).

In recent years, many researchers have been interested in designing planar antennas operating in the 3.5 GHz frequency band for 5G applications. The authors mainly proposed planar antennas with rectangular radiating surfaces and used the probed feeding method (Murugan, 2021). The antenna parameters of interest are the overall size (25.3×26.8 mm^2), return loss S_{11}, gain (4.2 dB), and bandwidth (100 MHz) without mentioning the radiated efficiency of the antenna. In general, with this design method, the overall size of the antenna is small, and the gain is relatively high, but the bandwidth is narrow. In addition, another research also presented rectangular microstrip antenna designs operating at the 3.5 GHz frequency band on different substrate materials such as FR-4, RT-5880, and TLC-30 (Ramli et al., 2020) with the feeding by microstrip line. The results of the antennas are compared to see the consequences when using different substrate materials. In this design, the antenna parameters of interest are mainly size, radiated coefficient, and gain. Corresponding to each type of background material, the parameters of each antenna will be different. The results of this research show that the size and gain of the antenna are inversely proportional to the dielectric constant of the substrate used to design it. Therefore, depending on the technical requirements of each design, it is possible to choose the appropriate substrate material. In general, the results of recent studies focus on the design of antennas with basic shapes as rectangles with probed and microstrip line methods without mentioning the solution to improve antenna performance. The main parameters of interest are operating frequency, gain, and bandwidth. Moreover, the results achieved by these studies are only shown in simulation models that have not been fabricated and measured for verification.

In this paper, we present a compact antenna flat design, operating at 3.5 GHz for 5G systems. The antenna is designed based on a combination of fractal geometry and metamaterial structure to greatly improve its performance such as reducing its size, enhancing its bandwidth, and improving its gain. In which, the inverted Fractal Minkowski geometry is used for the radiation plane, while the metamaterial structure is a complementary split-ring resonator (CSRR), which is loaded into the antenna's ground plane to generate DGS (Jangid et al., 2015).

2. Antenna design

This section describes the design process from a microstrip antenna to an antenna that uses fractal geometry combined with metamaterial cells. This work aims to improve the performance of the antenna such as reducing its size and increasing its bandwidth by designing the antenna with the radiating surface of the Minkowski island fractal geometry and the ground plane using the Complementary split ring resonators (CSRR) unit.

The original design was a rectangular microstrip antenna operating at 3.5 GHz. The antenna is designed on an FR4-epoxy microwave laminates with a thickness (h) of 1.6 mm dielectric constant (ϵ) of 4.4, loss tangent ($\tan \delta$) of 0.02 and fed with a microstrip line. From the obtained results of the microstrip antenna, we proceed to form the Minkowski island fractal antenna by removing parts of the copper layer on the radiating surface of the antenna. This will increase the electrical length of the antenna, so it will operate at lower frequencies. Therefore, we must decrease the size of the fractal antenna so that it operates at the desired frequency. The resulting Minkowski island fractal antenna is used as the basis for the next step of the design by removing the

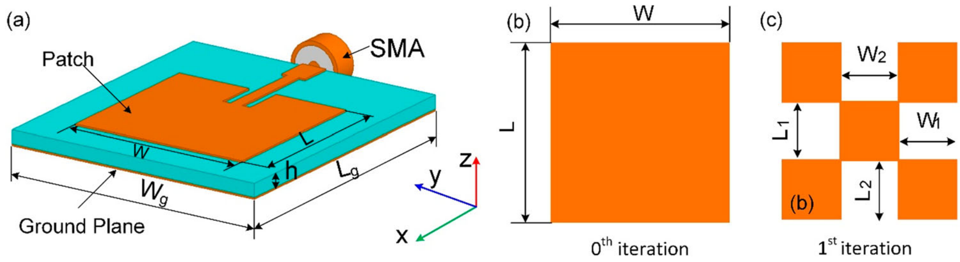

Figure 1. (a) Microstrip antenna configuration, (b) Iterations of Minkowski island fractal geometry: 0th iteration, (c) 1st iteration.

part of the copper layer of the ground plane corresponding to a unit cell CSRR so that the antenna's ground plane is a defected ground structure (DGS).

2.1. Microstrip patch antenna

The configuration of the rectangular microstrip antenna is shown in Figure 1 a. In which, the antenna parameters are calculated by the formulas (1) – (6) and optimized to operate in the frequency range.

$$W = \frac{C}{2f_r\sqrt{\varepsilon_r + 1}} \tag{1}$$

where: W is the length of the patch; fr is the resonant frequency; ϵ_r is the relative dielectric constant of the substrate; c is the speed of light in a vacuum, respectively.

In the microstrip antenna, a transmission line model applies to the case of the infinite dimension of the ground plane. However, in fact, the size of the ground plane has finite size. In that case, the permittivity of the substrate must be modelled by an equivalent value of permittivity, ϵ_{reff}. The effective dielectric constant ϵ_{reff} is determined by (Balanis, 2005; Cao & Krzysztofik, 2018; Meena & Kannan, 2018):

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

Modification of ϵ_r makes the size expansion of the microstrip antenna.

$$\Delta L = 0.412h\frac{(\varepsilon_{reff} + 0.3)\left(\frac{W}{h} + 0.262\right)}{(\varepsilon_{reff} - 0.258)\left(\frac{W}{h} + 0.813\right)} \tag{3}$$

So, the effective length of the antenna L_{eff} is determined from

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} \tag{4}$$

and, the resulting length of the radiation patch L is equal to

$$L = L_{eff} - 2\Delta L \tag{5}$$

It is necessary to adjust the finite size of the antenna ground so that it matches the device, which will be applied. The commonly used approximation is the six times of the substrate thickness all around the periphery of the patch. In this design, the dimension of the ground plane is limited to.

$$W_g = W + 6h \tag{6}$$

For the antenna microstrip to operate close to the desired frequency, we have to optimize its dimensions during simulation. The overall size of the microstrip antenna operating at 3.5 GHz is $34.3 \times 30.9\ mm^2$.

2.2. Minkowski island fractal antenna

This section presents the fractal antenna formation process by transforming the shape of the patch from a rectangular to a Minkowski island fractal geometry. A mathematical process is used to form the Minkowski fractal geometry, which can be described based on a series of affine transformations through the Iterative Function Systems (IFS) algorithm. Equation (7) is used to describe affine transformations in planes (Caloz & Itoh, 2006; Krzysztofik, 2013). The IFS algorithm creates the shape of the Minkowski fractal with different iterations, after each iteration, the Minkowski fractal creates its subsets, with the shape of each subset being the same as the fractal's shape in the previous iteration.

$$w(x, y) = Ax + t = \begin{pmatrix} a & b \\ c & d \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} e \\ f \end{pmatrix} \tag{7}$$

where x, y are coordinates of a point x; t is a translation factor; a, b, c, d are coefficients controlling the rotation and scaling of fractal parts, while e and f are the linear translation. All six parameters are real numbers (Kubacki et al., 2018; Luo et al., 2009). The generic square patch and three iterations of Minkowski fractal island geometry are shown in Figure 1 b and c.

An important parameter of fractal geometry is the fractal dimension (DS), which is the ratio that provides a statistical indicator of the complexity of the details in a pattern at different stages of iterations. It is given by the formula (Krzysztofik, 2013)

$$DS = \frac{LogN}{log\frac{1}{\delta}} \tag{8}$$

where, N is the number of hyper cubes (similar sections), of side length δ (scaling factor) required to cover the object. For the Minkowski fractal, these quantities are $N = 5$, $\delta = 1/3$, and $DS = 1.465$ (Dhar et al., 2013; Krzysztofik, 2008; Vargas, 2014).

Formulas (1) and (2) are used to calculate the size of the rectangular microstrip antenna, then use the PSO algorithm (Particle Swarm Optimization) to select the dimensions appropriate to the operating frequency. To reduce the overall size, the radiating surface of the antenna is changed to the Minkowski Island fractal geometry with the first iteration. The overall size of the microstrip antenna operating at 3.5 GHz is $30.4 \times 26.6\ mm^2$. The result obtained after applying the Minkowski island fractal geometry for the surface radiation of the antenna is that the overall size is reduced by about 25% compared to the original overall size.

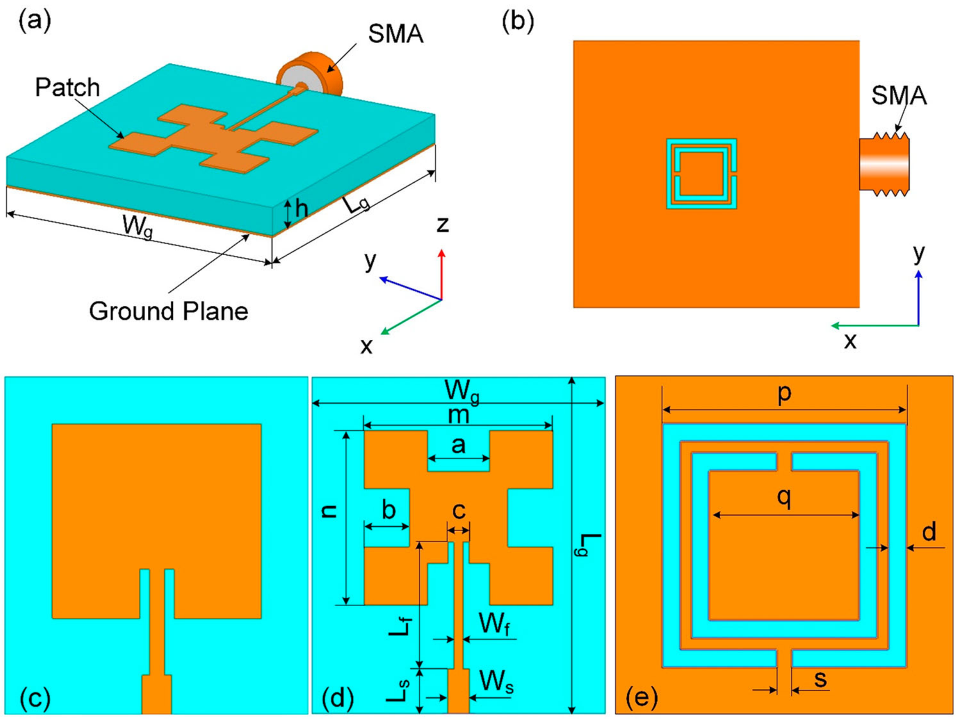

Figure 2. Schematic diagram of the proposed antenna: (a) 3-D view, (b) bottom-view, (c) top-view of microstrip (d) top-view of Minkowski island fractal surface, and (e) enlarged views of CSRR unit cell.

2.3. Proposed antenna configuration

From the achievement of using island fractal geometry in antenna design, the authors designed a fractal antenna combined with the use of CSRR structure, which is loaded into the ground to create a defected ground structure. The result of this combination is to make the antenna operate at a lower frequency than the antenna fractal. Therefore, the overall size of this antenna has to be adjusted smaller for it to work at the desired frequency. The size adjustment is performed simultaneously on both the radiation side and the unit cell size (Mitra et al., 2016; Phan et al., 2016; Raval et al., 2015). This work can be done by optimizing with an algorithm, which is built on the relationships between the antenna dimensions. The overall size of the antenna after combining the use of Minkowski island fractal geometry for the radiation surface with the CSRR metamaterial unit as the DGS for the ground plane is 22.7×20.4 mm^2. It has been reduced by 56% compared to the size of the original antenna. The configuration of this antenna parameter are shown in Figure 2a, d,e and Table 1.

Table 1. The dimensions of of Minkowski island fractal antenna with CSRR for 5G at 3.5 GHz.

Parameters	L_g	W_g	m	n	a	b	L_s
Value [mm]	22.7	20.4	10.8	10.1	3.6	2.4	2
Parameters	W_s	L_f	W_f	*p*	q	d	s
Value [mm]	1	9.5	0.3	10.2	7.6	0.5	0.4

Table 2. The comparison of the antenna parameters.

Types of antenna	Ant.1	Ant.2	Ant.3
Overall size *(mm × mm)*	34.3 × 30.9	30.4 × 26.6	22.7 × 20.4
Bandwidth *(MHz)*	65	120	200
Gain *(dB)*	2.269	3.21	4.46
Efficiency *(%)*	67.8	69.43	89.3

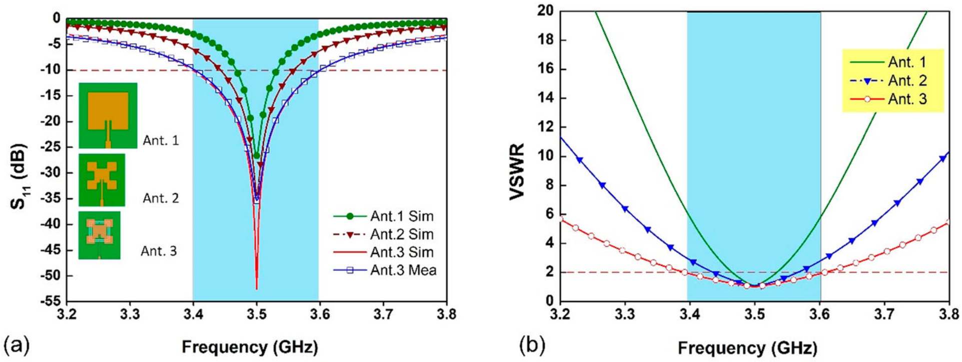

Figure 3. Comparison of antenna parameters (a) Return loss S_{11}, (b) VSWR.

3. Results and discussion

This section describes the results achieved in improving antenna performance through the application of Minskoski island fractal geometry in combination with the CSRR unit cell in the design. After each design improvement, the performance of the antenna is greatly improved as size reduction, bandwidth enhancement, gain improvement, and radiation efficiency >80%. The improvement of antenna performance is shown by comparing its parameters in Table 2, Figures 3 and 4. The antenna symbols in Figure 3 are conventionally named Ant.1 – Microstrip antenna, Ant.2 – Minkowski island fractal antenna, and Ant.3 – proposed antenna.

Figure 4 shows the gain (Figure 4a) and radiated efficiency (Figure 4b) of the proposed antenna, it is clear that the simulation results and measurement results are

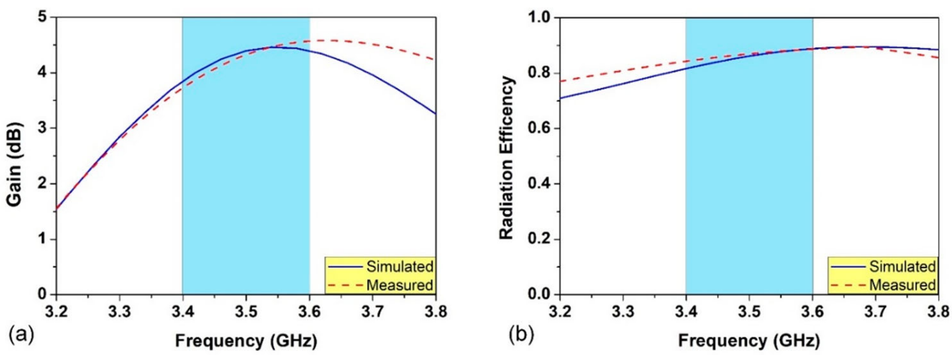

Figure 4. (a) Gain and (b) radiation efficiency of the proposed antenna.

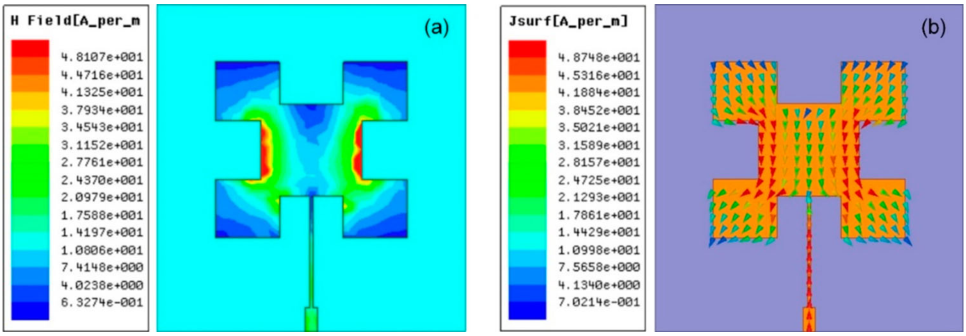

Figure 5. (a) Simulated electric field distributions and (b)surface current at 3.5 GHz of the proposed antenna.

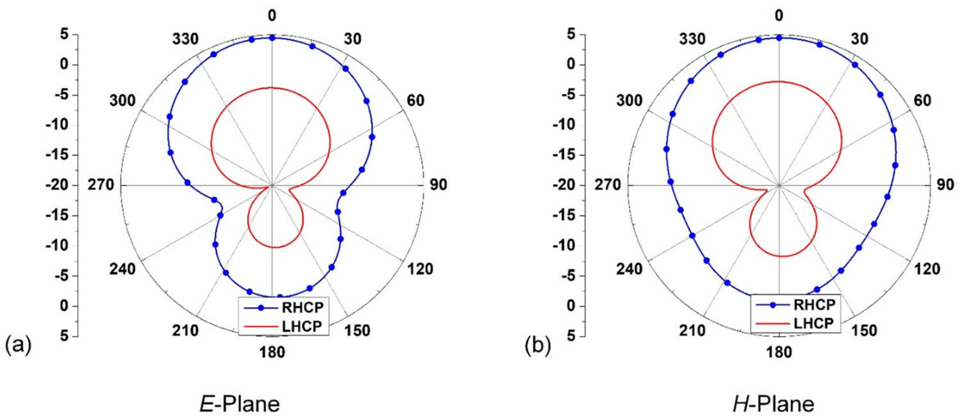

Figure 6. Radiation patterns of the proposed antenna in (a) E-plane and (b) H-plane at various frequencies of 3.5 GHz, respectively.

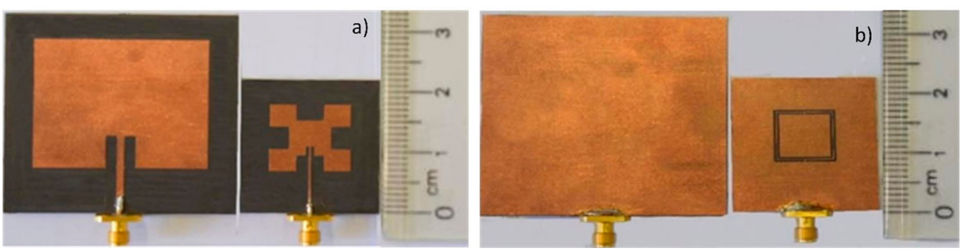

Figure 7. The photos of a fabricated rectangular microstrip antenna and proposed antenna: (a) top – view (a), and (b) bottom – view.

compatible with each other as well as in accordance with the requirements of antennas operating at 3.5 GHz for 5G applications. The simulated electric field distributions and radiation patterns for the proposed antenna at 3.5 GHz are shown in Figures 5 and 6. The simulated electric field distributions and radiation patterns for the proposed antenna at 3.5 GHz are shown in Figure 5 and Figure 6. From the results, it is shown

Table 3. The performance comparison of the proposed antenna with other antennas operating at 3.5 GHz

Refs.	Substrate	Total size *(mm³)*	BW *(MHz)*	Gain *(dB)*	Efficiency *(%)*
(Murugan, 2021)	FR4-epoxy	25.3 × 26.8 × 1.6	100	4.2	–
(Ramli et al., 2020)	FR4-epoxy	36 × 28 × 1.6	130	3.38	60.13
(Ferdous et al., 2019)	FR4-epoxy	25.2 × 48 × 1.6	–	5.1	–
This work	***FR4-epoxy***	***22.7 × 20.4 × 1.6***	***200***	***4.46***	***89.3***

that the parameters achieved by the antenna are satisfactory. The fabricated microstrip antenna and fabricated Minkowski island fractal antenna combined CSRR are shown in Figure 7.

From the above-obtained results, it shows that the efficiency of combining both fractal geometry with metamaterial structure in planar antenna design has significantly improved the performance of antennas operating at 3.5 GHz for 5G application. The comparison of this design with other previously published designs is shown in Table 3.

4. Conclusions

An antenna design process using Minkowski island fractal geometry combined with a CSRR unit cell at 3.5 GHz for 5G application was investigated and designed. The antennas are designed on an FR4-epoxy microwave laminate with a thickness h = 1.6 mm dielectric constant $\epsilon = 4.4$, loss tangent (tan δ) of 0.02, and fed with a microstrip line. The antenna design process in turn goes through the stages of changing the antenna’s radiating surface to have a Minkowski island fractal shape, then establishing the antenna’s ground plane as a defect with the removed part corresponding to a CSRR cell unit.

The result of the study is to create a compact antenna and increased bandwidth. Its size was reduced by about 56% and its bandwidth enchanced by 207%. This is an attractive result, which should be taken care of and applied in the design of other systems. In addition, this design method can be used with different dielectric materials, having higher dielectric coefficients that will produce more compact antennas.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Notes on contributors

Dr. Thanh Nghia Cao is a Lecturer at Vinh University - Vietnam, he was a PhD student at Wroclaw University of Science and Technology - Poland with the topic: Design and investigations of modern antennas based on fractal geometry and metamaterials. His researches on antennas and metamaterials have been published in journals such as IET, AIP Advances, Optik, Materials Research Express,

IEEE Photonics Journal, etc. Currently, he is working on improving the performance of antenna designs by combining the use of fractal geometry with metamaterials.

Thi Quynh Hoa Nguyen received the Ph.D. degree in materials engineering from Chungnam National University, South Korea, in 2009. She is currently an Associate Professor with Vinh University. Her research interests include synthesis and application of advanced functional materials into electronic, energy, and RF/microwave devices.

Thi Nha Nguyen received the B.S. degree from Vinh University, in 2009, and the M.Sc. degree from Vinh University, Nghe An, Vietnam, in 2019. Currently, she is a technician at the Experimental Practice Center of Vinh University. Her research interest is an information technology.

Dr. Nguyen Ngoc Hieu is President of Nghe An University of Economics. He received his Bachalor degree in Informatics from Vinh University, Vietnam, the master degree in Information Technology from Hanoi University of Technology, Vietnam, and obtained the PhD degree in Computer Science from New Mexico State University, United States. His PhD thesis studied a framework for negotiation among dishonest agents and develops a framework for combining Answer Set Programming and Prolog used as a platform for negotiation. His current research includes Multi-Agent Systems, Logic Programming, Simulation Programming.

Le Dac Tuyen received the Ph.D. degree from National Chung Cheng University, Taiwan, in 2012. He is currently an Associate Professor of physics with the Hanoi University of Mining and Geology. His research interests include metamaterials and photonic crystals.

ORCID

Thanh Nghia Cao http://orcid.org/0000-0001-8839-9543

References

Balanis, C. A. (2005). *Antenna theory: analysis and design*, 3rd ed. John Wiley & Sons, Inc., Publication, 2005. ISBN: 0-471-66782-7.

Caloz, C., & Itoh, T. (2006). Electromagnetic metamaterials: Transmission line theory and microwave applications. Copyright © 2006 by John Wiley & Sons, Inc. All rights reserved.

Cao, T. N., & Krzysztofik, W. J. (2016). Hybrid Minkowski Fractal Island Antenna Operating in Two Bands of GPS Satellite System. 2016 IEEE Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (2016 IEEE APS & USNC-URSI 2016), June 26-July 1, 2016, Fajardo, Puerto Rico, USA, pp. 211-212.

Cao, T. N., & Krzysztofik, W. J. (2018). Fractal Antenna of MIMO System WLAN. 12th European Conference on Antennas and Propagation (EuCAP 2018), 9-13 April 2018, ExCel, London, UK, ISBN: 978-1-78561-815-4, e-ISBN: 978-1-78561-816-1, ISSN 0537-9989, pp. 1-5.

Chkraborty, M., Chkraborty, S. C., Reddy, P. S., & Samanta, S. (2017). High performance DGS integrated compact antenna for 2.4/5.2/5.8 GHz WLAN band. *Radioengineering*, *26*(1), 71–77. doi:10.13164/re.2017.0071

Cohen, N. (1997). Fractal antenna applications in wireless telecommunications. Professional Program Proceedings. Electronic Industries Forum of New England, ISBN: 0-7803-3987-8.

Dhar, S., Ghatak, R., Gupta, B., & Poddar, D. R. (2013). A wideband minkowski fractal dielectric resonator antenna. *IEEE Transactions on Antennas and Propagation*, *61*(6), 2895–2903. doi:10.1109/TAP.2013.2251596

Dong, Y., & Itoh, T. (2012). Metamaterial-based antennas. *Proceedings of the IEEE*, *100*(7). doi:10.1109/JPROC.2012.2187631

Ferdous, N., Hock, G. C., Hamid, S. H. A., Raman, M. N. A., Kiong, T. S., & Ismail, M. (2019). *Design of a small patch antenna at 3.5 GHz for 5G application*. in IOP Conference Series: Earth and Environmental Science, 2019, vol. 268, no. 1, p. 12152.

Jangid, K. G., Sharma, V., Sharma, R., Saxena, V. K., Bhatnagar, D., & Kulhar, V. S. (2015). Design of compact microstrip patch antenna with DGS structure for WLAN & Wi-MAX applications. *European Journal of Advances in Engineering and Technology*, *2*(1), 8–11. https://ejaet.com/PDF/2-1/EJAET-2-1-8-11.pdf

Krzysztofik, W. J. (2008). Printed multiband fractal antennas. In D. A. Sanchez-Hernandez (Ed.), *Multiband integrated antennas for 4G terminals* (Vol. 4, pp. 95–150). Artech House, INC.

Krzysztofik, W. J. (2013). Fractal geometry in electromagnetics applications - from antenna to metamaterials. *Microwave Review*, *19*(2), 3–14. http://www.mtt-serbia.org.rs/files/MWR/MWR2013dec/Vol19No2-02-WKrzysztofik.pdf

Krzysztofik, W. J., & Cao, T. N. (2017). Fractal geometry applied to design of communication systems antennas. Review of Telecommunications, Year XC, Telecommunications News, LXXXVI, ISSN 1230-3496, e-ISSN 2449-7487, Zeszyt 6 / 2017, str. 206-209 (on CD).

Krzysztofik, W. J., & Cao, T. N. (2018). Metamaterials in application to improve antenna parameters. Metamaterials and Metasurfaces book, chapter 4, InTech Open Science, pp 63-85.

Kubacki, R., Czyzewski, M., & Laskowski, D. (2018). Minkowski island and crossbar fractal microstrip antennas for broadband applications. *Applied Sciences*, *8*, 334. https://doi.org/10.3390/app8030334

Luo, Q., Salgado, H. M., & Pereira, J. R. (2009). Fractal monopole antenna design Using Minkowski Island geometry. 2009 IEEE Antennas and Propagation Society International Symposium, 1-5 June 2009, Charleston, SC, USA, ISBN: 978-1-4244-3647-7.

Meena, M., & Kannan, P. (2018). Analysis of microstrip patch antenna for four different shapes and substrates. *ICTACT Journal on Microelectronics*, *04*, 519–530. doi:10.21917/ijme.2018.0092

Mitra, D., Ghosh, B., & Sarkhel, A. (2016). A miniaturized ring slot antenna design with enhanced radiation characteristics. *IEEE Transactions on Antennas and Propagation*, *64*(1), 300–306. doi:10.1109/TAP.2015.2496628

Moghariya, D., Kothari, T., & Patel, M. P. (2013). Miniaturisation method to reduce the size of microstrip antenna for lower frequency. *International Journal for Scientific Research & Development (IJSRD)*, *1*(1), 26–28. https://ijsrd.com/Article.php?manuscript=IJSRDV1I1008

Murugan, S. (2021). *Compact MIMO shorted microstrip antenna for 5G applications*. *International Journal of Microwave and Wireless Technologies*, *11*(1), 22–27. doi:10.5815/ijwmt.2021.01.03

Parmar, S. R. S., & Singh, E. H. (2017). Analysis of fractal geometries and its applications in microstrip antenna. *International Journal of Advanced Research in Computer Science*, *8*(4), 194–198. doi:10.26483/ijarcs.v8i4.3731

Phan, D. T., Phan, H. L., & Nguyen, T. Q. H. (2016). A miniaturization of microstrip antenna using negative permitivity metamaterial based on CSRR loaded ground for WLAN applications. *Journal of Science and Technology*, *54*(6), 689–697. DOI: 10.15625/0866-708X/54/6/8375

Ramli, N., Noor, S. K., Khalifa, T., & Abd Rahman, N. H. (2020). Design and performance analysis of different dielectric substrate based microstrip patch antenna for 5G applications. *International Journal of Advanced Computer Science and Applications*, *11*(8). doi:10.14569/IJACSA.2020.0110811

Raval, F., Kosta, Y. P., & Joshi, H. (2015). Reduced size patch antenna using complementary split ring resonator as defected ground plane, AEU - International Journal of Electronics and Communications, *69*(8), 1126–1133. doi:10.1016/j.aeue.2015.04.013

Sarkar, S. B. (2015). Impact of metamaterial in antenna design: A review. *International Journal of Electronics and Communication Engineering*, *8*(1), 87–90. http://www.irphouse.com/ijece/ijecev8n1_11.pdf

Vargas, M. P. (2014). Fundamentals of Metamaterial Structures. Planar Metamaterial Based Microwave Sensor Arrays for Biomedical Analysis and Treatment, Springer Theses, doi:10.1007/978-3-319-06041-5_2, © Springer International Publishing Switzerland 2014.