STM JOURNALS
Journal of
Microwave Engineering & Technologies
ISSN: 2349-9001
Volume 12, Issue 1, 2025
January–April
DOI (Journal): 10.37591/JoMET
https://journals.stmjournals.com/jomet
Review
JoMET

A Novel Approach for Design and Optimization of Slot Antenna for WLAN Applications

L. Sarika[1,]*, B. Bhuvaneswari[2], D. Mani Kumari[2], M.V.R. Hari Priya[2], G. Yuva Teja Sree[2]

Abstract

The simulation and analysis of a micro-strip fed slot antenna array intended for operation in the 2.4 GHz ISM (Industrial, Scientific, and Medical) band, which is widely used for wireless technologies such as Wi-Fi and Bluetooth. A slot antenna is a type of antenna where a slot (cut or gap) is made on a metal surface, and it radiates electromagnetic waves. Utilizing ANSOFT HFSS software, the antenna's performance is optimized, achieving a half-power beam width (HPBW) of 57°, bandwidth of 7.7%, and directivity of 2.01 db. Antenna characteristics are determined using standard methods, and far-field radiation patterns, return loss, and voltage standing wave ratio (VSWR) are examined using HFSS simulations. The High-Frequency Structure Simulator, or HFSS, is a popular simulation tool for antenna design and optimisation. It explains how effective antenna designs are developed for ISM band applications. The expansion of wireless communication systems, especially for Wireless Local Area Network (WLAN) applications, has increased demand for small, high-performing antennas. This work offers a new method for creating and refining slot antennas that are compact, have a large bandwidth, and are very efficient. To improve performance metrics including return loss, gain, and radiation pattern, the slot shape and feed mechanisms were adjusted using sophisticated optimisation techniques like Genetic Algorithms (GA) and Particle Swarm Optimisation (PSO). The efficiency of the suggested design is confirmed by simulation results, which show a notable increase in bandwidth and a smaller physical footprint when compared to conventional slot antennas. For next-generation WLAN systems that need powerful yet compact antennas, this work is essential.

Keywords: Microstrip-fed slot antenna, antenna array, industrial, scientific, medical (ISM) band, Ansoft HFSS, Half-power beamwidth (HPBW), voltage standing wave ratio (VSWR), electromagnetic simulation

INTRODUCTION

Since power can move in both ways, an antenna is essentially a bidirectional device. It couples electromagnetic energy from the transmitter to free space and vice versa, functioning as both transmitting and receiving device, in accordance with the principle of reciprocity. Transmission lines enable guided wave propagation, which is the movement of electromagnetic energy from one location in a circuit to another. Here, an antenna transforms a guided wave field distributed into an emitted wave field distributions by acting as a mode transformer. A slot antenna is constructed from a metal surface, typically a flat plate, with a slot or hole cut into it. When energized at a specific frequency, the slot radiates electromagnetic waves in a manner similar to that of a dipole antenna. The radiation pattern is greatly influenced by the driving frequency, slot dimensions, and shape. The main

***Author for Correspondence**
L. Sarika
E-mail: sarikamaha@gvpcew.ac.in

[1]Assistant Professor, Department of Electronics and Communication Engineering, Gayatri Vidya Parishad College of Engineering for Women, Visakhapatnam, Andhra Pradesh, India
[2]Student, Department of Electronics and Communication Engineering, Gayatri Vidya Parishad College of Engineering for Women, Visakhapatnam, Andhra Pradesh, India

Received Date: December 21, 2024
Accepted Date: December 30, 2024
Published Date: January 09, 2025

Citation: L. Sarika, B. Bhuvaneswari, D. Mani Kumari, M.V.R. Hari Priya, G. Yuva Teja Sree. A Novel Approach for Design and Optimization of Slot Antenna for WLAN Applications. Journal of Microwave Engineering & Technologies. 2025; 12(1): 1–12p.

advantages of slot antennas include their compact size, design simplicity, and robustness. They are mechanically durable when mounted on rigid surfaces and are compatible with monolithic microwave integrated circuit (MMIC) designs. Additionally, printed circuit board (PCB) technologies makes it simple to modify slot antennas for mass-production purposes.

These antennas' distinctive characteristics include omnidirectional gain around the azimuth and horizontal polarisation. In a conventional microstrip line-fed slot antenna, a narrow rectangular slot is cut into the ground plane, and the slot is excited by a microstrip feed line with either a short or open termination. This feed configuration achieves a good impedance match with the narrow slot, resulting in a bandwidth of approximately 7.7%. Nevertheless, even if the slot is wider, the electromagnetic resistance of the slot antenna increases as well proportionately, which lowers the impedance bandwidth. To increase the bandwidth of a wide slot antenna, one can terminate the open end of the feed line within the width of the slot. However, significant improvements in bandwidth may not be realized with this method.

Conventional feeding structures for transverse slot antennas include centre feeding and offset feeding. The centre feed configuration generally has a higher radiation impedance compared to the offset feed. Consequently, the bandwidth of a centre-fed antenna tends to be narrower than that of an offset-fed antenna.

LITERATURE SURVEY

The literature on slot antennas reveals significant advancements and diverse applications across various studies. Ochieng focused on a 2.4 GHz slot antenna array, demonstrating its efficiency and suitability for wireless communication [1]. Kim and Ahn introduced a small dual-band slot antenna utilizing capacitor loading, effectively enhancing bandwidth while maintaining a compact design, which is particularly relevant for dual-frequency applications [2]. Kulkarni and Kasabegoudar explored bandwidth enhancement in a compact circular slot antenna for Ultra-Wideband (UWB) applications, showing that geometric modifications can significantly improve performance [3]. Parvathy and Thomaskutty examined a printed tree fractal-based cross slot antenna at 2.45 GHz, highlighting the advantages of fractal geometries in achieving miniaturization and improved efficiency [4]. Kuma and Shanmuganantham presented a clover slot antenna designed for biomedical applications, demonstrating its effectiveness for medical telemetry [5], while Fernandez *et al.* investigated a wearable slot antenna operating at 2.45 GHz, analysing off-body radiation efficiency and the impact of body absorption on performance [6]. Collectively, these studies underscore the ongoing innovation in slot antenna design, focusing on enhancing performance, bandwidth, and applicability in fields such as wireless communication and biomedical engineering.

DESIGN METHODOLOGY

A rectangular slot is selected as the foundation of the design due to its ease of fabrication and straightforward analysis. The microstrip line is employed as the feeding method because it is simple to fabricate, allows for easy impedance matching by adjusting the inset feed position, and is relatively easy to model. The antenna is specifically designed to operate within the 2.4 GHz ISM band, which encompasses a frequency range of 2.5 to 2.6 GHz, with a centre frequency of 2.58 GHz and a bandwidth of 100 MHz [7].

Design Procedure

The Flame Retardant (FR4) Glass Epoxy substrate, with a loss tangent of 0.002, is selected as the dielectric material. The resonant frequency, substrate elevation and substrate dielectric constant are the three main parameters that are defined for the design procedure. $h.\varepsilon_r=4.3, f_r=2.4$ GHz, $h=1.6$ mm. The practical width for an effective radiator that produces high radiation efficiency is:

$$W=0.1\,\lambda_g=7\text{ mm}, \tag{1}$$

Where, λ_g is the dielectric wavelength.

$$\varepsilon_{reff}=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-\frac{1}{2}}=3.27$$

The input impedance of the slot antennae must be equal to the intrinsic impedance of the line that is being transmitted in order for power transfer from the transmission line to the slot antennae to be effective [8]. Observations show that the impedance of a transmission line attached to the radiating edge increases as one moves towards the centre of the slot. Based on the transmission line's characteristic impedance, the feed point is chosen at an offset from the slot centre to achieve optimal impedance matching. This off-centre feed distance is calculated based on the desired impedance match.

Ground Plane

For the slot antenna design, the ground plane is ideally infinite in size to maximize performance. However, in practical applications, an infinite ground plane is challenging to implement, and a smaller ground plane is often preferred. Studies indicate that when the ground plane width is greater than length, the microstrip impedance closely approximates the impedance with an infinite-width ground plane [9]. Thus, the ground plane size for this design is chosen to be 100 mm in length and 97.5 mm in width.

Microstrip Discontinuities

Surface waves are electromagnetic waves that propagate along the dielectric interface layer of the microstrip. The two main modes of these waves are transverse magnetic (TM) and transverse electric (TE). Surface waves tend to occur at any discontinuity within the microstrip, where they travel and radiate, often coupling with other microstrips in the circuit [10]. This results in reduced isolation between networks and increased signal attenuation. In multimicrostrip circuits, surface waves are a source of crosstalk, coupling, and attenuation, making them an undesirable phenomenon.

Discontinuities in a microstrip arise from abrupt changes in the strip conductor's geometry, which modify the electric and magnetic field distributions near these points. This alteration in the electric field distribution increases capacitance, while changes in the magnetic field distribution affect inductance.

Microstrip Feed and Distance Between Elements

The feed connection needs to be carefully planned to establish an even number of in-phase slot components in the two-element array, as depicted in Figure 1. The distance from the 50 Ω Sub-Miniature version A (SMA) source to each slot element should be identical or in multiples of the wavelength (λ). Unequal line lengths would cause phase shifts, resulting in fixed beams that are angled away from the broadside. The 50 Ω microstrip line is fed using a 50 Ω SMA connector.

For effective in-phase radiation, the distance between slot elements needs to be optimized to achieve peak gain. A separation distance of λ/2 has been determined to provide optimal gain, which in this design corresponds to 35 mm. This distance was implemented to ensure the highest possible performance for the array in terms of gain and beam direction.

Matching Microstrip Lines to Source

The characteristic impedance of a transmission line of the micro-strip feed was designed with respect to the source impedance. The characteristic impedance of the transmission line from the source with respect to the source impedance was:

Z0=Zs, Z0=50 Ω.

Quarter-Wave Transformer

Regarding the input susceptibility of a transmission line of length L that is attached to a load with impedance ZA and has a characteristic impedance Z0:

$$Z_{in}(-L) = Z_o \left[\frac{Z_A + jZ_o \tan(\beta L)}{Z_O + jZ_A \tan(\beta L)}\right]$$

when the transformer's maximum length is a quarter wavelength length. Therefore, the 50 Ω inset feed line is matched to where Z0= characteristic impedance of the quarter wavelength transformer by employing a transmission line with a characteristic impedance of 50 Ω [11]. This ensured that no power would be reflected back to the SMA feed point as it tried to delivers power to the antenna. The quarter wavelength transformer's length is computed as

$$Z_{in}\left(L = \frac{\lambda}{4}\right) = \frac{Z_0^2}{Z_A}$$

$$Z_0 = \sqrt{50 \cdot 50 = 50\, ohms}$$

$$L = \frac{\lambda_g}{4} = 17.5\, mm$$

SIMULATION

The antenna array design is carried out using Ansoft HFSS 13.0, a 3D full-wave electromagnetic field simulator. The Finite Element Method (FEM), a numerical approach that breaks down a large structure into smaller subunits known as finite elements, is utilised by HFSS. In HFSS, these finite elements are represented by tetrahedral shapes, collectively forming a mesh.

Both near-field and far-field patterns of radiation can be computed and visualised by HFSS using this approach. It also computes critical antenna parameters, such as gain, radiation efficiency, and directivity. The software’s parametric tools allow for precise adjustments of structural dimensions, such as slot sizes, enabling the optimization of antenna performance characteristics like impedance matching and bandwidth. HFSS provides a comprehensive platform to model, simulate, and optimize antenna designs, ensuring they meet desired specifications in real-world applications. The antenna array design is carried out using Ansoft HFSS 13.0, a 3D full-wave electromagnetic field simulator. The Finite Element Method (FEM), a numerical approach that breaks down a large structure into smaller subunits known as finite elements, is utilised by HFSS. In HFSS, these finite elements are represented by tetrahedral shapes, collectively forming a mesh. HFSS provides a comprehensive platform to model, simulate, and optimize antenna designs, ensuring they meet desired specifications in real-world applications.

RESULTS

VSWR Plot

For the purpose of transmission lines, which are electrical cables that carry radio frequencies and are used to connect radio transmitters and receivers with their antennas, VSWR is an estimate of efficiency that ranges from 1 to 2 (Figure 1).

Smith Chart

The smith chart is a graphical representation of the normalized characteristic impedance. It provides the information about the impedance match of the radiating slot. The smith chart for the designed slot antenna array shown in Figure 2, shows an input impedance of 50.78+10.5i Ω at resonant frequency 2.58 GHz. The magnitude of the input impedance is 51.85 Ω which showed that accurate matching is not achieved. This is due to shifting of the inset feed position away from the edge of the ground plane.

Reflection Coefficient and Bandwidth

The suggested antenna's reflection coefficient (S11) is displayed in dB in Figure 3. The coefficient of reflection at the inset feed point, where the micro-strip slot antenna's input is applied, is provided by S11. Less than –10 dB is required for a suitable operation. It shows that the proposed antenna had a frequency of resonance of 2.58 GHz. The simulated impedance bandwidth of about 200 MHz (2.5022–2.7023 GHz) is achieved at −10 dB reflection coefficient (VSWR≤2). At this resonant frequency, a reflection coefficient value of –15.33 dB was obtained. This reflection coefficient value indicated that the frequency point below the –10 dB zone has satisfactory matching.

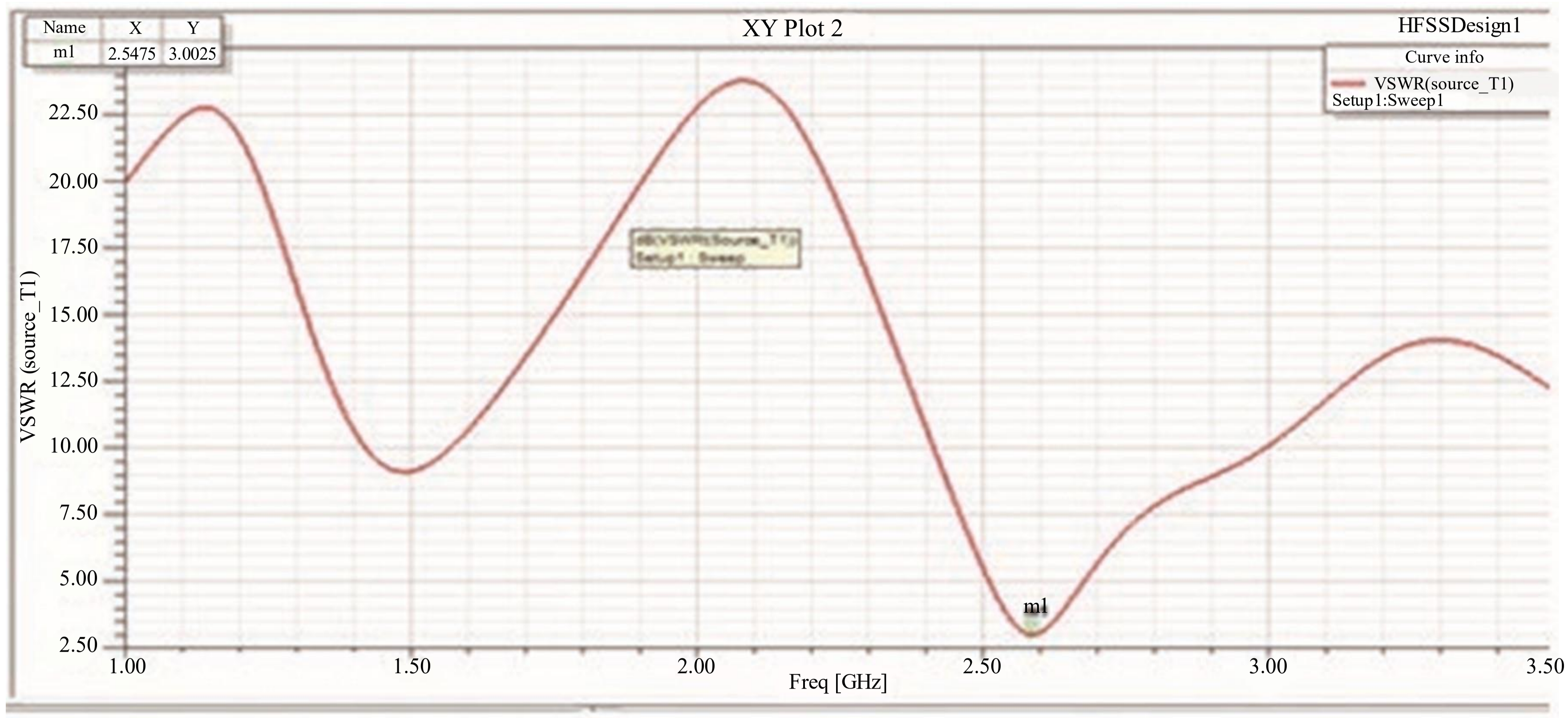
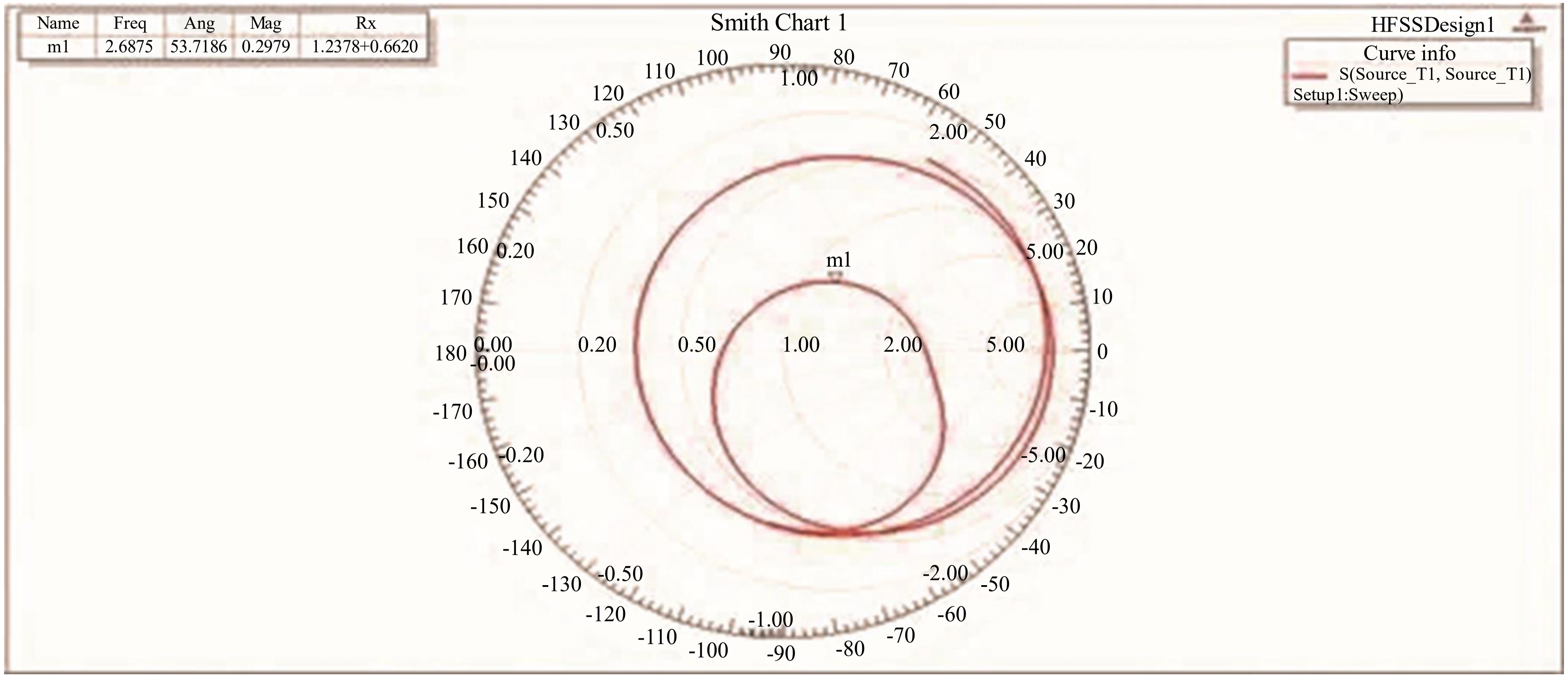


Figure 1. Shows the VSWR plot.



Name	Freq	Ang	Mag	Rx
m1	2.6875	53.7186	0.2979	1.2378+0.6620

Figure 2. Smith Chart for the slot antenna array.

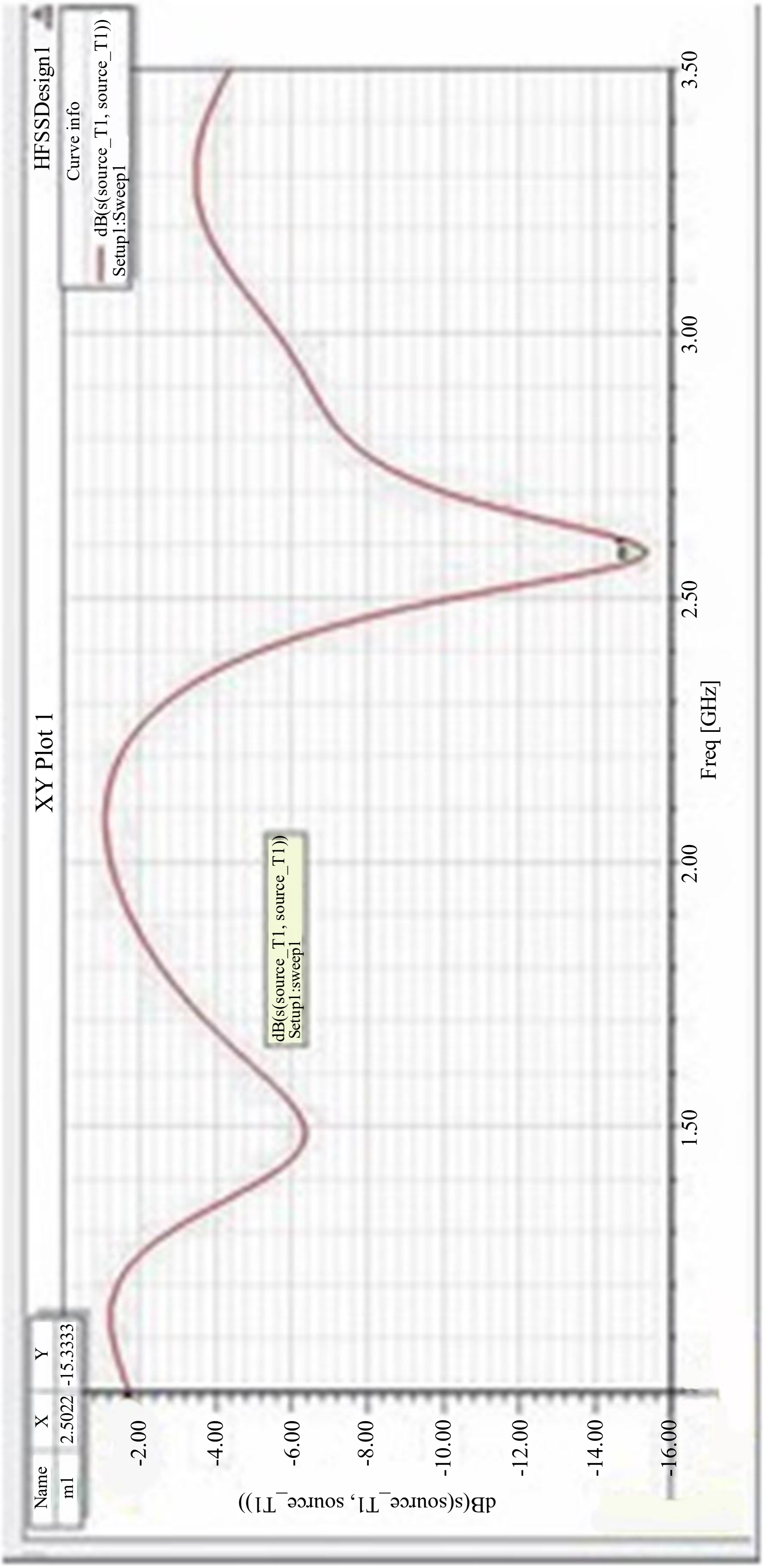


Figure 3. Return loss S11 obtained for the slot antenna.

Table 1. Simulation result slot antenna by adjusting width.

Width, mm	Resonance frequency (GHz)	Return loss S11 (dB)	Bandwidth (MHz)
5.0	2.71	–10.5	165
5.5	2.68	–14.9	173
6.0	2.64	–25.5	188
6.5	2.62	–18.74	195
7.0	2.58	–15.33	200

Variation of Slot Length and Width

The dimensions calculated during the design process are utilized to create a two-element slot antenna array. To shift the S11 minima towards the desired centre frequency, the length and width of the slot are varied. At the target frequency of 2.58 GHz, the width of the slot antenna is adjusted through five values, ranging from 5.0 to 7.0 mm in increments of 0.5 mm, while the length is fine-tuned to achieve impedance matching. Simulation results for return loss (S11), resonance frequency, and bandwidth are presented in Table 1. These results indicate that changes in the width of the slot antenna directly impact the resonance frequency.

Radiation Pattern

The radiation characteristics in the E-plane, $\Phi=0^\circ$ and $\Phi=90^\circ$, respectively. Figure 4 shows the radiation pattern of the E-total at 2.58 GHz yz plane ($\Phi=90^\circ$).

Other Antenna Parameters

An overview of the antenna characteristics from the HFSS program is displayed in Figure 5. The directivity and efficiency are 2.0109. The front to back ratio is 1.2224. Figure 6 shows E-plane and H-plane from which the antenna has two main lobes which were 180° out of phase with each other. Determine the half-power beam widths for the radiation patterns as the peaks and 3 dB points below them could easily be picked.

APPLICATIONS OF SLOT ANTENNA

The design, simulation, and analysis of a compact microstrip-fed slot antenna, specifically for WLAN (Wireless Local Area Network) applications. The proposed antenna is a microstrip-fed slot antenna. A slot is cut in the ground plane, and a microstrip feedline is used to excite the slot, allowing electromagnetic radiation. The design of the slot and its feeding mechanism are crucial for determining the antenna’s operating frequency, bandwidth, and radiation characteristics. The shape and placement of the slot, along with the position of the feedline, are optimized to achieve resonance at 5.8 GHz. One important element influencing the antenna's performance is the substrate material chosen for the design. Although this study does not elaborate on multiple substrates, the substrate material is chosen to ensure a good balance between performance and manufacturability for WLAN applications. The resonant frequency, connectivity, and radiation effectiveness are all significantly influenced by the substrate's thickness and dielectric constant (εr).

The dimensions of the antenna are derived from mathematical formulas based on the operating frequency (5.8 GHz) and the properties of the substrate material. The slot’s width, length, and the feedline’s position are all optimized to achieve minimal return loss and efficient radiation at the target frequency.

Return Loss (S11) Curves

The simulation results demonstrate that the antenna resonates at 5.8 GHz with a return loss below –10 dB, indicating good impedance matching. This ensures minimal power reflection and maximum power transfer from the feedline to the radiating slot.

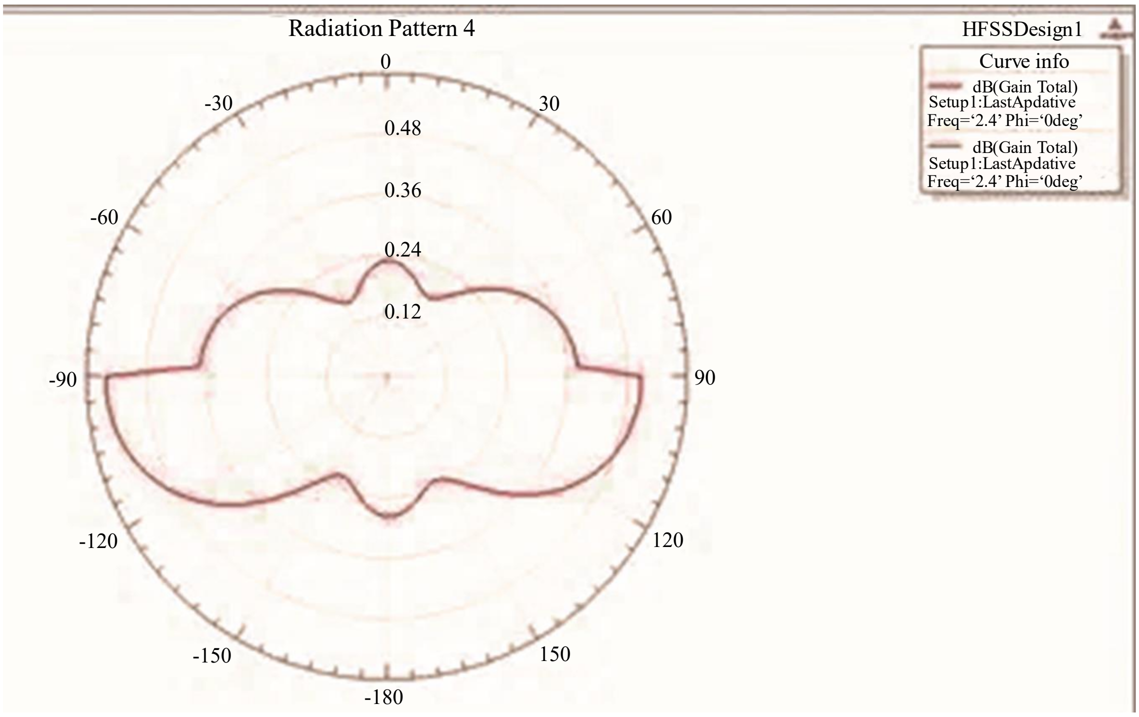
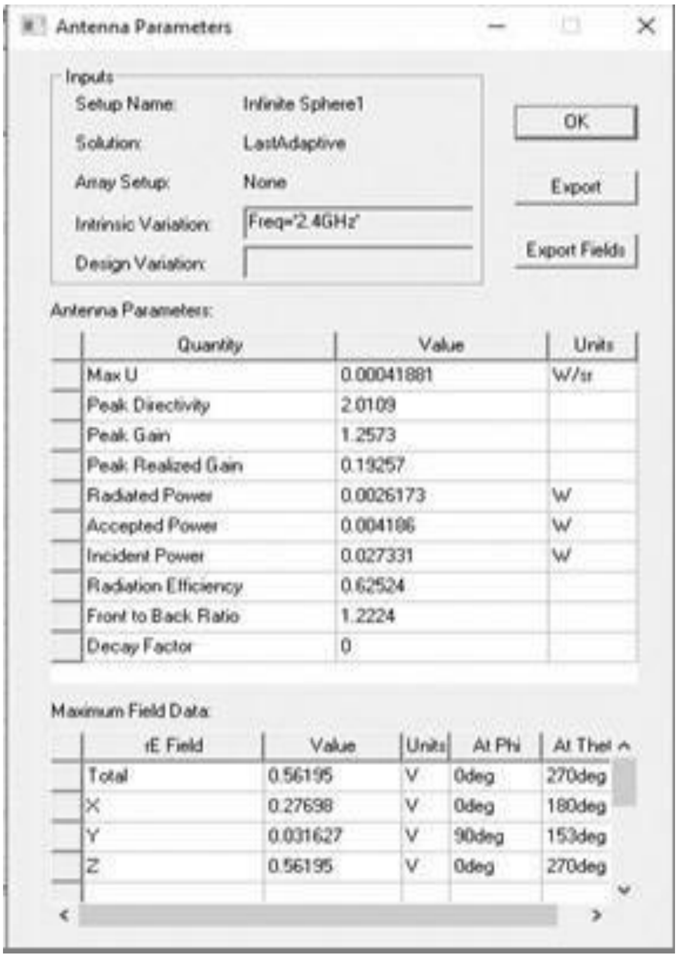


Figure 4. Radiation pattern of E-total at 2.58 GHz yz plane (Φ=90°).



Inputs
Setup Name: Infinite Sphere1
Solution: LastAdaptive
Array Setup: None
Intrinsic Variation: Freq='2.4GHz'
Design Variation:

Antenna Parameters:

Quantity	Value	Units
Max U	0.00041881	W/sr
Peak Directivity	2.0109	
Peak Gain	1.2573	
Peak Realized Gain	0.19257	
Radiated Power	0.0026173	W
Accepted Power	0.004186	W
Incident Power	0.027331	W
Radiation Efficiency	0.62524	
Front to Back Ratio	1.2224	
Decay Factor	0	

Maximum Field Data:

rE Field	Value	Units	At Phi	At Thet
Total	0.56195	V	0deg	270deg
X	0.27698	V	0deg	180deg
Y	0.031627	V	90deg	153deg
Z	0.56195	V	0deg	270deg

Figure 5. Summary of antenna parameters.

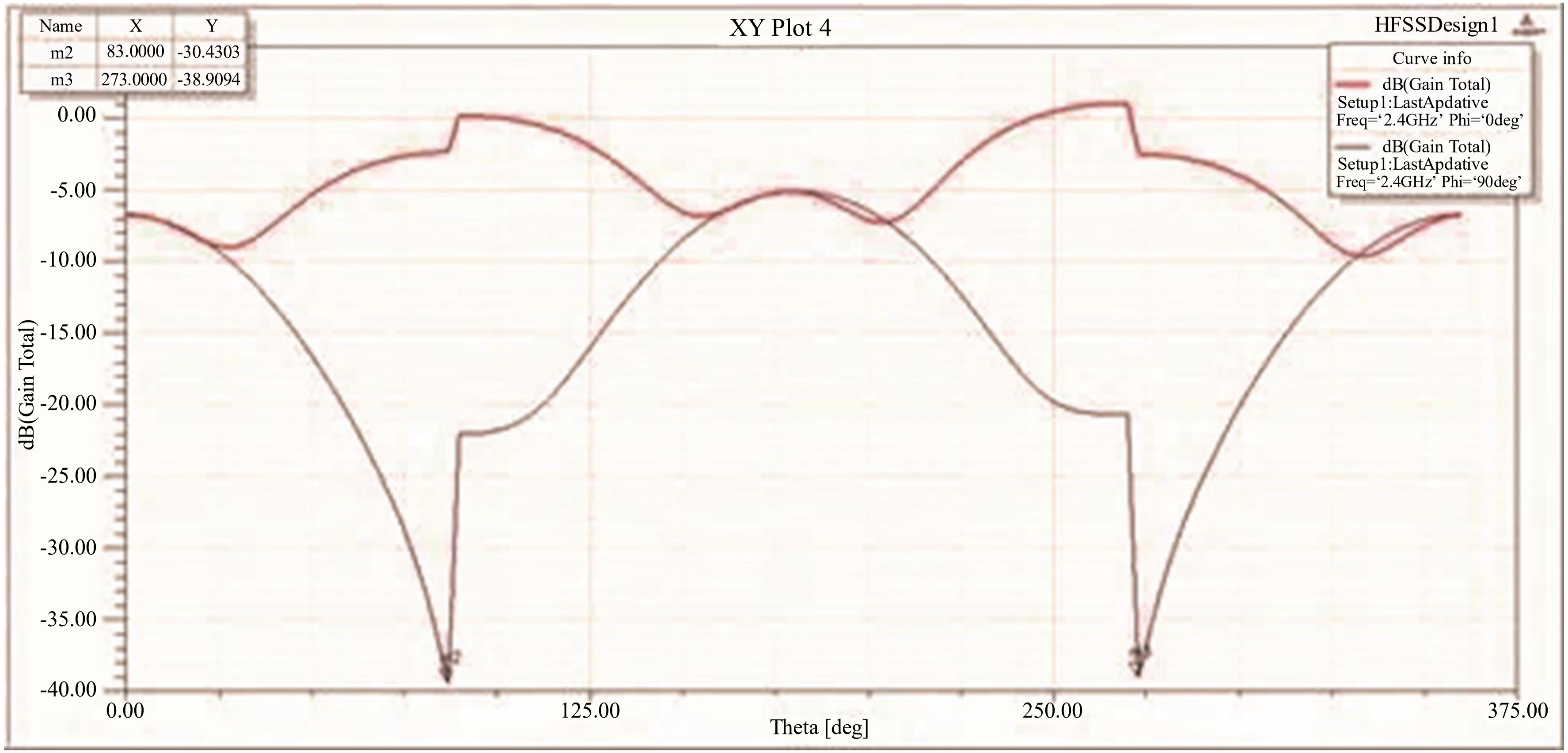


Figure 6. E-Plane and H-Plane patterns in rectangular coordinates.

Radiation Patterns

The radiation pattern is omnidirectional in the H-plane, which is essential for WLAN applications as it allows for consistent communication in all directions. The antenna's E-plane radiation pattern exhibits moderate directivity, which can help focus the signal towards the receiver, improving link quality.

Gain and Efficiency

The antenna's gain is calculated to be adequate for shortrange WLAN applications at 5.8 GHz. The efficiency of the antenna is also analysed, ensuring that most of the input power is radiated, with minimal losses due to reflection or absorption by the substrate material.

Optical Performance

The results highlight that the design successfully covers the 5.725–5.825 GHz frequency band, making it ideal for 5.8 GHz WLAN applications. The antenna's compact size and low return loss make it suitable for integration into modern wireless devices.

Substrate and Feeding

The choice of substrate and the feeding method (microstrip feedline) are critical in achieving the desired performance. The microstrip-fed slot antenna provides a balance between performance, size, and ease of integration into devices like routers or access points as shown in Figure 7. Comparison between slot antenna of 2.4 and 5.8 GHz has been shown in Table 2.

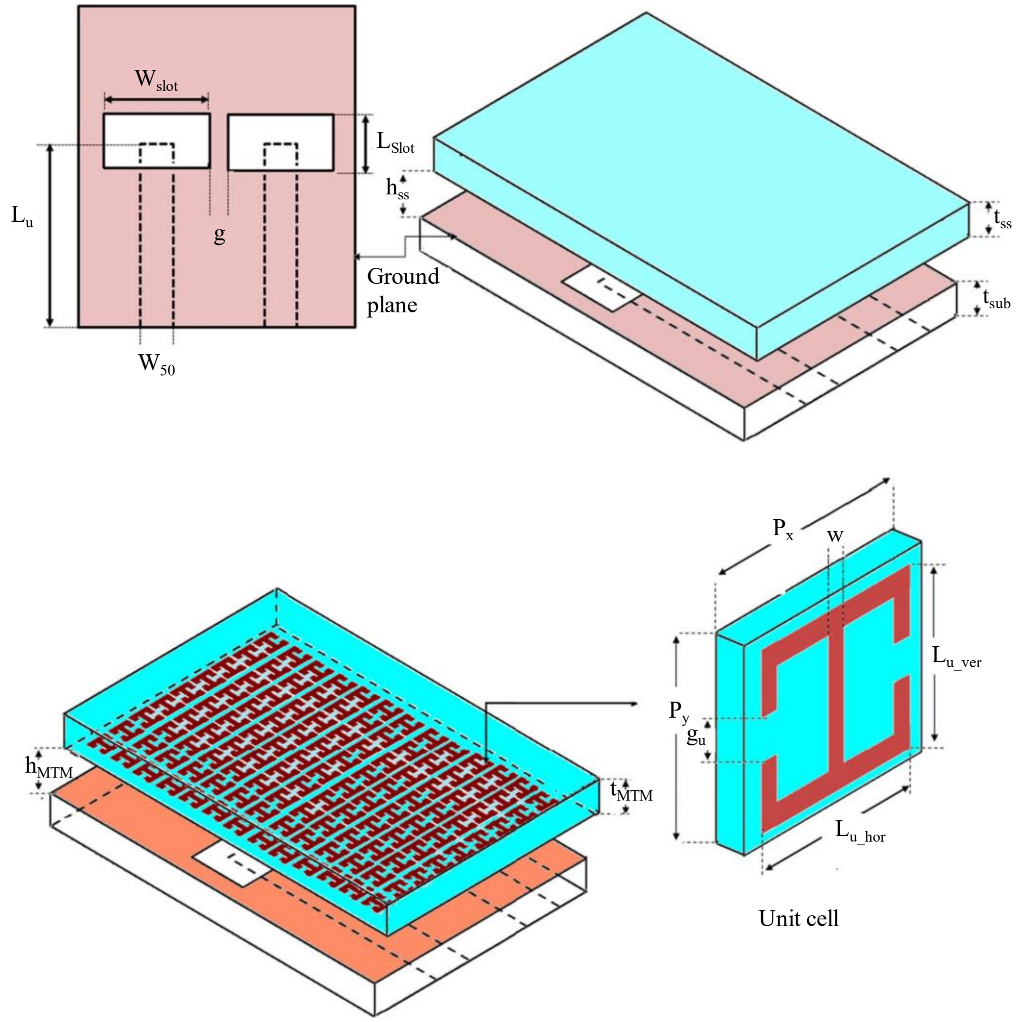


Figure 7. Microstrip Feedline Slot antenna.

Table 2. Comparison between slot antenna of 2.4 and 5.8 GHz.

Parameters	Slot antenna	Slot antenna for WLAN
1. Frequency	2.4 GHz	5.8 GHz
2. Antenna dimensions	L=35 mm, W=7 mm	L=18 mm, W=2 mm
3. Ground plane size	100 mm×97.5 mm	24 mm×30 mm
4. Bandwidth	7.7%	12.5%
5. Gain	1.25 dBi	4.2 dBi
6. Directivity	2.01 dB	6.1 dB
7. Efficiency	62.5%	80%

CONCLUSION

Both antennas demonstrate efficient slot antenna designs for wireless communication. Continued research and development on antennas will enable improved performance, miniaturization, and integration into emerging wireless technologies. Microstrip fed slot antenna for WLAN shows significant improvements in size reduction, bandwidth, gain, and radiation efficiency.

Future Scope

Slot antenna designs holds significant potential to enhance wireless communication systems. Further development will focus on achieving greater miniaturization, which is crucial for seamless integration into compact devices across IoT, mobile, and wearable technologies. Advancements in microstrip-fed slot antennas, especially for WLAN, promise further improvements in size reduction, bandwidth, gain, and radiation efficiency, making them ideal for next-generation networks. Moreover, optimizing materials and feed configurations will enhance durability and performance across various frequencies, including the ISM and emerging 5G bands. Overall, continued innovation in slot antenna technology will support the evolving demands of high-speed, efficient wireless communication in modern applications.

REFERENCES

1. Ochieng E. A 2.4 GHz slot antenna array. Graduation Project. Kenya: University of Nairobi; 2016.
2. Kim JH, Ahn CH. Small dual-band slot antenna using capacitor loading. Microw Opt Technol Lett. 2017 Sep; 59(9): 2126–31.
3. Kulkarni SP, Kasabegoudar VG. Bandwidth enhancement of compact circular slot antenna for UWB applications. Glob J Res Eng. 2017;17(1):26–31.
4. Parvathy A, Thomaskutty M. A printed tree fractal based cross slot antenna for 2.45 GHz. Procedia Comput Sci. 2017; 115: 80–86.
5. Kuma S, Shanmuganantham T. Design of clover slot antenna for biomedical applications. Alex Eng J. 2017; 56(3): 313–317.
6. Fernandez M, Espinosa H, Thiel D, Arrinda A. Wearable slot antenna at 2.45GHz for off-body radiation: Analysis of efficiency, frequency shift, and body absorption. Bioelectromagnetics. 2018; 39(1): 25–34.
7. Permana CG, Munir A. Printed multiband antenna for mobile and wireless communications. In 2011 IEEE 6th International Conference on Telecommunication Systems, Services, and Applications (TSSA). 2011 Oct 20; 236–240.
8. Korowajczuk L, editor. LTE, WiMAX and WLAN Network Design, Optimization and Performance Analysis. New Jersey, United States: John Wiley & Sons; 2011.
9. Ihsan RR, Munir A. Utilization of artificial magnetic conductor for bandwidth enhancement of square patch antenna. In 2012 IEEE 7th International Conference on Telecommunication Systems, Services, and Applications (TSSA). 2012 Oct 30; 192–195.
10. Cheng YJ. Substrate integrated antenna conformal to 3D-printing cone. In 2016 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP). 2016 Jul 20; 1–4.
11. Izzuddin A, Dewantari A, Setijadi E, Palantei E, Rahardjo ET, Munir A. Design of 2.4 GHz Slotted SIW Array Antenna for WLAN Application. 2020 International Conference on Radar, Antenna, Microwave, Electronics, and Telecommunications (ICRAMET), Tangerang, Indonesia. 2020; 70–73. doi: 10.1109/ICRAMET51080.2020.9298646.