1. Charinsak SAETIAW[1], 2. Suwit PHUCHADUEK[1]

Rajamangala University of Technology Isan, Khon-Kean Campus (1)
ORCID: 1. 0000-0002-0281-9947; 2. 0000-0002-9429-5203

doi:10.15199/48.2021.08.09

3D Printed Capsule-shaped Dipole with Multi-Slot Antenna Based on Metallic Filament Material

***Abstract**. This article presents the design of a 3D printed capsule-shaped dipole with a multi-slot antenna for ISM band centered at 2.45GHz. The mixed metallic composed of filament called "Electrifi" was used as a conductive layer and Polylactic acid (PLA) filament as a support layer on the bottom side. The main objective of this research is to demonstrate the ability to design and construct capsule-shaped dipole with multi-slot antennas using conductive filament materials directly from a 3D printer. The results of the simulation showed that the proposed antenna can cover the entire ISM bandwidth at a central frequency of 2.45GHz. However, the 2D radiation pattern of the antenna is almost omni-directional on the YZ plane (x-axis). The simulation results showed that the maximum gain was 2.44dB and covered bandwidth from 2.19GHz to 2.80GHz. Finally, the measurement results showed that the impedance bandwidth of -10 dB was 2.04GHz to 2.59GHz, and the maximum gain was 2.35dB, at the frequency center was 2.45GHz, which was agree with the simulation results.*

*Streszczenie.. W artykule przedstawiono projekt drukowanego w 3D dipola w kształcie kapsuły z anteną wieloszczelinową dla pasma ISM wyśrodkowanego na 2,45 GHz. Mieszany metaliczny złożony z filamentu o nazwie „Electrifi" został użyty jako warstwa przewodząca i filament kwasu polimlekowego (PLA) jako warstwa nośna na spodniej stronie. Głównym celem tych badań jest wykazanie możliwości zaprojektowania i zbudowania dipola w kształcie kapsuły z antenami wieloszczelinowymi z wykorzystaniem przewodzących materiałów filamentowych bezpośrednio z drukarki 3D. Wyniki symulacji pokazały, że proponowana antena może pokryć całe pasmo ISM przy centralnej częstotliwości 2,45GHz. Jednak charakterystyka promieniowania 2D anteny jest prawie dookólna na płaszczyźnie YZ (oś x). Wyniki symulacji wykazały, że maksymalny zysk wyniósł 2,44 dB i obejmował pasmo od 2,19 GHz do 2,80 GHz. Ostatecznie wyniki pomiarów wykazały, że pasmo impedancji -10 dB wynosiło od 2,04 GHz do 2,59 GHz, a maksymalne wzmocnienie 2,35 dB, w centrum częstotliwości 2,45 GHz, co było zgodne z wynikami symulacji. (**Drukowany w drukarce 3D dipol w kształcie kapsułki z wieloszczelinową anteną na bazie metalicznego włókna**)*

Keywords: printed capsule-shaped dipole antenna, 3D printed antenna.
Słowa kluczowe: in the case of foreign Authors in this line the Editor inserts Polish translation of keywords.

Introduction

Nowadays, wireless communication is necessary and very important to everyday life, for both voice and data communication. In particular, an extremely important component in a wireless communication system is the antenna. Antenna designs are becoming more complex and varied to match the configuration and type of equipment to be used with the antenna. The most popular antennas used in modern wireless communication systems are monopole antennas, dipole antennas, and low-profile antennas such as micro-strip patch antenna [1-5].

However, one interesting technology that could be developed in antenna design is 3D printing technology. 3D printing technology, initially implemented in recent years with FDM (Fused Deposition Modeling) technique, is one of the most evolving techniques for rapid prototyping. In recent years, it has grown considerably as an affordable product that can be easily made available. 3D printing is extremely competitive and there are many techniques and methods of fabrication; however, the most pervasive is FDM, which consists of a important component as well as plastic filaments.

For the use of 3D printing technology developed in conjunction with the creation of electromagnetic objects, the strengths of 3D printing technology are used to create complex-structured objects and the speed of prototyping, such as a custom printed antenna for the RFID tag presented in [6,7] and a fully 3D printed antenna in [8,9]. In addition, a design with a flexible substrate was proposed in [10].

Generally, the plastic properties of all 3D printed materials are limited, and in most cases this technique is applied to non-conductive structures [11] . However, there are certain fibers with conductive properties, particularly those made from plastic with a mixture of conductive materials called "Electrifi" produced by Multi3d [12]. The produced filaments provide good conductivity enough to enable a full 3D-printed antenna prototype [13].

The main contribution of this work was to study the ability to design a capsule-shaped dipole with multi-slot antenna that was fabricated with 3D printing technology. In the design, a multi-slot technique was used to reduce the size of the antenna's conductive layer in order to reduce the use of less conductive filament materials. The designed antenna will retain the same overall antenna properties as the base antenna prior to enhancement by adding a multi-slot.

The simulation results, compared to the prototype antenna measurement produced by a 3D printer, reflected the antenna's radiation pattern, and other characteristics such as antenna gain, and bandwidth were discussed.

The paper was divided into five sections as follows. The first section is the introduction of 3D printing technology and the background of this study. The second section is the structural design along with discussion on capsule-shaped dipole antenna. Then, the effect of multi-slot was shown as a result of simulations. Then, the results of measurement from the prototype antenna were discussed. Finally, the last section is conclusion.

Antenna Design

Antennas are normally found in many different shapes and types. The most common antenna for wireless communication applications is the dipole antenna, which is fundamental to modern antenna design. The dipole antennas were first designed in the 19th century by Heinrich Hertz Rudolph [1] which are suitable in many ways. The dipole antennas generally use a thin wire conductor called wire dipole antenna. However, today they are designed to be manufactured in conjunction with other devices on printed circuit boards known as printed dipole or strip dipole antennas.

For a basic dipole antenna structure, it consists of two straight line conductors separated by a small gap. The main parameter to determine the operating frequency is the total length of the strip dipole antenna. It is typically half the wavelength obtained from the designed operating frequency. In addition, the strip width can be adjusted using a wire dipole antenna as shown in Fig. 1.

From [14] we have the relation of wire dipole diameter (a_{eq}) compared to strip dipole antenna width (w) as

$$a_{eq} = \frac{2w}{4} \tag{1}$$

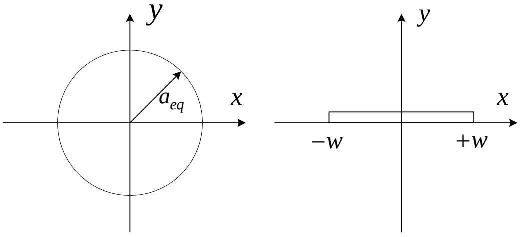


Fig. 1. Cross section diagram of wire dipole antenna converted to strip dipole antenna.

Basically, a strip width has an effect on the resonant frequency including the radiation pattern of antenna. A larger strip width increases the power radiated and also increases the bandwidth [2,14]. We can model a strip dipole antenna with required properties related to thin-wire dipole model as shown in Fig. 2.

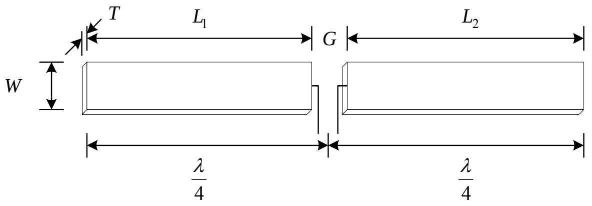


Fig. 2. Schematic of half-wave strip dipole antenna

A strip dipole can be designed for the lowest resonant frequency using transmission line model [15]. Thus,

$$\lambda = \frac{c}{f\sqrt{\varepsilon_{eff}}} \tag{2}$$

When the effective dielectric constant (ε_{eff})of a strip line was

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\sqrt{1 + \frac{12d}{w}}\right)^{-1} \tag{3}$$

Where: ε_r = dieletric constant; d = substrate thickness; W = width of strip line

Then, a gap (G) between each arm of antenna is too small compare to total length of antenna, equal to 1.2 mm. The length of each rectangular arm is about quarter-wavelength. In this case the length of each rectangular arm for strip dipole was $L_1 = L_2 = \lambda / 4$.

3D capsule-shaped dipole antenna

The capsules-shaped dipole based on basic rectangular strip dipole antenna with two halves of the circular at both ends was purposed. So, the first component that was rectangular strip dipole antenna was designed to the procedure described in [3].

To design the antenna, a conductive filament and PLA substrate were used to model an antenna using simulation software centered at 2.45GHz. So, the two halves of circular shape were added at both ends for improving bandwidth [3], as shown in Fig.3.

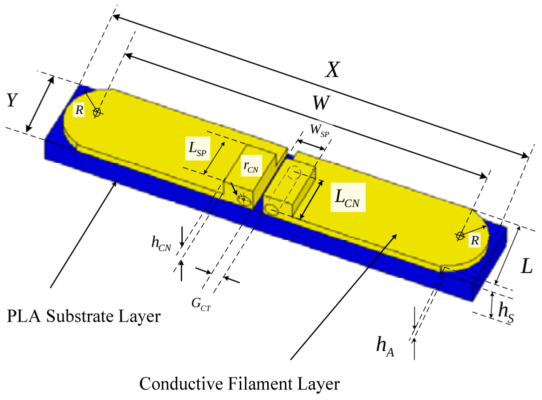


Fig. 3. 3D printed basic capsule-shaped dipole antenna model.

The PLA substrate layer was used to hold the antenna segments in place and can be directly built from a 3D printer. Additionally, thicker sections had also been added in order to install the connectors into the center of the antenna. The dimension of each parameter was shown in Table 1.

Table 1. 3D printed basic capsule-shaped dipole antenna parameters

Parameter Name	Value (millimeter(s))	Parameter Name	Value (millimeter(s))
X	50.00	Y	9.00
W	48.20	L	9.00
h_S	3.00	h_A	1.00
h_{CN}	3.00	r_{CN}	0.50
W_{SP}	4.00	L_{SP}	7.00
G_{CT}	1.20	L_{CN}	4.00
R	$L/2$		

The antenna model was simulated by simulation software [16]. According to the simulation, the designed antenna was expected to operate at the center frequency of 2.45GHz with 1.9893GHz to 3.0152GHz fractional bandwidth for 10 dB return loss as shown in Fig. 4.

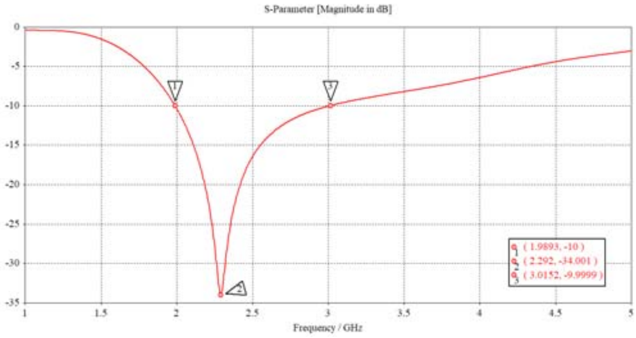
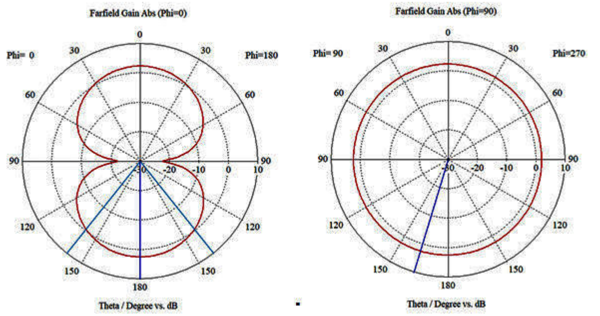


Fig. 4. S11 results for 3D printed capsule-shaped dipole

The result shown in Fig. 5 presents the simulated 2D far-field radiating patterns of the capsule-shaped dipole antenna using conductive filament at 2.45GHz. The antenna's layout was laid on XY-plane. According to the simulation, the maximum antenna gain was 2.46dB. The antenna was a directional antenna consisting half power beam-width (HPBW) equal to 77.3 degree for vertical plane.



a) vertical plan b) horizontal plan

Fig. 5 Radiation pattern of capsule-shaped patch antenna from simulation.

To optimize the characteristic of antenna and still minimize the size of the radiating layer, the multi-slot technique was implemented. The dimension of each slot can be designed using the simulation optimize process as the result of the dimension of antenna parameter as shown in Table 2.

Table 2. 3D printed capsule-shaped dipole with multi-slot antenna parameters

Parameter Name	Value (millimeter(s))	Parameter Name	Value (millimeter(s))
X	50.00	Y	9.00
W	42.50	L	9.00
h_S	3.00	h_A	1.00
h_{CN}	3.00	r_{CN}	0.50
W_{SP}	4.00	L_{SP}	7.00
G_{CT}	1.20	L_{CN}	4.00
L_{G1}	5.00	L_{G2}	4.00
W_{G1}	3.00	W_{G2}	4.00
X_{G1}	5.00	X_{G2}	10.00
R	9.00		

The total length of radiating section after being modified with multi-slot was reduced 29.26% (only length W was reduced from 48.20 mm. to 42.50 mm.) as shown in Fig.6.

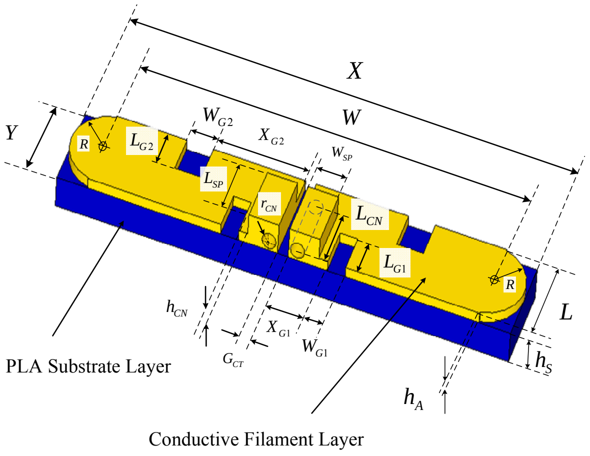


Fig. 6. 3D printed capsule-shaped dipole with multi-slot antenna model.

Another reason for adding the multi-slot was to reduce the conductive material because it was still expensive when comparing with basic conductive materials such as copper sheet or other type of conductive PLA.

Fully 3D-printed prototype antenna and measurements

To verify the design and simulation results, the prototype antennas were constructed according to the dimensions in Table 2 and the results were measured in an anechoic chamber with a Keysight E5063A network analyzer. In order to be able to print all the prototype antennas with a 3D printer, the antenna components will be exported from the designed program after the appropriate size is achieved.

The prototyping process is recognized in three stages:

1. printing the PLA substate base plate: the base parts were printed with PLA material.

2. conductive printing: The antenna radiation layer was directly printed on the top of the PLA substrate material, adding a rectangular connector's support on both arms so that the connector can be installed without requiring additional soldering.

In order to obtain good printing results, appropriate settings must be made for each material type, especially the settings used in the prototyping process as shown in Table 3.

Table 3. Printing Settings

Parameter	PLA	Conductive filament
Extruding Temperature (Celcious)	205	140
Printing Speed (mm/min.)	2600	600
Nozzle Diameter (mm.)	0.5	0.5
Extrusion Multiplier (%)	100	120

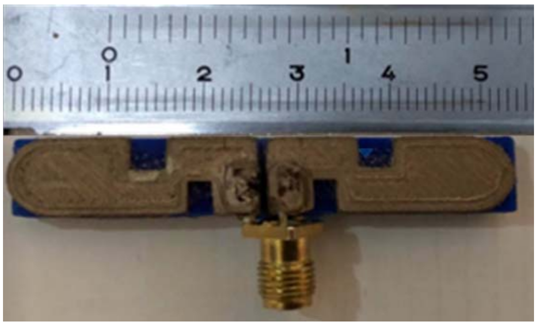


Fig. 7. 3D printed capsule-shaped dipole with multi-slot antenna prototype.

Moreover, a prototype designed to accommodate SMA connectors was fabricated for measuring an antenna properties. The completed antenna was illustrated in Fig. 7. As can be seen, the average printing temperature of the conductive filaments is lower than that of PLA as well as the print speed. Nevertheless, the two materials were bonded well together, no need to be glued. The comparison between simulated and measured |S11| was shown in Fig. 8. Apparently, both simulation and measurement results |S11| are reasonably in good agreement.

According to the simulation, the bandwidth of 3D printed capsules-shaped dipole with multi-slot antenna was 2.19GHz to 2.80GHz and from the measurement results started at 2.04GHz to 2.59GHz as shown in Fig 8. Then, the radiation pattern from the simulation and measurement of 3D printed capsules-shaped dipole with multi-slot antenna was shown in Fig. 9. From the simulation results, the antenna offered a gain of 2.44dB and the measurement result of the prototype antenna was 2.35dB on front direction.

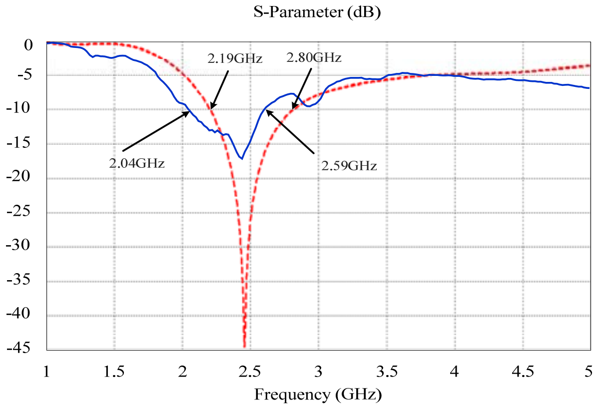
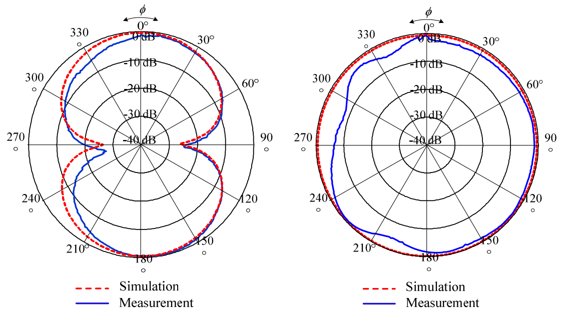


Fig. 8. S11 results for 3D printed capsule-shaped dipole with multi-slot antenna



a) Horizontal plane b) Vertical plane

Fig. 9. Radiation pattern for modified capsule-shaped patch antenna from measurement.

Conclusion

The utilization of conductive filaments in conjunction with 3D printing technology has become a promising new prototyping technique for electromagnetic applications. In this paper, the design and measurement of a 3D-printed capsule-shaped dipole with multi-slot antenna were presented. The 3D printed capsule-shaped dipole with multi-slot antenna for the 2.45 GHz ISM band was studied with conductive filament material. The designed antenna performance was simulated to reduce the overall size of the antenna radiation layer while retaining the antenna's core characteristics. The simulation results showed that the antenna bandwidth was 2.19GHz to 2.80GHz, compared to bandwidth 2.04GHz to 2.59GHz of the results from the prototype antenna measurements. However, the measurements showed that the antenna gain was lower than the simulation. Based on the simulation results, the antenna offered a gain of 2.44dB but the measurement result of the prototype antenna was 2.35dB. The study revealed that the 3D printed capsule-shaped dipole with multi-slot antenna provided the suitable antenna for applying with a wide range of communication applications because the radiated layer length was 29.26% smaller than the original size.

Acknowledgements

The authors deeply appreciate for simulation facility supported by Dr. Pichaya Chaipanya from Department of Electrical Engineering, Srinakharinwirot University. The authors also appreciate the valuable comments of the reviewers and recommends to be advantageous for revisions this paper. This research project is supported by Thailand Science Research and Innovation (TSRI). Contract No. FRB630010/0174-P7-06.

Authors*: Dr. Charinsak Saetiaw, Department of Electronics and Telecommunication Engineering. Rajamangala University of Technology Isan, Khon-Kean Campus, Muang District, Khon-Kean, 40000, Thailand E-mail: charinsak.sa@rmuti.ac.th; Mr. Suwit Phuchaduek, Studying Electrical Engineering (Master's degree), Department of Electronics and Telecommunication Engineering. Rajamangala University of Technology Isan, Khon-Kean Campus, Muang District, Khon-Kean, 40000, Thailand E-mail: suwit.pc@rmuti.ac.th.*

REFERENCES

[1] Balanis, C. A., Antenna Theory: Analysis and Design, 4th Ed, Wiley, 2016.
[2] Milligan, T. A., Modern antenna design, 2nd ed., John Wiley & Sons, 2005.
[3] 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, 1-4
[4] Garbaruk M., Mieczynska M., Design and characteristics of dual-band antenna with parasitic elements for Wi-Fi applications, Przegląd Elektrotechniczny, 12 (2017), R. 93, 6-9.
[5] 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, 238-241.
[6] Colella R., Catarinucci L., "Wearable UHF RFID Sensor-Tag based on Customized 3D-Printed Antenna Substrates," IEEE Sensors Journal, vol. 18, no. 21 ,8789-8795.
[7] Jankowski Mihułowicz P., Tomaszewski G., Węglarski M., Flexible antenna design for semi-passive HF RFID transponder in ink-jet technology, Przegląd Elektrotechniczny (Electrical Review), NR4/2015, 1-5.
[8] Xia Z., Leung K. W. and Lu K., "3-D-Printed Wideband Multi-Ring Dielectric Resonator Antenna," in *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 10, 2110-2114, October. 2019.
[9] Jun S.Y., Elibiary A., Sanz-Izquierdo B., Winchester L., Bird D. and McCleland A., "3-D Printing of Conformal Antennas for Diversity Wrist Worn Applications,"in *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 8, no. 12, 2227-2235, December 2018.
[10] Moscato S. *et al.*, "Infill-Dependent 3-D-Printed Material Based on NinjaFlex Filament for Antenna Applications," in *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 1506-1509, 2016.
[11] Pizarro F., Salazar R., Rajo-Iglesias E., Rodríguez M., Fingerhuth S. and Hermosilla G., "Parametric Study of 3D Additive Printing Parameters Using Conductive Filaments on Microwave Topologies," in *IEEE Access*, vol.7, 106814-106823, 2019.
[12] Multi3Dllc, "Electrifi"" info page.
[13] Roy S., Qureshi M. B., Asif S. and Braaten B. D., "A model for 3D-printed microstrip transmission lines using conductive electrifi filament," *2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*, San Diego, CA, 2017, 1099-1100.
[14] Saetiaw C. and Thongsopa C.. "Multilayer Strip Dipole Antenna Using Stacking Technique and Its Application for Curved Surface "International Journal of Antennas and Propagation, vol.2013, 1-10.
[15] Jamaluddin M. H., M. Rahim K. A., Aziz M. Z. A. A. and Asrokin A., "Microstrip dipole antenna for WLAN application," 2005 1st International Conference on Computers, Communications, & Signal Processing with Special Track on Biomedical Engineering, Kuala Lumpur, Malaysia, 2005, 30-33.
[16] CST® Microwave Studio, Research Base, 2016