Journal of Engineering and Technological Sciences

Research Paper

Bandwidth and Gain Enhancement of Microstrip Leaky-Wave Antennas with Slot and Defected Ground Structure

Fitri Yuli Zulkifli & Muhamad Wahyu Iqbal*

Departement Electrical Engineering, Universitas Indonesia, Kampus Baru UI Depok 16424, Indonesia

Corresponding author: muhamad.wahyu@ui.ac.id

Abstract

This paper discusses the design, simulation, and realization of a leaky-wave microstrip antenna with multiple slots and defected ground structure (DGS). The leaky-wave microstrip antenna with multiple slots and DGS was designed to operate at 5.925-6,425 GHz for wireless local area network applications (WLANs), with a gain of ≥4dBi. The antenna uses FR-4 epoxy as the substrate with a dielectric constant of 4.6 and a thickness of 1.6 mm. The leaky-wave microstrip antenna has dimensions of 45.1 mm × 24.8 mm × 1.6 mm, while the leaky-wave microstrip antenna with multiple slots and DGS has dimensions of 40.6 mm × 25 mm × 1.6 mm. The simulation results showed that adding multiple slots and DGS to the leaky-wave microstrip antenna increased the bandwidth from 280 MHz (5.859–6.139 GHz) to 691 MHz (5.854–6.545 GHz) while the gain increased from 4.47 to 5.04 dBi. Meanwhile, the measurement results showed that the bandwidth parameter increased from 273 MHz (5.877–6.150 GHz) to 684 MHz (5.845–6.529 GHz) and the gain parameter from 4.53 to 5.06 dBi at 6 GHz.

Keywords: *defected ground structure; double u-slot; e-slot; leaky-wave antenna; leaky-wave microstrip antenna.*

Introduction

Wireless local area network (WLAN) technology is evolving rapidly. One of the WLAN technologies is Wi-Fi. According to a 2018 CISCO report, Wi-Fi technology has reached 169 million hotspots and is expected to reach 628 million hotspots by 2023 [1]. Wi-Fi technology has considerable economic value. It was $2 trillion in 2018 and is expected to be worth $3.5 trillion by 2023 [2]. It contributes to global IP traffic, accounting for 43% of global IP traffic in 2017, which is expected to increase to 51% by 2022 [3]. It has been widely used to aid daily activities especially during the pandemic, such as improving connectivity, high-quality video streaming, virtual reality devices, and connectivity between modern household equipment. Examples of Wi-Fi technology for daily activities are wireless connectivity for video meeting applications, game consoles and mobile phones, remote office cloud computing, and home automation. It must have high reliability, high throughput, and low latency because the use of Wi-Fi continues to grow and become more popular, as it is increasingly required [2,4-7]. Wi-Fi technology based on the IEEE 802.11 standard has the following parameters: bandwidths of 40, 80, 160, and 320 MHz, an impedance of 50 Ω, a gain of ≥4 dBi, and operating frequencies of 2.4 GHz, 5 GHz (5.725–5.859 GHz), and 6 GHz (5.925–6.425, 5.940–6.425, 6.425–6.525, 6.525–6.875, and 6.875–7.125 GHz) [8-10].

The antenna is one of the technological devices used to facilitate Wi-Fi technology. A microstrip antenna is commonly used in Wi-Fi technology. Microstrip antennas are extensively utilized in the telecommunications industry, including for Wi-Fi technology, due to their small dimensions, inexpensiveness, and easy fabrication. Microstrip antennas also have disadvantages, namely, gain limitations, low power, and narrow bandwidth [11]. The problem of narrow bandwidth can be overcome by using slots, notches, or more than one antenna element, an electromagnetic band gap (EGB), a leaky-wave antenna [12], or modifying the antenna's shape.

One method to increase the bandwidth is using a leaky-wave antenna. A leaky-wave antenna is part of the travelling wave antenna. The primary mechanism of leaky-wave antennas is the antenna part. Leaky-wave antennas are classified into four types based on their structure: simple, microstrip, uniform, and periodic leaky-wave antennas (P-LWA). P-LWA leak waves travel through a uniform structure, while constant-type leaky-wave antennas leak waves through structures with nonperiodic modulation. P-LWAs are easy to fabricate and analyze

Copyright ©2023 Published by IRCS - ITB

compared with uniform leaky-wave antennas. Microstrip leaky-wave antennas can enhance bandwidth parameters, are easy to design, and can have a beam scanning frequency and narrow beam; however, they reduce the parameter gain of conventional microstrip antennas [12,13]. Microstrip leaky-wave antennas are used for 5G communication system applications, low-cost radars, human tracking, and WLAN [13,14].

In References [14-21], increased gains and bandwidths were achieved. In [14], a leaky-wave microstrip antenna with a periodic type was created with a binomial array. In [15], the antenna used an H-slot and array technique with a size of 2 × 1. In [16], a leaky-wave microstrip antenna of the periodic type was created using a quadrangle as a patch with the array technique and with a size of 1 × 5. In [17], microstrip antennas were created using vertex-fed antennas with E slot. In [18], microstrip antennas with hexagon-shaped slots modified the rectangular ground plane. In [19], a leaky-wave microstrip antenna with a period of 24 used slots was used on the patch. In [20], the leaky-wave microstrip antenna used a circle slot on the edge of the patch. In [21], the leaky-wave microstrip antenna combined a double U slot with an E slot. Previous research using slots and a defected ground structure (DGS) succeeded in increasing the bandwidth and gain. This study proposes using E and U slots or multiple slots on the patch, as well as a DGS at a frequency of 6 GHz, to enhance the bandwidth and gain of a conventional leaky-wave microstrip antenna.

Designing and Method

In this study, the leaky-wave microstrip antenna with multiple slots and DGS had the following specifications: an operating frequency of 5.925–6.425 GHz, an impedance of 50 Ω and a gain of ≥4 dBi. This study used FR-4 as the substrate containing a dielectric constant of 4.6 mm and a thickness of 1.6 mm. The antenna's dimensions were calculated using Eqs. (1) to (5) [21]:

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

The length (L) of the patch was calculated using Eqs. (2) to (5):

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2}\left[\frac{\varepsilon_r-1}{2}\left(\frac{1}{\sqrt{1+12\frac{h}{W_F}}}\right)\right] \tag{2}$$

$$\mathrm{L_{eff}} = \frac{\mathrm{c}}{2\mathrm{xF_r}\sqrt{\varepsilon_{\mathrm{eff}}}} \tag{3}$$

$$\Delta\mathrm{L} = 0.412 \text{ x h } \frac{(\varepsilon_{\mathrm{ff}}+0.3)\left(\frac{\mathrm{W}}{\mathrm{h}}+0.264\right)}{(\varepsilon_{\mathrm{ff}}-0.258)\left(\frac{\mathrm{W}}{\mathrm{h}}-0.8\right)} \tag{4}$$

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

The dimensions of the ground plane and substrate were calculated using Eqs (6) and (7) [22]:

$$L_S \geq L + 6h \tag{6}$$

$$W_S \geq W + 6h \tag{7}$$

The slots were calculated using Eqs. (8) to (10) [23]:

$$E = F = \frac{\lambda}{60} \tag{8}$$

$$\frac{C}{W} \geq 0{,}3 \tag{9}$$

$$D = \frac{C}{F_{low}\sqrt{\varepsilon_{eff}}} - 2(L + 2\Delta L - U_A) \tag{10}$$

Figure 1 illustrates the dimensions of the U-slot.

DOI: 10.5614/j.eng.technol.sci.2023.55.3.6

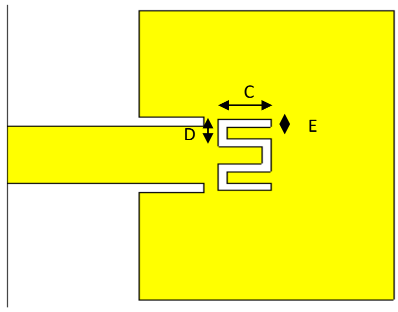


Figure 1 Dimensions of the U-slot.

The dimensions size of the patch, the leaky-wave microstrip antenna, the substrate, and the ground were determined using Eqs. (1) to (7). Figure 2 shows the design of the plane of the leaky-wave microstrip antenna based on the calculation. Table 1 shows the dimensions of each dimension parameter according to the calculation.

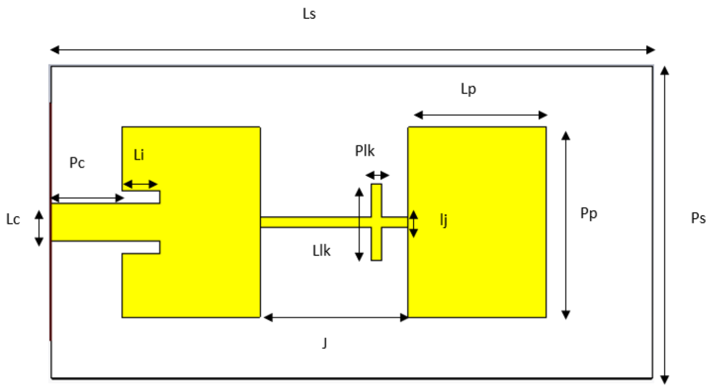


Figure 2 Design of the conventional leaky-wave microstrip antenna as per calculation.

Table 1 Antenna dimensions as per calculation.

Parameters	Dimensions (mm)	Parameters	Dimensions (mm)
Ps	47	Plk = lj	0.83
Ls	24.5	Llk	5.76
PP	10.8	Pc	6.25
Lp	14.9	Lc	2.983

The simulation employed CST Suite Studio. Iteration 0 used the leaky-wave microstrip antenna as per calculation. Iteration 1 increases the dimension of the width of the distance between the patch (Plk) and the width of the leaky wave (lj) from 0.83 to 1 mm. Finally, iteration 2 changed the dimensions of the distance between the patch (J) from 11.6 to 10.3 mm, the dimensions of the width of the distance between the patch (Plk) and the width of the leaky wave (lj) from 1 to 1.4 mm, the length of the leaky-wave (Llk) from 5.76 to 10.2 mm, the dimensions of the substrate antenna from 47 mm × 24.5 mm to 45.1 mm × 24.8 mm, and the dimensions of the patch antenna from 10.6 mm × 14.9 mm to 12.4 mm × 15.5 mm. Figure 3 shows the final design of the leaky-wave microstrip antenna, and Table 2 shows the dimensions of the leaky-wave microstrip antenna.

The simulation results are categorized into the S_{11}, bandwidth, and gain parameters. In iterations 0 to 2, the values of S_{11} at 6 GHz were −4.522, −23.39, and −21.74 dB, respectively; the bandwidth results showed operating frequencies ranging from 6.167 to 6.426 GHz (259 MHz), 5.863 to 6.087 GHz (224 MHz), and 5.859 to 6.139 GHz (280 MHz), respectively; the gain result at 6 GHz is 4.46, 4.53, and 4.47 dBi, respectively. Figure 4 shows the comparison result of the S_{11} simulation for iterations 0 to 2. Figure 5 shows the comparison results of the gain simulation for iterations 0 to 2.

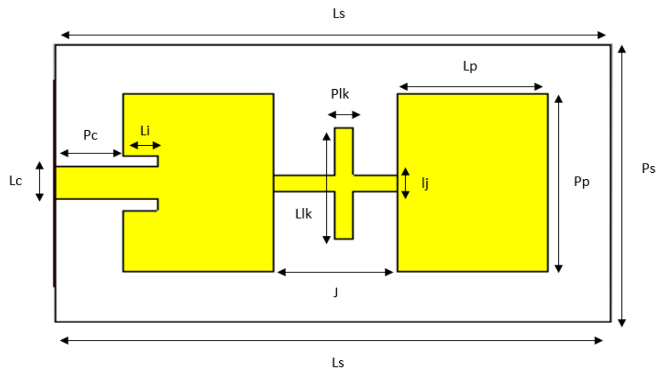


Figure 3 Final design of conventional leaky-wave microstrip antenna.

Table 2 Final design of conventional leaky-wave microstrip antenna dimensions.

Parameter	Dimensions (mm)	Parameter	Dimensions (mm)
Ps	45.1	Plk = lj	1.4
Ls	24.8	Llk	10.2
Pp	12.4	Pc	6.25
Lp	15.5	Lc	2.98
J	10.3	Li	3

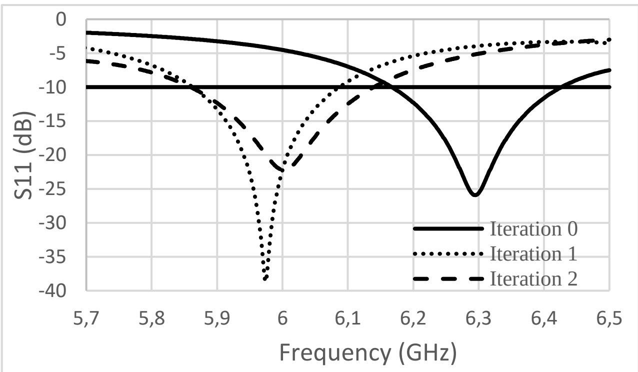


Figure 4 Comparison of S_{11} simulation results for the conventional leaky-wave microstrip antenna.

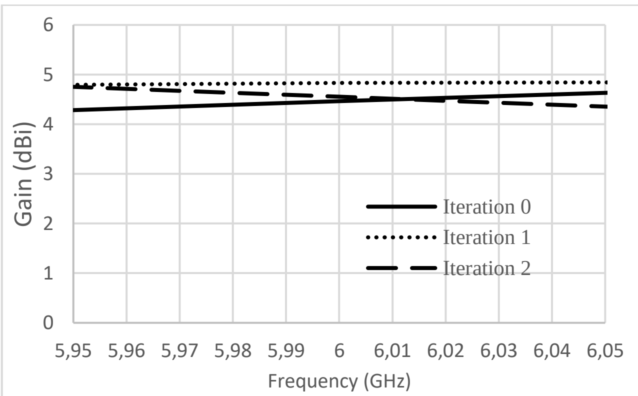
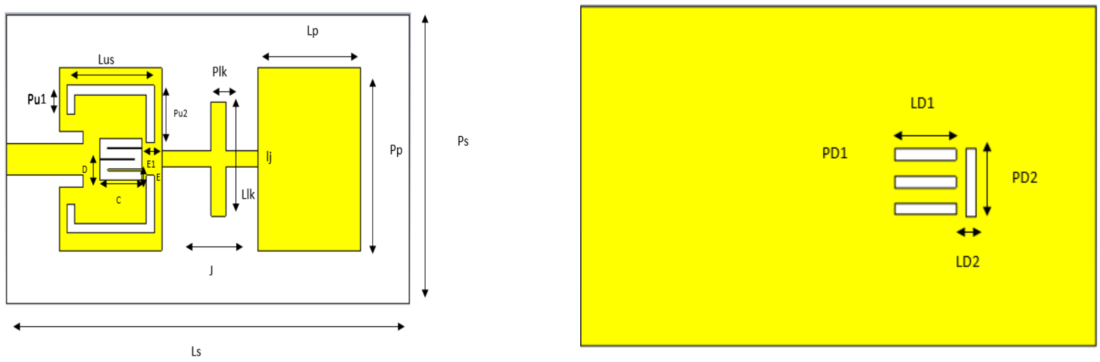


Figure 5 Comparison of gain simulation results for conventional microstrip leaky-wave antenna.

DOI: 10.5614/j.eng.technol.sci.2023.55.3.6

Eqs. (8) to (10) were used to increase the bandwidth and gain parameters when designing the slots and the DGS. Figures 6(a) and 6(b) show the design of the leaky-wave microstrip antenna design with multiple slots and DGS, respectively. Table 3 shows the dimensions of the leaky-wave microstrip antenna with multiple slots and DGS as per calculation.



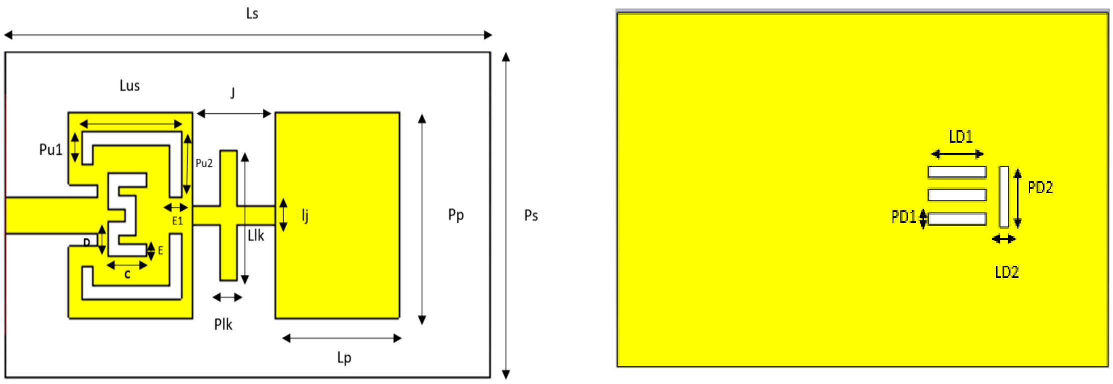
(a) (b)

Figure 6 Design of the modified leaky-wave microstrip antenna with (a) multiple slots and (b) DGS, as per calculation.

Table 3 Dimensions of modified leaky-wave microstrip antenna with multiple slots and DGS as per calculation.

Parameter	Dimensions (mm)	Parameter	Dimensions (mm)
Ps	42	C	4,4
Ls	25	E=E1	0.83
Pp	11.6	Lus	8.3
Lp	15	Pu1	1.67
J	10	Pu2	4.4
Plk=lj	1.5	LD1	4.4
Llk	9.9	PD1=LD2	0.83
D	1.7	PD2	4.4

Based on calculations, iteration 0 was a leaky-wave antenna with multiple slots and DGS. In iteration 1, the widths of the E slot (E) and double U slot (E1) on the front of the antenna were changed from 0.83 to 1 mm, and the widths of the DGS (PD1) and (LD2) were changed from 0.83 to 1 mm. In iteration 2, the dimensions of the patch were changed from 10.8 mm × 14.9 mm to 10.7 mm x 15.8 mm, the lower and upper outer length of the U slot on both sides (Lus) from 8.3 to 8.6 mm, the length of side 1 of the U (Pu1) slot from 1.67 to 2.7 mm, the length of side 2 of the U (Pu2) slot from 4.4 to 5 mm, the dimensions of the distance between the patch (J) from 9.9 to 7.2 mm, the dimensions of the width of the E slot (E) and double U slot (E1) on the front of the antenna from 1 to 0.8 mm, the length of the leaky-wave (Llk) from 9.9 to 10.1 mm, the dimension of the width of the distance between the patch (Plk) from 1 to 1.3 mm, the width of the leaky wave (lj) from 1 to 1.4 mm, the dimensions of the substrate antenna from 42 mm × 25 mm to 40.6 mm × 25 mm, the dimensions of the patch antenna from 11.6 mm × 15 mm to 10.7 mm × 15.8 mm, the width of DGS (PD1) from 1 to 0.8 mm, the width of DGS (LD2) from 1 to 0.8 mm, the length of DGS (LD1) from 4.4 to 4.8 mm, and the length of DGS (PD2) from 4.4 to 4.3 mm. Figure 7 shows the final design of the leaky-wave microstrip antenna with multiple slots and DGS, and Table 4 shows the dimensions.



(a) (b)

Figure 7 Final design of the modified leaky-wave microstrip antenna with (a) multiple slots and (b) DGS, as per calculation.

Table 4 Final dimensions of modified leaky-wave microstrip antenna with multiple slots and DGS.

Parameters	Dimensions (mm)	Parameters	Dimensions (mm)
Ps	40.6	C	3.4
Ls	25	E=E1	1
Pp	10.7	Lus	8.6
Lp	15.8	Pu1	2.7
J	7.2	Pu2	5
Plk	1.3	LD1	4.8
lj	1.4	PD1	0.8
Llk	10.1	LD2	0.8
D	2.6	PD2	4.3

The simulation results obtained were of the S_{11}, bandwidth, and gain parameters. In iterations 0 to 2, the value of S_{11} at 6 GHz was obtained at −18.79, −5.47, and −25.49 dB, respectively; the bandwidth showed operating frequencies of 5.877–6.1301 GHz (251 MHz), 5.52–5.702 GHz (194 MHz), and 5.854–6.529 GHz (691 MHz), respectively; the gain result was obtained at 5.3, 5.12, and 5.04 dBi. Figure 8 shows the comparison result of the S_{11} simulation for iterations 0 to 2. Figure 9 shows the comparison result of the gain simulation for iterations 0 to 2.

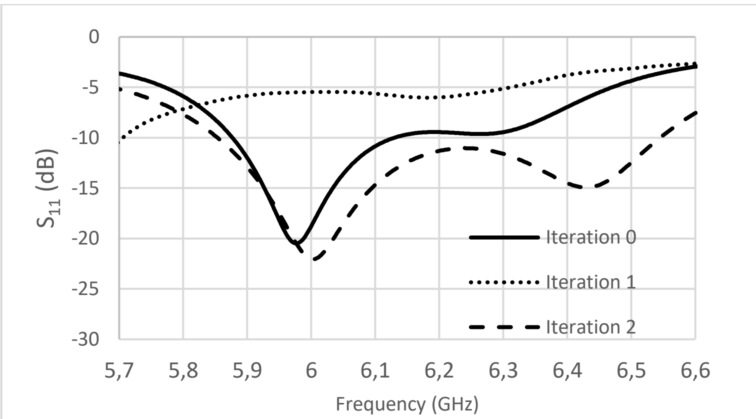


Figure 8 Comparison of S_{11} simulation result for the modified leaky-wave microstrip antenna with multiple slots and DGS.

DOI: 10.5614/j.eng.technol.sci.2023.55.3.6

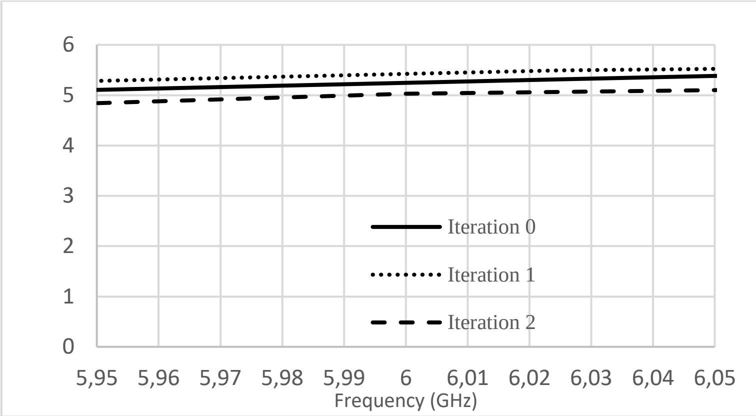
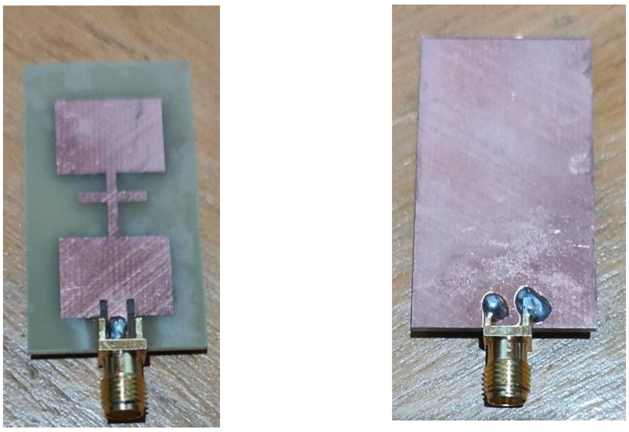


Figure 9 Comparison of gain simulation result for the modified leaky-wave microstrip antenna with multiple slots and DGS.

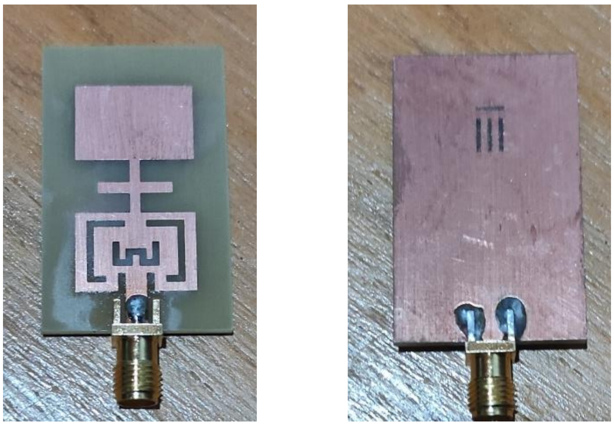
Results and Discussion

Figures 10(a) and 10(b) show fabrication images of the conventional leaky-wave microstrip antenna, top and bottom view respectively. Figures 11(a) and 11(b) show fabrication images of the modified leaky-wave microstrip antennas with multiple slots and DGS, top and bottom views, respectively.



(a) (b)

Figure 10 Fabrication images of the conventional leaky-wave microstrip antenna: (a) top view, (b) bottom view.



(a) (b)

Figure 11 Fabrication images of the modified leaky-wave microstrip antenna with multiple slots and DGS: (a) top view, (b) bottom view.

The following process was the measurement of the fabricated antennas using a vector network analyzer (VNA). The parameters measured were S_{11}, bandwidth, and gain. Figures 12 and 13 show a comparison between the simulation and measurement results for S_{11} and gain of the conventional leaky-wave microstrip antenna, respectively. Figures 13 and 14 show a comparison between the simulation and measurement results for S_{11} and gain from the modified leaky-wave microstrip antenna with multiple slots and DGS, respectively.

In Figure 12, the dotted black line represents the simulation result of the leaky-wave microstrip antenna, with an S_{11} value of −22.2 dB, an operating frequency ranging from 5.845 to 6.529 GHz, and a bandwidth of 280 MHz. The thick line represents the measurement results of the leaky-wave microstrip antenna; the antenna had an S_{11} value of –23.21 dB at 6 GHz, an operating frequency ranging from 5.877 to 6.150 GHz, and a bandwidth of 273 MHz.

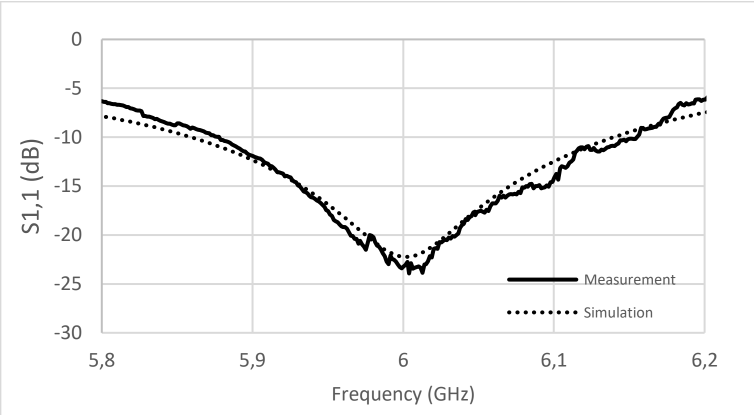


Figure 12 The Comparison of simulation and measuremet result of s_{11} conventional microstrip leaky-wave antennas.

In Figure 13, the dotted black line represents the simulation results for the antenna. The gain obtained during the simulation was 4.47 dBi at 6 GHz. The thick black line represents the measurement results of the antenna, showing a gain of 4.38 dBi at 6 GHz.

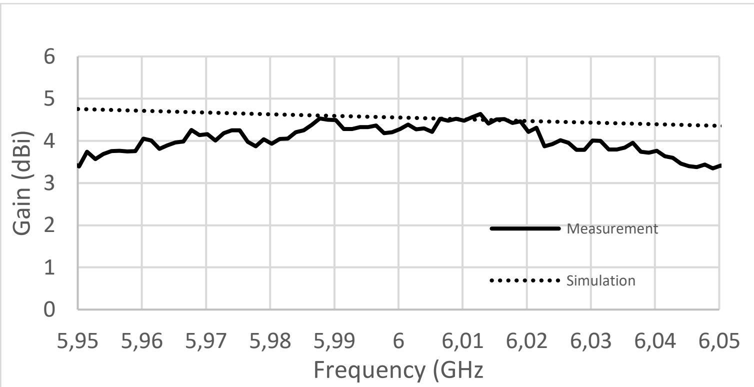


Figure 13 Comparison between simulation and measurement result of gain for conventional leaky wave microstrip antennas.

In Figure 14, the dotted black line represents the results of the antenna simulation; it had an operating frequency ranging from 5.854 to 6.545 GHz, a bandwidth of 691 MHz, and an S_{11} value of −22.06 dB at 6 GHz. The thick black line represents the results of the antenna measurements; it had an operating frequency ranging from 5.845 to 6.529 GHz, a bandwidth of 684 MHz, and an S_{11} value of −21.36 dB at 6 GHz.

DOI: 10.5614/j.eng.technol.sci.2023.55.3.6

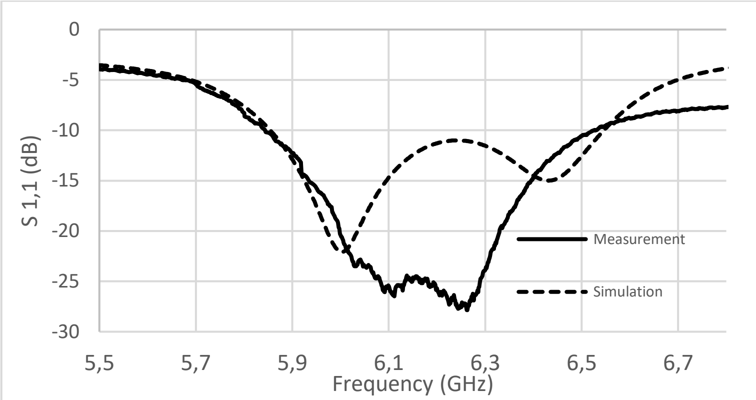


Figure 14 Comparison between the simulation and measurement results of parameter S_{11} for the modified leaky-wave microstrip antenna with multiple slots and DGS.

In Figure 15, the dotted black line represents the result of the antenna simulation. The antenna gain obtained during the simulation was 5.04 dBi at 6 GHz. The thick black line represents the result of the antenna measurements. The antenna gain obtained during measurement was 5.06 dBi at 6 Ghz.

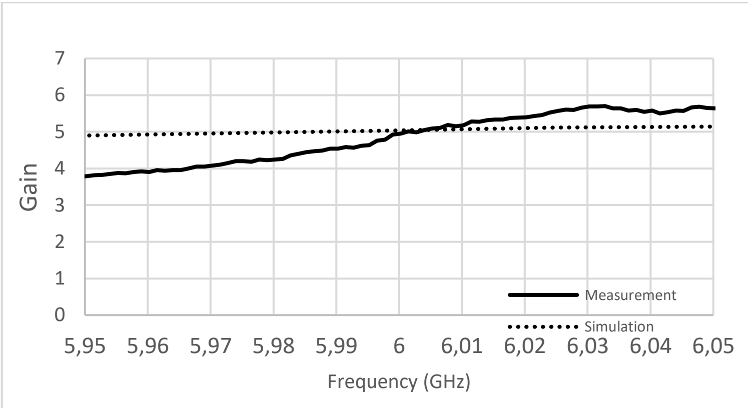


Figure 15 Comparison of the simulation and measurement results of gain for the modified leaky-wave microstrip antenna with multiple slots and DGS.

From the simulation results, the bandwidth and gain parameters of the leaky-wave microstrip antenna with multiple slots and DGS increased from 280 to 691 MHz or 411 MHz and from 4.47 to 5.04 dBi or 0.57 dBi at 6 GHz, respectively, while the measurement results showed an increase in the bandwidth and gain from 273 to 684 MHz or 411 MHz and from 4.38 to 5.06 dBi or 0.68 dBi at 6 GHz, respectively.

Table 5 shows a comparison between the simulation and measurement results of the bandwidth and gain enhancement for the conventional and modified leaky-wave microstrip antennas with multiple slots and DGS. Table 6 shows a comparison of the proposed antenna and previous antennas. In this research, the antenna was smaller than those used in [16]-[21] and had a wider bandwidth than those in [16] and [21]. In [15], the antenna had a working frequency of 64.2 GHz and 91.5 GH, which makes it unsuitable for Wi-Fi application.

Table 5 Comparison of simulation and measurement of bandwidth and gain enhancement.

Parameter		**Enhancement**
Simulation	Bandwidth	280 MHz (5.859–6.139 GHz) to 691 MHz (5.854–6.545 GHz)
	Gain	4.47 dBi to 5.04 dBi
Measurement	Bandwidth	273 MHz (5.877–6.150 GHz) to 684 MHz (5.845–6.529 GHz)
	Gain	4.38 dBi to 5.06 dBi

Table 6 Comparison between proposed antenna and previous antennas.

Ref	Frequency (GHz)	Bandwidth	Gain (dBi)	Dimensions (mm)
[14]	4.28 –7.15	2.8 GHz	7.5 at 6 GHz and peiak gain is 10.31 at 5 GHz	180 × 40 × 1.575
[15]	63.2 and 91.5	1.33 GHz and 15.83 GHz	7.33 and 12.56	14 × 14 × 0.3
[16]	4.3–6.3	2 GHz	10 at 5 GHz	250 × 100 × 1.575
[17]	3.18–5.17, 4.95–5.35, and 5.76 –6.01	430, 400, and 250 MHz	2.25, 3.01, and 4.11	50 × 50 × 1.5
[18]	5.16–7.53	2.3691 GHz	3.9	34 × 20 × 0.79
[19]	4–6	2 GHz	10 at 4.3 GHz	250 × 100 × 1.575
[20]	4.28–6.5	2.22 GHz	10.31 at 5 GHz	180 × 40 × 1.575
[21]	5.843–6.458	615 MHz	6.16	41.9 × 23.90 × 1.6
This Works	5.845–6.529	685 MHz	5.06	40.6 × 25 × 1.6

Conclusion

This study investigated the design, simulation, fabrication, and measurement of a conventional leaky-wave microstrip antenna and a modified leaky-wave microstrip antenna with multiple slots and DGS. The latter was successfully designed for WLAN applications at 6 GHz. The dimensions for fabrication of the conventional leaky-wave microstrip antenna were 45.1 mm × 24.8 mm × 1.6 mm, and 40.6 mm × 25 mm × 1.6 mm for the leaky-wave microstrip antenna with multiple slots and DGS. The simulation and measurement results showed that adding multiple slots and a DGS increased the bandwidth and gain parameters of the leaky-wave microstrip antenna. The simulation results showed that the bandwidth increased from 280 MHz (5.859–6.139 GHz) to 691 MHz (5.854–6.545 GHz) and the gain increased from 4.47 to 5.04 dBi, while the measurement results showed that the bandwidth increased from 273 MHz (5.877–6.150 GHz) to 684 MHz (5.845–6.529 GHz) and the gain increased from 4.38 to 5.06 dBi.

Acknowledgement

This work was supported by Postgraduate Research - Master's Thesis Research (*Penelitian Pascasarjana-Penelitian Tesis Magister*/PPS-PTM) from the Ministry of Education, Cultural Research, and Technology (Kemendikbud), Republic of Indonesia, under contract number NKB-1033/UN.RST/HKP.05.00/2022.

Nomenclature

c	=	free-space velocity of light (3×10^8 M/S)
fr	=	resonant frequency (Hz)
h	=	substrate thickness
εr	=	dielectric constant of the dielectric substrate (F/M)
ε_{eff}	=	the effective dielectric constant of the substrate (F/M)
ΔL	=	element edge field effect

References

[1] Perspectives, Executive, and Cisco Report. *Cisco Annual Internet Report - Cisco Annual Internet Report (2018–2023) White Paper*, 2020. https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html, (20 November 2022).

[2] Lopez-Perez, D., Garcia-Rodriguez, A., Galati-Giordano, L., Kasslin, M. & Doppler, K., *IEEE 802.11be Extremely High Throughput: The Next Generation of Wi-Fi Technology Beyond 802.11ax*, IEEE Communications Magazine, **57**, pp. 113-119, 2019

DOI: 10.5614/j.eng.technol.sci.2023.55.3.6

[3] Yang, M. & Li, B., *Survey and Perspective on Extremely High Throughput (EHT) WLAN — IEEE 802.11be*, Mobile Networks and Applications, **25**, pp. 1765-1780, 2020.

[4] Garcia-Rodriguez, A., Lopez-Perez, D., Galati-Giordano, L. & Geraci, G., *IEEE 802.11be: Wi-Fi 7 Strikes Back*, IEEE Communications Magazine, **59**, pp. 102-108, 2021.

[5] Naik, G., Park, J., Ashdown, J. & Lehr, W., *Next Generation Wi-Fi and 5G NR-U in the 6 GHz Bands: Opportunities and Challenges*, IEEE Access, 8, pp. 153027-153056, 2020.

[6] Garcia-Rodriguez, A., Lopez-Perez, D., Galati-Giordano, L., & Geraci, G., *IEEE 802.11be: Wi-Fi 7 Strikes Back*, IEEE Communications Magazine, **59**, pp. 102-108, 2021.

[7] Deng, C., Fang, X., Han, X., Wang, X., Yan, L., He, R., Long, Y. & Guo, Y., IEEE 802.11be Wi-Fi 7: New Challenges and Opportunities, IEEE Communications Surveys & Tutorials, 22, pp. 2136-2166, 2020.

[8] Federal Communications Commission (FCC), *FCC Opens 6 GHz Band to Wi-Fi and Other Unlicensed Uses*, Apr 2020. https://www.fcc.gov/document/fcc-opens-6-ghz-band-wi-fi-and-other-unlicensed-uses, (21 November 22).

[9] Directorate-General for Communications Networks, Content and Technology, European Comission, *Mandate to CEPT to Study Feasibility and Identify Harmonized Technical Conditions for Wireless Access Systems Including Radio Local Area Networks in the 5925–6425 MHz Band for the Provision of Wireless Broadband Services*, http://ec.europa.eu/newsroom/dae/document.cfm?doc_id=50343, (20 November 2020).

[10] Au, E., *Specification Framework for TGbe,* 17 January 2021. https://mentor.ieee.org/802.11/dcn/19/11-19-1262-23-00be-specification-framework-for-tgbe.docx, (21 November 2022).

[11] Surjati, I*., Microstrip Antenna: Concept and Application*, DKI Jakarta: Universitas Trisakti, 2010. (Text in Indonesian)

[12] Balanis, C.A., *Modern Antenna Handbook, 4th ed*., New York, N.Y: Wiley, 2008.

[13] Suliman H.M., *Applications of Leaky-wave Antennas: A Review, International Journal of Wireless and Microwave Technologies*, **10**, pp. 56-62, 2020. doi:10.5815/ijwmt.2020.03.05.

[14] Aziz, H., Moubadir, M., Farkhsi, A. & Amar N.T., *Sidelobe Suppression in Array-Pattern Synthesis Using Periodic Leaky-Wave Antenna and Binomial Array*, Modelling and Simulation in Engineering, **2020**, pp. 1-6, 2020.

[15] Badreddine, T., Zahra, H., & Tahar, G., *Design of a Novel Efficient High-Gain Ultra-Wide-Band Slotted H-Shaped Printed 2x1 Array Antenna for Milimeter-Wave Applications with Improvement of Bandwidth and Gain via the Feed Line and Elliptical Edges*, Journal of Engineering and Technological Sciences, **55**(1), pp. 60-78, 2023

[16] Aziz, H., Moubadir, M., Touhami, N., & Farkhsi, *Planar Leaky-wave Antenna at 6GHz*, Procedia Manufacturing, **22**, pp. 527-532, 2018.

[17] Surendrakumar, P. & Chandra B.M., *A Triple-Frequency, Vertex-Fed Antenna for WLAN\/WiMAX Applications [Antenna Applications Corner]*, IEEE Antennas and Propagation Magazine, **60**, pp. 101-106, 2018.

[18] Paul, L., Jim, M., Rani, T., Samsuzzaman, M., Sarker, N. & Azim, R., *A Compact Wideband Slotted Hexagonal Patch Antenna with a Modified Ground Structure for WiFi-5/6 Communication*, 2021 Emerging Technology in Computing, Communication and Electronics (ETCCE), 2021.

[19] Kasim, J., Isa, M., Zakaria, Z., Hussein, M. & Mohsen, M., *Radiation beam scanning for leaky wave antenna by using slots*, TELKOMNIKA (Telecommunication Computing Electronics and Control), **18**, pp. 1237, 2020.

[20] Mohsen, M., Isa, M., Isa, A., Abdulhameed, M., Attiah, M. & Dinar, A., *Enhancement Bandwidth of Half Width-Microstrip Leaky Wave Antenna Using Circular Slots*, Progress in Electromagnetics Research C, **94**, pp. 59-74, 2019.

[21] Wahyu Iqbal, M., Zulkifli, F. & Rahardjo, E. Increased Bandwith and Gain of Microstrip Leaky-Wave Antenna with Multi slot for WLAN Applications, ELKOMIKA: Jurnal Teknik Energi Elektrik, Teknik Telekomunikasi, & Teknik Elektronika, 10, pp. 432, 2022. (Text in Indonesian)

[22] Balanis, C.A., *Antenna: Theory: Analysis and Design, 4th ed*., New York, N.Y: Wiley, 2016.

[23] Anindito, A., Putranto, A., Surjati, I., Alam, S., Sari, L. & Vaswami, R., *Design of a 2x1 Microstrip Antenna with Inset and Slit Techniques for 5G Communication System*, Jurnal Telematika, **16**, pp. 18-14, 2021. (Text in Indonesian)

[24] Sandi, E., Rusmono, R., Diamah, A. & Vinda, K., *Ultra-wideband Microstrip Array Antenna for 5G Millimeter-wave Applications*, Journal of Communications, **15**, pp. 198-204, 2020.

Manuscript Received: 10 November 2022
1st Revision Manuscript Received: 25 March 2023
2nd Revision Manuscript Received: 9 June 2023
Accepted Manuscript: 20 June 2023