1. Charinsak SAETIAW[1], 2. Suthasinee LAMULTREE[1], 3. Jatuporn NAKORNTEP[1], 4. Suwit PHUCHADUEK[1]

Rajamangala University of Technology Isan, Khon-Kean Campus (1)
ORCID: 1. 0000-0002-0281-9947; 2. 0000-0003-3124-3980, 3. 0009-0001-9332-0462, 4. 0000-0002-9429-5203

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The Design of Capsule-Shaped Patch Antenna with Multiple Rectangular Slotted for 3D Printing Technology using Conductive PLA Material

***Abstract**. This research presents the use of 3D printing technology with advanced electromagnetic materials to apply to prototyping and improving antenna design processes. A capsule-shaped patch antenna is used as a representative antenna model that can be combined with multiple rectangular slotted techniques to produce antennas suitable for future wireless communications applications. The design and construction of the antenna starts with a rectangular patch antenna using a microstrip feed technique and a PLA base material. In addition, the conductive PLA material was chosen instead of the copper material for the radiating layer. After that, a co-planar waveguide feeding was used to convert the ground plane from the back to the front layer. For the antenna part, modifications are made at both ends of the patch with semi-circles to form the shape of the capsule. Ultimately, the multiple rectangular slotted technique will be used to increase bandwidth requirements as well as improve the area of the radiation section with reduced material consumption. Mathematical simulation results showed that the antenna design was optimized by calculating the final dimensions of the antenna to be able to support 5GHz ISM-band for the WLAN/WiMAX standard. It included the WiFi-6E standard with an operating frequency of 6GHz, that is, coverage from 5.1411GHz to 7.9261GHz and had an antenna gain of 3.52dBi. The prototype antenna was fabricated using 3D printing technology with normal PLA and conductive PLA material. For the measurement results of the prototype antenna, the impedance bandwidth at -10dB was 4.5672GHz to 7.9127GHz and the gain was 3.49dBi. The measurement results of the prototype antenna were found to be consistent with the results from the simulation.*

***Streszczenie.** W pracy przedstawiono zastosowanie technologii druku 3D z wykorzystaniem zaawansowanych materiałów elektromagnetycznych do zastosowania w prototypowaniu i udoskonalaniu procesów projektowania anten. Antena patchowa w kształcie kapsułki jest reprezentatywnym modelem anteny, którą można łączyć z wieloma technikami prostokątnych szczelin w celu wytworzenia anten odpowiednich do przyszłych zastosowań komunikacji bezprzewodowej. Projekt i konstrukcja anteny rozpoczyna się od prostokątnej anteny krosowej wykorzystującej technikę podawania mikropaskowego i materiału bazowego PLA. Ponadto na warstwę promieniującą wybrano przewodzący materiał PLA zamiast materiału miedzianego. Następnie zastosowano współpłaszczyznowe zasilanie falowodu w celu przekształcenia płaszczyzny uziemienia z warstwy tylnej na przednią. W przypadku części antenowej modyfikacje przeprowadza się na obu końcach łaty za pomocą półkoli, aby uzyskać kształt kapsułki. Docelowo zastosowana zostanie technika wielu prostokątnych szczelin, aby zwiększyć wymagania dotyczące szerokości pasma, a także poprawić obszar sekcji promieniowania przy zmniejszonym zużyciu materiału. Wyniki symulacji matematycznych wykazały, że projekt anteny został zoptymalizowany poprzez obliczenie ostatecznych wymiarów anteny, aby mogła obsługiwać pasmo ISM 5 GHz w standardzie WLAN/WiMAX. Obejmował standard WiFi-6E o częstotliwości roboczej 6 GHz, czyli zasięgu od 5,1411 GHz do 7,9261 GHz i miał zysk anteny 3,52 dBi. Prototypowa antena została wykonana przy użyciu technologii druku 3D ze zwykłego PLA i przewodzącego materiału PLA. W przypadku wyników pomiarów prototypowej anteny szerokość pasma impedancji przy -10 dB wynosiła od 4,5672 GHz do 7,9127 GHz, a wzmocnienie wyniosło 3,49 dBi. Stwierdzono, że wyniki pomiarów prototypowej anteny są zgodne z wynikami symulacji. (**Projekt anteny krosowej w kształcie kapsułki z wieloma prostokątnymi szczelinami do technologii druku 3D przy użyciu przewodzącego materiału PLA**)*

Keywords: capsule-shaped patch antenna, 3D printing technology, conductive PLA material.
Słowa kluczowe: antena patch w kształcie kapsułki, technologia druku 3D, przewodzący materiał PLA

Introduction

In recent years, various fields of engineering technology have developed rapidly and continuously. In particular, communication technology is considered to be the technology that has had its origins in development for a long time and is very necessary and important to our lives today, especially wireless communication technology.

Wireless communications technology involves transmission of data without the use of wires, cables, or any other conductors over long distances. Wireless communications are growing exponentially due to the huge business benefits from wireless technologies that deliver network speed, flexibility, and efficiency. This makes wireless communication technology a powerful tool as it facilitates easy data sharing and increases productivity as well as gaining the freedom to roam freely anywhere without worrying about the connection to the data network.

However, one important subsystem device in wireless communication technology that is responsible for converting electrical signals into electromagnetic waves is the antenna. For antennas, many basic antennas can be applied together. Therefore, antennas can be designed to have different characteristics to meet the needs and purposes of use, including being able to be combined with other components.

For this reason, choosing or designing an antenna with the appropriate size and form can reduce antenna installation problems in different operating conditions. The basic types of antennas that are often chosen to be designed and fabricate for a variety of applications include monopole, dipole, and microstrip patch antennas [1-16].

Microstrip patch antenna is a basic type of antenna having been continuously developed and improved for using in a variety of modern wireless communication systems. In addition, in antenna design, various techniques were presented and many new materials were studied in conjunction with patch antennas [5,8,11-13,15-16].

The main objective of this research is to study the capability of 3D printing technology as well as conductive materials that can be used to replace conventional antenna designs using FR4 materials combined with copper etching processes. In creating an antenna with such processes, it creates a part that uses the appropriate electricity to function as an antenna, but it causes complexity in the process of designing and fabricating.

This research aimed to investigate whether the use of 3D printing technology including with conductive filament materials can be used in the design of common patch antennas or other shape with difference useful techniques. Many antenna design techniques have been developed to improve antenna performance and properties in various aspects, such as bandwidth improvement, modifying the radiation pattern, and increasing antenna gain.

Rectangular patch antenna design typically begins with determining the appropriate antenna size as well as the microstrip feeder characteristics. Then, the rectangular patch (RP) antenna converting with a co-planar waveguide (CPW) feeding technique to convert the ground plane from the back to the front layer. After that, the patch turned into a capsule-shaped patch (CSP) antenna with a multiple rectangular slotted (MRS) to optimize the result of bandwidth. Results from the simulation software were used to compare with the results from measurements of antennas fabricated with polylactic acid or PLA-based materials and conductive PLA materials.

The structure of this article can be organized by topic into 5 main sections. The first section introduces antenna technology and the approaches of this research. The next step is to design the structure and size of a simple RP antenna with a ground layer on the back. Next, the original antenna is modified into a CSP antenna with a ground layer in front, and then MRS technique is added as a final step. The simulation software is then used to obtain appropriate adjustments to tighten the size of the radiation layer, which will be reflected in the simulation results. The model is then used to create an antenna made of PLA and conductive PLA materials, and measurements from the prototype antenna are compared with those obtained from the initial simulation. In the last section, the conclusions drawn from this research will be discussed.

Antenna Design

For the antenna design flow in this paper, a basic patch antenna for 5GHz WLAN/WiMAX applications including the WiFi-6E standard is proposed, which is fed by a coplanar waveguide. A patch antenna has three main components consisting of a ground layer separated by a substrate layer and a top layer containing the signal input combined with a rectangular patch antenna. After that, the modified patch antenna with semi-circular shaped was added to the end of patch. The patch shape became a modified rectangular with semi-circular shape called capsule-shaped patch antenna. The operation bandwidths of the proposed antenna are ISM WLAN standard, which satisfy the required bandwidth of the 5.2 and 5.8GHz WLAN and 5.5GHz WiMAX with S11 better than -10dB.

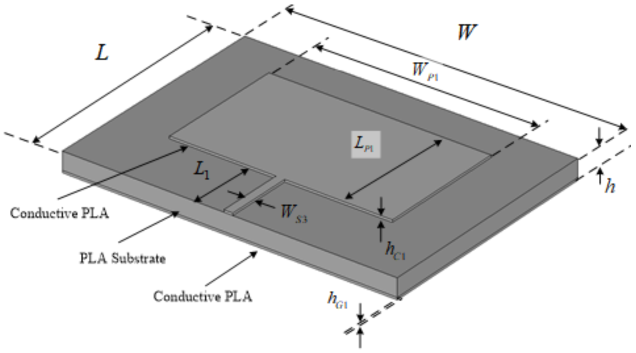


Fig. 1. The RP antenna model using conductive PLA and PLA substrate.

From Fig.1, it shows the parameters of the dimensional properties of modern RP antennas. This RP antenna was fabricated with a basic microstrip feeding technique that used conductive PLA for the radiation layer and PLA as the substrate layer, where W_{P1} and L_{P1} are the parameters of the width and height of the radiated part of the antenna on the top layer, respectively. The maximum dimensions of both the PLA substrate layer and the conductive PLA substrate as antenna ground layer are W and L for width and length, respectively. The thickness of the PLA substrate layer is h. So, the thickness of the conductive layer on the upper and lower layers were shown as h_{C1} and h_{G1}.

The microstrip feed is connect from the middle of the lowest surface of the patch to the bottom edge of the substrate with a width (W_{S3}) to provide proper impedance matching [17,18].

A layer of electrical conductors on top that serves as an antenna can be designed as described in the methodology in [18] using equations (1)-(4).

$$W = \frac{c}{2 f_r} \sqrt{\frac{2}{\varepsilon_r + 1}} \quad (1)$$

$$L = \frac{c}{2 f_r \sqrt{\varepsilon_{reff}}} - 2\Delta L \quad (2)$$

Where

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \quad (3)$$

$$\Delta L = 0.412h \frac{\left(\varepsilon_{reff} + 0.3\right)\left(\frac{w}{h} + 0.264\right)}{\left(\varepsilon_{reff} - 0.258\right)\left(\frac{w}{h} + 0.8\right)} \quad (4)$$

For the antenna design, an operating frequency (f_r) of 5.5GHz was used. The corresponding basic RP antenna parameters can be calculated using the PLA dielectric layer thickness (h) value of 2.0 mm. and the ε_r is 1.9. From the above specification, the results of various sizes for use in the simulation were presented in Table 1.

Table 1. Basic RP antenna parameters

Parameter	Value (mm.)	Parameter	Value (mm.)
W	59.00	L	55.00
W_{P1}	22.60	L_{P1}	18.52
W_{S3}	3.00	L_1	10.17
h	2.00	h_{C1} , h_{G1}	1.00

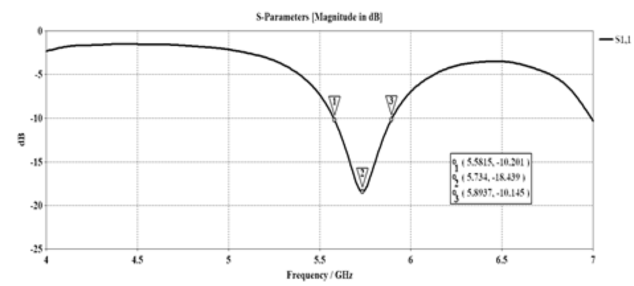
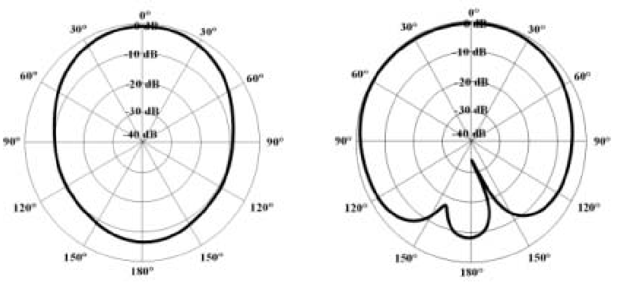


Fig. 2. S11 from simulation results of regular RP antenna with PLA



a) Horizontal plane b) Vertical plane

Fig. 3. 2D radiation pattern from simulation results of a 5.7 GHz RP antenna with conductive PLA and PLA substrate.

From the simulation results based on the values in Table 1, the RP antenna operates at a frequency of 5.734GHz with a bandwidth value of 5.5815-5.8937GHz as shown in Fig. 2.

The results of mathematical simulation were able to present the 2D radiation pattern of the RP antenna as shown in Fig. 3. For the antenna ground layer and the PLA substrate layer, they were set to lie in the XY-plane. The results showed that the gain value of the antenna was about 3.26dBi in the Z-direction.

Capsule-shaped Patch Antenna

For designing and prototyping antennas with 3D printers, multiple layers of materials will increase the time it takes to produce a prototype. Therefore, in the antenna design process, the design was adapted to include only two layers of material using the CPW feed technique. A CPW feed technique that converted the ground plane to the front layer was reported in [19]. Different types of CPW feed technique were reported to enable changes in antenna characteristics such as multiband, wideband and antenna miniaturization [20-23]. Then, the modification of RP on both end of the patch with the half circular to make the shape of capsule-shaped patch (CSP) antenna was purposed.

The size and parameter values of the CSP antennas with CPW feed were obtained by software simulation [24] at a design frequency of 5.5GHz as shown in Fig. 4, and the results for the obtained size results were shown in Table. 2.

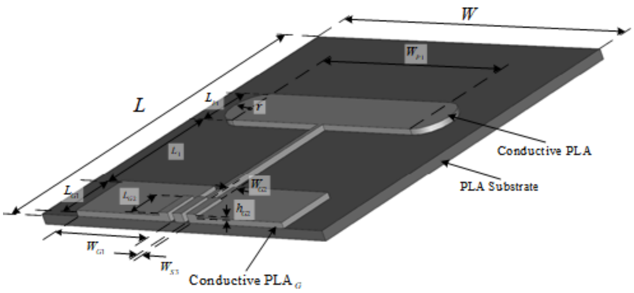


Fig. 4. A CSP antenna with CPW feed model.

Table 2. CSP antenna with CPW feed parameters

Parameter	Value (mm.)	Parameter	Value (mm.)
W	59.00	L	55.00
W_{P1}	30.00	L_1	18.00
W_{G1}	20.00	L_{P1}	7.00
W_{S3}	1.30	L_{G1}	10.00
W_{G2}	3.00	L_{G2}	4.00
r	3.50	h	1.60
h_{G2}	0.50	h_{G1}	0.90

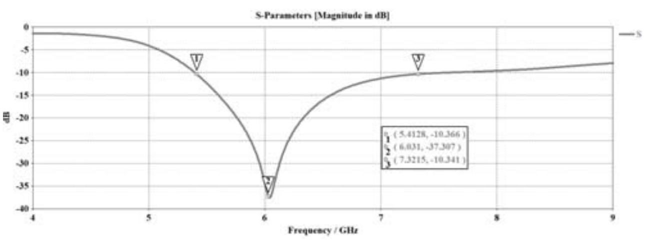


Fig. 5. S11 results for CSP antenna.

According to the results from simulation in Fig. 5, the proposed CSP antenna design at 5.5GHz resonance frequency had a fractional bandwidth from 5.4218GHz to 7.3215GHz. Moreover, the results showed that the CSP antenna can extend the bandwidth to cover the 6GHz band of WiFi-6E standard (5.925-7.125GHz) [25].

CSP Antenna with Multiple Rectangular Slotted Technique

To improve the antenna's radiation layer, an advanced Multiple Rectangular Slotted (MRS) technique was applied to the CSP antenna in the previous process. The position, dimensions and number of slotted can be redesigned using a software simulation optimization process. Then, the model of antenna and the antenna dimensions were shown in Fig. 6 and Table 3, respectively.

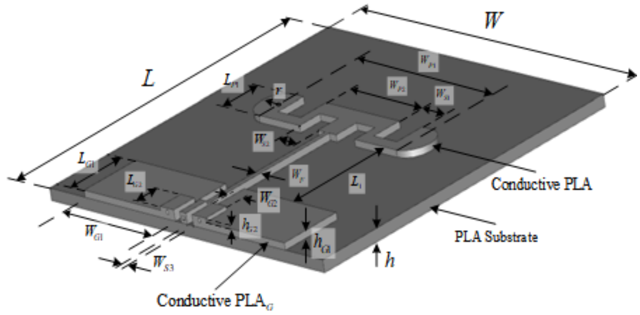


Fig. 6. Model of the CSP with the MRS technique.

Table 3. MRS with CSP antenna parameters

Parameter	Value (mm.)	Parameter	Value (mm.)
W	59.00	L	55.00
W_{P1}	30.00	L_1	18.00
W_{P2}	16.00	L_{P1}	7.00
W_{S1}	4.00	L_{G1}	10.00
W_{S2}	4.00	L_{G2}	4.00
W_{S3}	1.30	h	1.60
W_{G1}	20.00	h_{G1}	0.90
W_{G2}	3.00	h_{G2}	0.50
r	3.50		

Considering the simulation results, the antenna operates at a center frequency of 5.5GHz with an operating bandwidth in the frequency range of 5.1411-7.9261GHz as reported in Fig. 7.

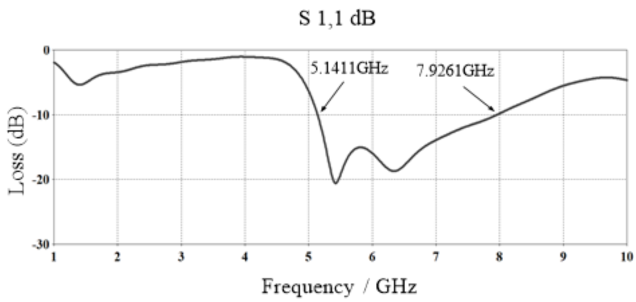


Fig. 7. S11 from simulation results of regular CSP antenna with the MRS antenna using conductive PLA and PLA substrate

Based on simulation results, the modified antenna with the MRS technique improved a bandwidth from 5.4128-7.3215GHz to 5.1411-7.9261GHz, that increased 16.09% bandwidth. However, the total size of radiation was not difference but reduce the material used around 25.76% for the hole from a slotted.

The 3D radiation pattern simulation results in Fig. 8-10 showed that the optimal gain of the antenna was 3.21dBi, 3.52dBi, and 3.5dBi for the frequencies 5.2GHz, 5.5GHz, and 5.8GHz, respectively.

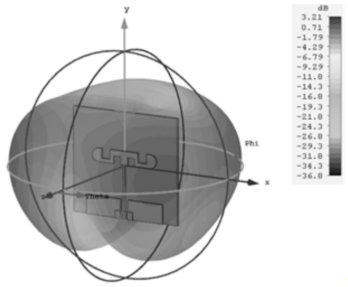


Fig. 8 3D radiation pattern from simulation results of a 5.2 GHz the CSP antenna with the MRS technique using conductive PLA and PLA substrate.

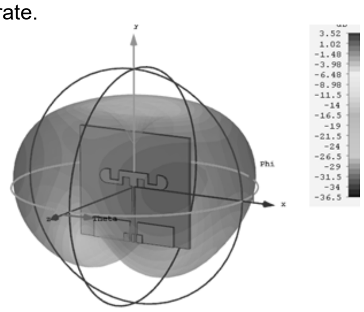


Fig. 9 3D radiation pattern from simulation results of a 5.5 GHz the CSP antenna with the MRS technique using conductive PLA and PLA substrate.

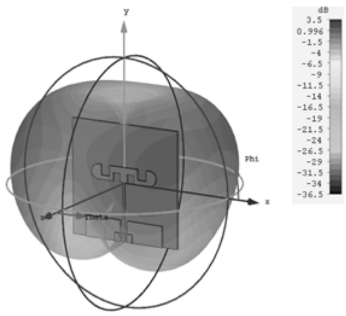
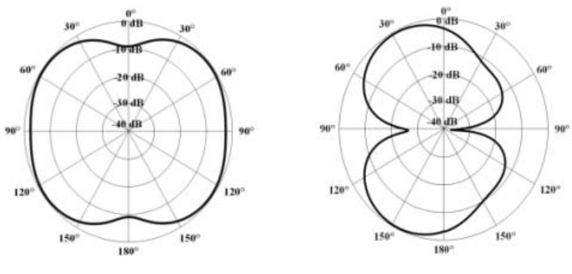
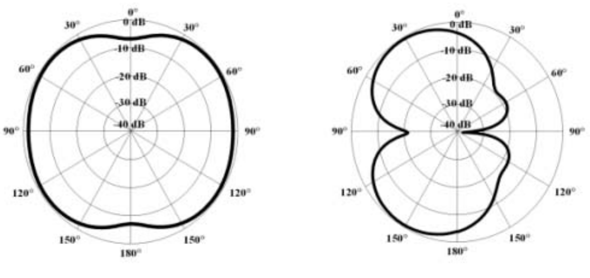


Fig. 10 3D radiation pattern from simulation results of a 5.8 GHz the CSP antenna with the MRS technique using conductive PLA and PLA substrate



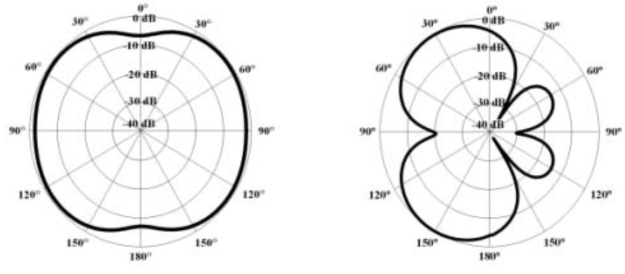
a) Horizontal plane b) Vertical plane

Fig. 11. 2D radiation pattern from simulation results of a 5.2 GHz CSP antenna with the MRS technique using conductive PLA and PLA substrate.



a) Horizontal plane b) Vertical plane

Fig. 12. 2D radiation pattern from simulation results of a 5.5 GHz CSP antenna with the MRS technique using conductive PLA and PLA substrate.



a) Horizontal plane b) Vertical plane

Fig. 13. 2D radiation pattern from simulation results of a 5.8 GHz CSP antenna with the MRS technique using conductive PLA and PLA substrate

Fig. 11-13 presented the simulation results of 2D radiation patterns of the CSP antenna with the MRS technique using conductive PLA and PLA substrate at 5.2GHz, 5.5GHz and 5.8GHz, respectively.

Antenna Fabrication and Measurement

A final prototype antenna was fabricated to measure the antenna properties as shown in Fig. 14. In Fig.15, the results of |S11| were compared between the simulated values and the measured results obtained from a prototype antenna which was created by a 3D printer using conductive PLA material.

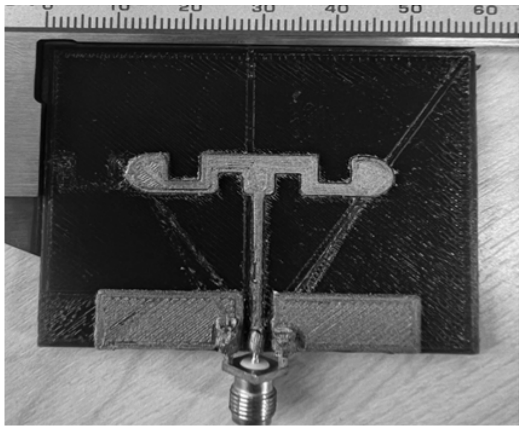


Fig. 14. The CSP antenna with the MRS technique prototype

From the simulation output data, the bandwidth of the CSP antenna combined with the MRS technique was 5.1411GHz to 7.9261GHz, and from the prototype measurement results, the antenna bandwidth value was from 4.5672GHz to 7.9127GHz. Considering both the simulation and measurement results of S11, it was found to be reasonable.

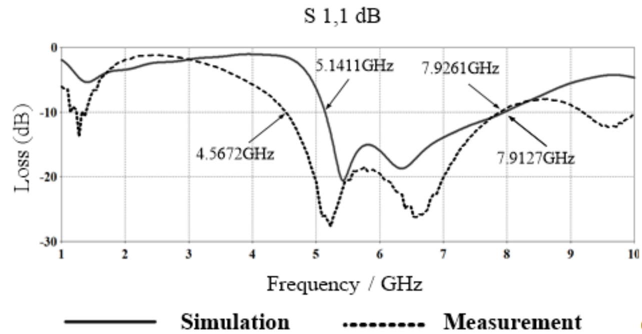
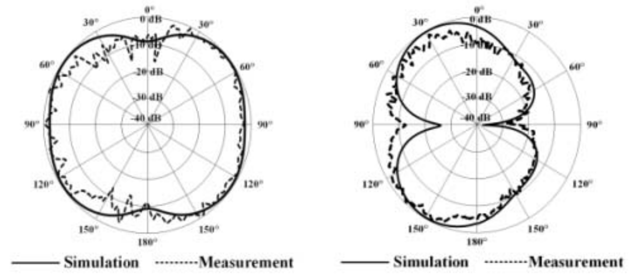


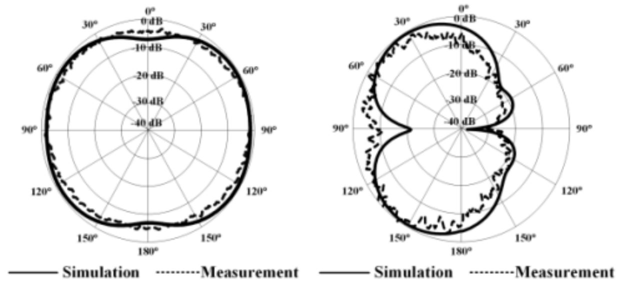
Fig. 15. S11 measurement and simulation results for the CSP antenna with the MRS technique.

In Fig. 16 to Fig.18, the radiation pattern from the simulation results and antenna measurements were presented. The CSP antenna with MRS technique provides a gain of 3.52dBi from the simulation results and a measurement result of 3.49dBi.



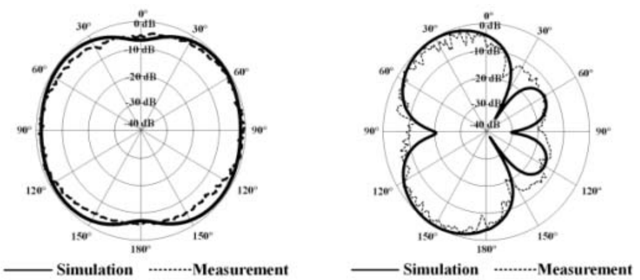
a) Horizontal plane b) Vertical plane

Fig. 16. 2D radiation pattern for the CSP antenna with the MRS technique from simulation and measurement at frequency 5.2 GHz



a) Horizontal plane b) Vertical plane

Fig. 17. 2D radiation pattern for the CSP antenna with the MRS technique from simulation and measurement at frequency 5.5 GHz



a) Horizontal plane b) Vertical plane

Fig. 18. 2D radiation pattern for the CSP antenna with the MRS technique from simulation and measurement at frequency 5.8 GHz

Table 4 shows a comparison of some antenna properties of other literature with the proposed antenna.

Table 4. Comparison to other related works

Ref.	Size (mm.)	Substrate	Frequency (GHz)	Bandwidth (GHz)	Gain (dBi)
[26]	36x35	FR4	3.45/5.9	3.3–4.2 GHz and 5.9–7.1 GHz	3.83
[27]	20x8.7	FR4	6.2	5.15–7.29	2.25
[28]	35x33	RT Duroid	5.5	5.04–6.05	7.0
This Work	59x55	PLA	5.5/6	4.5672-7.9127	3.49

According to the performance comparison in Table 4, some important characteristics of the proposed antenna are based on PLA substrate and the fabrication process with 3D printing technology is fast and cost-effective compared to basic FR4 or using expensive materials like RT Duroid. Otherwise, the antenna meets minimum gain criteria, especially bandwidth, covering a wider frequency range than other research and is suitable for use in current wireless applications such as Wi-Fi, WiFi-6E and WiMAX.

Conclusions

In this paper, a CSP antenna with the MRS technique for the ISM 5GHz and WiFi-6E 6GHz bands was studied and designed with a conductive PLA material. The main characteristics of the antenna were studied to reduce the use of antenna radiation layer materials while maintaining the antenna core characteristics. The simulation results showed that the fractional bandwidth of the proposed antenna is 5.1411GHz to 7.9261GHz, compared with the 4.5672GHz to 7.9127GHz bandwidth of the results from the prototype antenna measurement. Adopting the multi-slot technique achieves a 16.09% increase in bandwidth compared to the original shape. Otherwise, the simulation results showed that the antenna achieves a gain of 3.52dBi, but the prototype antenna measurement results are only 3.49dBi. So, from the measurement results, the antenna gain differs from the simulation results by less than 1%. For the overall size of the antenna when the multiple slotted technique was added, the multiple slotted technique can cause the material used to make the slotted to be reduced by approximately 25.76%. Finally, this study found that CSP antennas combined with the fabrication process using 3D printing technology can help improve prototype production as it is a more cost-effective and faster process than using traditional FR4 materials. From the above results, the method presented in this research can be well applied to design the antenna for modern wireless communication applications.

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***Authors**: Charinsak Saetiaw, Department of Electronics and Telecommunication Engineering. Faculty of Engineering, Rajamangala University of Technology Isan, Khon-Kean Campus, Thailand E-mail: charinsak.sa@rmuti.ac.th; Suthasinee Lamultree, Department of Electronics and Telecommunication Engineering, Faculty of Engineering, Rajamangala University of Technology Isan Khonkaen Campus, Thailand, E-mail: suthasinee.la@rmuti.ac.th; Jatuporn Nakorntep, Studying in Electrical Engineering (Master's degree), Department of Electronics and Telecommunication Engineering. Faculty of Engineering, Rajamangala University of Technology Isan, Khon-Kean Campus, Thailand E-mail: jatuporn.na@rmuti.ac.th. Suwit Phuchaduek, Studying in Electrical and Computer Engineering (Docteral's degree), Department of Electronics and Telecommunication Engineering. Faculty of Engineering, Rajamangala University of Technology Isan, Khon-Kean Campus, Thailand E-mail: suwit.pc@rmuti.ac.th.*

REFERENCES

[1] Saetiaw C., Juntakun A., Taonok C. and Phuchaduek S., "The 4G Monopole Antenna Design for Vehicular Wireless Communication," in The 12th International Conference on Science, Technology and Innovation for Sustainable Well-Being (STISWB XII), Silpakorn University, Thailand, 2020.

[2] Lamultree S., Jansri C., Phongcharoenpanich C., Design of a compact wideband circular monopole antenna for 5G applications, *Przegląd Elektrotechniczny*, 4(2021), R. 97, 9-21

[3] Lamultree, S., Srisukhot, S., Saetiaw, C., Nuangwongsa, K., & Phongcharoenpanich, C., Design of a compact wideband bi-directional pattern antenna for 5G applications. *EUREKA: Physics and Engineering*, (4), 40-51.

[4] Zahra H, Hussain M, Naqvi SI, Abbas SM, Mukhopadhyay S. A Simple Monopole Antenna with a Switchable Beam for 5G Millimeter-Wave Communication Systems. *Electronics*. (2021) 10(22):2870, 1-12.

[5] Saetiaw C. and Phuchaduek S., 3D Printed Capsule-shaped Dipole with Multi-Slot Antenna Based on Metallic Filament Material, *Przegląd Elektrotechniczny*, 8 (2021), R. 97, 48-51.
[6] Jang T. H. et al., "Wideband Wide Beam-Width Modified Angled Dipole Antenna for 5G Millimeter-Wave IoT Applications," in IEEE Access, 11(2023), 63324-63332.
[7] Taonok C., Saetiaw C., "Design of Unbalance Slot Printed Dipole Antenna with Triangle Parasitic Element for DTV Receiver," 17th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), Phuket, Thailand, June 2020, pp. 238-241.
[8] Saetiaw C., "Design of Flexible Triple-layer Folded Dipole Antenna on Curved Surface for WBAN," in 8th International Conference of Information and Communication Technology for Embedded Systems (IC-ICTES2017), Chonburi, Thailand,
[9] Saetiaw C. and Thongsopa C.. "Multilayer Strip Dipole Antenna Using Stacking Technique and Its Application for Curved Surface", *International Journal of Antennas and Propagation*, 2013 (2013), 1-10.
[10] An W, Tian X, Wang J, Wang S. Low-Profile Dual-Polarized Double-Layer Microstrip Antenna for 5G and 5G Wi-Fi. *Micromachines*. 2023;
[11] Luzon M. A. and Gerasta O. J., "Slotted Circular Polarized Rectangular Microstrip Patch Antenna with Enhanced Bandwidth for Wireless Communication in 2.45GHz," IEEE 10th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM), November 2018, pp. 1-6
[12] Saetiaw C., Lamultree S. and Phuchaduek S., "Design of Trapezoidal Patch with Multi-Slot Antenna for Wireless Communication Applications," *Przegląd Elektrotechniczny*, 3 (2023), 294-297.
[13] Saetiaw, C. "Design of Textile Capsule-Shaped Patch Antenna for WBAN Applications," *9th International Conference on Information Technology and Electrical Engineering (ICITEE),* Phuket, October 2017, pp.1-4.
[14] Shimu N. J. and Ahmed A., "Design and performance analysis of rectangular microstrip patch antenna at 2.45 GHz," 2016 5th International Conference on Informatics, Electronics and Vision (ICIEV), May 2016, pp. 1062-1066.
[15] Saetiaw C. and Phuchaduek S., "The Design and Measurement of Modified Capsules-Shaped Patch Antenna with Textile Material," Engineering Access, 7 (2021), R. 2, 126-130.
[16] Wahiba B., Miloud B. and Mohammed M. S., "Microstrip Antenna Based on Crystal Polymer Liquid (LCP) Textile for RFID Medical application.," 2nd International Conference on Advanced Electrical Engineering (ICAEE), February 2022, pp. 1-6.
[17] Balanis, C. A., Antenna Theory: Analysis and Design, 4th Ed, Wiley, 2016.
[18] Milligan, T. A., Modern antenna design, 2nd ed., John Wiley & Sons, 2005.
[19] Wen C. P., "Coplanar Waveguide: A Surface Strip Transmission Line Suitable for Nonreciprocal Gyromagnetic Device Applications," in IEEE Transactions on Microwave Theory and Techniques, vol. 17, no. 12, pp. 1087-1090.
[20] H. Huang, Y. Liu, S. Zhang and S. Gong, "Multiband Metamaterial-Loaded Monopole Antenna for WLAN/WiMAX Applications," in IEEE Antennas and Wireless Propagation Letters, 2015,vol. 14, pp. 662-665,
[21] Azim R., Alam T., Paul L. C., Aktar R., Moinul Hoque Meaze A. K. M. and Islam M. T., "Low Profile Multi-slotted Patch Antenna for Lower 5G Application," 2020 IEEE Region 10 Symposium (TENSYMP), Dhaka, Bangladesh, 2020, pp. 366-369,
[22] Sinha S., B. Rana, Ghosh C.K. and Parui S.K.,."A CPW-fed microstrip antenna for WLAN application", *Procedia Technology*, (2012)vol. 4, pp. 417-420.
[23] Bagwari A., Tiwari R. and Kushwah V. S., "CPW-Fed Micro-Strip Patch Antenna for Wireless Communication," *2020 Global Conference on Wireless and Optical Technologies (GCWOT)*, Malaga, Spain, (2020) pp. 1-5
[24] CST® Studio Suit, Academic Version, 2023
[25] Brunner H., Stocker M., Schuh M., Schu M., Boano C. A. and Romer K., "Understanding and Mitigating the Impact of Wi-Fi 6E Interference on Ultra-Wideband Communications and Ranging," 2022 21st ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN), Milano, Italy, 2022, pp. 92-104
[26] Noor, S.K.; Jusoh, M.; Sabapathy, T.; Rambe, A.H.; Vettikalladi, H.; M. Albishi, A.; Himdi, M. A Patch Antenna with Enhanced Gain and Bandwidth for Sub-6 GHz and Sub-7 GHz 5G Wireless Applications. Electronics 2023, 12, 2555.
[27] Kulkarni, J.; Sim, C. Wideband CPW-Fed Oval-Shaped Monopole Antenna for Wi-Fi 5 and Wi-Fi 6 Applications. Prog. Electromagn. Res. C 2021, 107, 173–182.
[28] Kumar, A., A. A. Althuwayb, and M. J. Al-Hasan, “Wideband triple resonance patch antenna for 5G Wi-Fi spectrum,” Progress In Electromagnetics Research Letters, Vol. 93, 89–97, 2020.