Study on Defected Ground Structure Models with Miniaturized Patches for Broadband Wireless Systems

Yus Natali[1,*], Riva Irvana[2], Yosi Juliana[2], Yudiansyah[2], Dian Widi Astuti[3], Dwi Astuti C.[4], Catur Apriono[5]

[1] Telecommunication Engineering, Faculty of Applied Sciences, Universitas Telkom, Jakarta Barat, Indonesia
[2] Telecommunication Engineering, Faculty of Electrical Engineering, Universitas Telkom, Jakarta Barat, Indonesia
[3]Department of Electrical Engineering, Universitas Mercubuana, Jakarta Barat, Indonesia
[4]Department of Electrical Engineering, Universitas Muhammadiyah Prof. Dr. HAMKA, Jakarta, Indonesia
[5]Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia, Depok, Indonesia
Email: yusnatali@telkomuniversity.ac.id (Y.N.); rivairvanaa@student.telkomuniversity.ac.id (R.I); yosijuliana@telkomuniversity.ac.id (Y.J); yudiansyah@telkomuniversity.ac.id (Y.A); dian.widiastuti@mercubuana.ac.id (D.W.A); dwi.cahyasiwi@uhamka.ac.id (D.A.C); catur@eng.ui.ac.id (C.A)
*Corresponding author

***Abstract*—This study presents a Defected Ground Structure (DGS) mechanism and improves its antenna properties. Three DGS models are discussed: two including a single antenna and one including an array microstrip antenna design. The microstrips are designed for broadband wireless frequencies of 2.1 GHz (5G Technology) for a single antenna, and 5.8 GHz (wireless local area network) for an array antenna. These frequencies are achieved using three shapes of DGS in the simulations and the results are suitable for broadband applications. The antenna patches are rectangular with two types of DGS, and an array circular with one type of DGS. The results show the DGS provides better bandwidth and gain for a single antenna. Nevertheless, DGS achieves gain enhancement for an array antenna and this design yields a miniaturized array antenna of 69.92% and 73.47% in width and length, respectively. The three shapes of DGS have different designs: rectangular patch antenna with frame-shaped DGS, rectangular antenna with rectangular slot-shaped DGS, and array circular antenna with rectangular slots of DGS. A rectangular patch antenna with frame-shaped DGS and an array circular antenna with rectangular slots of DGS yields bandwidths of 533 MHz and 327 MHz. The single antenna improves the fractional bandwidth by 25.38% with a miniaturized patch. Nonetheless, the array circular antenna with DGS obtains a gain enhancement of 16 dB greater than the initial array without DGS.**

***Keywords*—microstrip antenna, defected ground structure, resonant frequency, impedance bandwidth, gain, miniaturized patch**

I. INTRODUCTION

The trend of miniaturization has been prevalent in various fields of electrical engineering. This trend also affects the field of electromagnetics devices, specifically antennas [1]. One mechanism to miniaturize the antenna is using modified ground planes. Engineered ground planes are demonstrated as Defected Ground Structure (DGS), and have evolved from Electromagnetic Band-Gap (EBG) structures [1–3]. A DGS is a structure that is used to alter the electrical characteristics of a microstrip transmission line or any other similar structure. This alteration affects the behavior of microstrip antennas [4]. Moreover, DGS is widely used in designing antennas, filters, integrated circuits, and more. DGS for filter design is discussed in [5–10]. A CMOS with DGS for low-phase noise is discussed in [11].

Re. [12], a design approach for transforming an L-shaped stub into a U-shaped stub antenna using DGS was presented. The models give fractional bandwidths of 5.7% and 6.89% for resonant frequencies of 3.5 GHz and 5.8 GHz. A fractional bandwidth of 7 % is discussed in Ref. [7] and the DGS model can cancel the harmonics frequencies. A modified antenna using DGS and diodes is shown in Ref. [13] and gives a fractional bandwidth of 20.1%. A bow-tie antenna using DGS gives a fractional bandwidth of 13.37% as discussed in Ref. [14]. A model of DGS design to reduce cross-polarization is performed in Ref. [15]. A super fractional bandwidth of 183.17% is achieved in Ref. [16] using DGS. Ref. [17], a monopole circular patch is investigated, exhibiting an impedance bandwidth of 8.1%. Furthermore, at frequencies of 2.9 GHz and 9.1 GHz, the antenna demonstrates enhanced gains of 8.4 and 8.2 dBi, respectively. These findings highlight the improved performance characteristics of antennas across a wide frequency range. The study in Ref. [18] investigates the integration of an edge-located EBG structure with a DGS, emphasizing their combined effects on noise. However, the specific characterization of

Manuscript received July 20, 2023; revised October 20, 2023, accepted December 7, 2023; published March 26, 2024.

fractional bandwidth is not explicitly addressed in this context. The authors described in Ref. [19] focuses on the implementation of multiple gradual semicircle-shaped DGS incorporated into the rear end of the antipodal Vivaldi antenna. The utilization of these DGSs resulted in a fractional bandwidth of 15.63% and an approximately 2 dB enhancement in gain.

An antenna with Multiple-Input Multiple-Output (MIMO) is proposed in Ref. [20] and minimizes the mutual coupling effect between antenna pairs. Asymmetrical pyramidal antenna design employing MIMO techniques and incorporating DGS is introduced in Ref. [21]. This antenna is optimized for operation at 7.5 GHz, demonstrating a fractional bandwidth of 116%. The study in Ref. [22] presents a comprehensive examination of innovative techniques employed in omnidirectional patch antenna design. Its focus is on achieving omnidirectionality in the H-plane through the incorporation of a DGS. The investigation reveals a fractional bandwidth of 5.51% and a gain of 2.3 dB, demonstrating the effectiveness of the proposed design. A MIMO antenna design incorporating DGS is discussed in Ref. [23]. This antenna design exhibits favorable characteristics, including isolation and circular polarization gain across the entire frequency band of 3.4 GHz to 3.8 GHz, with a gain of 5 dB. Additionally, the MIMO antenna achieves a fractional bandwidth of 11.43%.

An impedance bandwidth of 33.85% is discussed in Ref. [24] for an array antenna with DGS. To validate the efficacy of a surrogate-assisted DGS in Ref. [25], a 2×2 array of microstrip antennas was employed for testing. The investigation confirms the utility of the surrogate-assisted DGS approach, yielding a minimum fractional bandwidth of 28.57%. Ref. [26], the fractional bandwidth of a 2×2 array antenna with DGS is 12.8%.

The abovementioned references [7, 12, 14–16, 18–22] do not discuss the miniaturization or enlargement of the patches or substrates after the DGS implementation on the antenna. In this study, a DGS impact on the antenna dimension point of view is discussed. This research provide insight into the design of single and array microstrip antennas using DGS.

DGS design affects the antenna properties, particularly the resonant frequency. This study investigates the DGS impact on the resonant frequency and the solution to obtain the target of the resonant frequency. To obtain the resonant frequency of the antenna, there must be a dimension change on the substrate, patch, or feedline. The single antenna design is meticulously studied here, with modifications to the substrate dimensions, to achieve a resonant frequency of 2.1 GHz. Furthermore, the array antenna has been miniaturized, including both patches and substrates, to attain a resonant frequency of 5.8 GHz. The resulting antennas are convenient for operating in resonant frequencies and with broadband properties.

This paper is divided into five sections. The introduction is discussed in Section I regarding various DGS models that have been carried out to improve antennas' properties. Section II discusses the initial antenna designs without DGS. Next, Section III discusses the DGS models proposed. The DGS models are two designs of a single antenna and one design of an array antenna. The antenna patches are miniaturized in DGS designs. Section IV discusses the DGSs impact on the antenna properties. In this section proves that common DGS models proposed improve the antenna properties and miniaturize designs. This section also presents the feasibility DGS models with others. In the final stage, Section V is the conclusion of this study.

II. Single and Array Antenna Design

Commonly, a substrate is a Flame Retardant (FR) with material four levels of epoxy resin and glass fabric compound. The detailed characteristics of this material are shown in Table I. The antennas are designed using FR-4 in simulations. The relevant process is shown in Fig. 1. The first initial antenna design is a rectangular patch antenna for a resonant frequency of 2.1 GHz. The second is an array 2×1 circular patch antenna for 5.8 GHz. Detailed antenna characteristics are shown in Tables II and III. The resonant frequencies are chosen for broadband communication as Long-Term Evolution (LTE) or 5G technology and WLAN (wireless local area network). LTE has several frequencies for its networks, and the resonant frequencies of 2.1 GHz for downlink communication in LTE networks and unlicensed LTE of 5.8 GHz [27] are chosen. The 5.8 GHz can also be used for wireless broadband, WLANs. The first step of this study is mathematically designing each antenna based on the resonant frequency requirement and material characteristics. This step yields the initial antenna dimensions. Furthermore, the antenna designs are simulated using CST software and the modified ground plane to obtain the antenna requirements. For a single antenna, an initial rectangular shape is modified using two types of DGS. The first shape is a frame of the DGS, and the second is a rectangle including the DGS. For the array antenna, the antenna characteristic is optimized using one shape of DGS. The circular array antenna is designed using two rectangular slots of DGS.

TABLE I. Antenna Substrate Specifications

Antenna Parameter	Unit
Substrate Type	FR-4 epoxy
Relative permittivity (Dielectric Constant), ε_r	4.3
Loss Tangent Dielectric, δ	0.0265
Substrate Height, h	1.6 mm

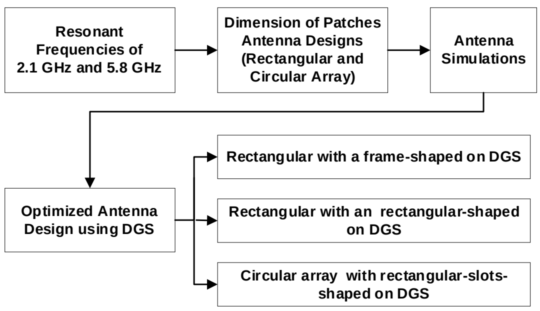


Fig. 1. Study process of DGS.

A. Rectangular Patches Antenna Design

The rectangular microstrip is designed for a resonant frequency of 2.1 GHz. The rectangular microstrip has a width, W, and length, L and can be designed using Eqs. (1–2) in [1], where v_o is the free-space speed of light, f_r is the resonant frequency, μ_o is the permeability of free-space, and ε_o is the permittivity of free space.

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

$$L = \frac{v_o}{2f_r\sqrt{\mu_o\varepsilon_o}\sqrt{\varepsilon_{reff}}} \tag{2}$$

The effective dielectric constant of the patch, ε_{reff} is calculated using Eq. (3).

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

The front and rear views of the rectangular antenna are shown in Figs. 2–3. The rectangular patch has a width, W) of 44 mm and a length (L) of 33 mm, including of a feedline width of 3mm and a length of 16.61 mm. The detailed patch rectangular antenna designs are shown in Figs 2–3; and Table II.

TABLE II. RECTANGULAR ANTENNA SPECIFICATIONS

Parameter	Parameter Meaning	Unit (mm)
W	width of patch	44
L	length of patch	33
W_f	width of feedline	3
L_f	length of feedline	16.61
W_s	width of substrate	57
L_s	length of substrate	57

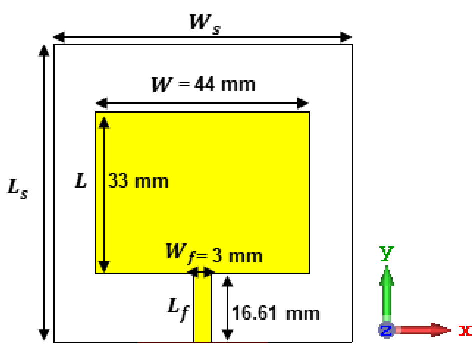


Fig. 2. Front view of a rectangular antenna.

Fig. 3 shows the initial ground plane design with a dimension of 57 mm in width and length and the same size as its substrate. At this stage, the antenna is not optimized in the initial design; nevertheless, the resonant frequency is achieved.

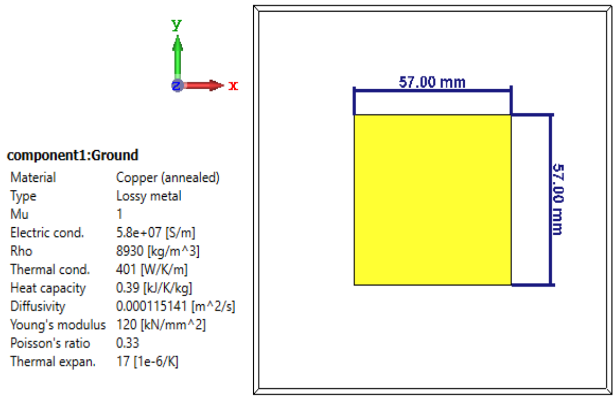


Fig. 3. Rear view of the rectangular antenna without DGS.

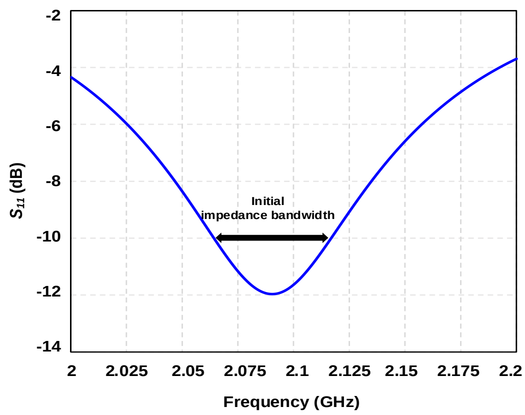


Fig. 4. The initial impedance bandwidth of rectangular antenna.

The initial rectangular antenna, as depicted in Fig. 2, has an impedance bandwidth of 52 MHz. However, this bandwidth does not meet the requirements of broadband applications. Consequently, the antenna design is optimized using software simulations to obtain a suitable impedance bandwidth for broadband communication.

B. Array Patches Antenna Designs

The 2×1 array microstrip antenna design consists of two circular patches. The antenna is designed for 5.8 GHz with the circular patches' radius, a_o are calculated using Eq. (4). The F parameter is designed using Eq. (5) such that the circular patch radius, a_o is 58.59 mm:

$$a_o = \frac{F}{\left\{1+\frac{2h}{\pi\varepsilon_r F}\left[\ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{1/2}} \tag{4}$$

$$F = \frac{8{,}794\ x\ 10^9}{f_r\cdot\sqrt{\varepsilon_r}} \tag{5}$$

The array element has a distance of d_o, and is calculated using Eq. (6):

$$d_o = \frac{\lambda}{2} \tag{6}$$

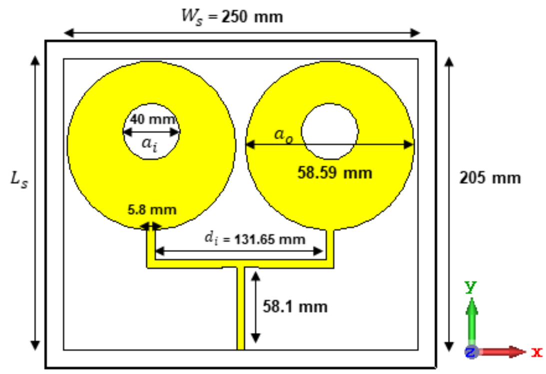


Fig. 5. Front view of a circular array antenna.

The front view of the array antenna is shown in Fig. 5 and the ground plane without DGS. The substrate has a width of 250 mm and a length of 205 mm. Each circular patch has a diameter of 58.59 mm and an inner circular slot of 40 mm diameter. A feedline is connected to the circular patches at the middle point of the patches. The feedline separates the antenna in 131.65 mm for the inner feedline and it has a width of 5.8 mm. Detailed antenna parameters are shown in Table III.

TABLE III. CIRCULAR ARRAY ANTENNA SPECIFICATIONS

Parameter	Parameter Meaning	Unit (mm)
a_o	Outer circular patch	58.59
a_i	inner circular slot	40
d_i	width of inner feedline	131.65
d_o	width of outer feedline	137.15
W_s	width of substrate	250
L_s	length of substrate	205

III. DGS DESIGN

The DGS designs results are presented in this section; showing how the ground structure designs change the antenna characteristics. Therefore, to achieve resonant frequencies, the patches, feeds, or substrate dimensions are accordingly adjusted.

The rectangular patch antenna is designed using two shapes of DGS. The first rectangular antenna is designed as a frame-shape, and subsequently uses a rectangular-shaped DGSs. The circular array antenna is designed using a single shaped of DGS based on: two rectangular slot-shaped designs.

A. Rectangular Patch Antenna with Frame-shaped DGS

The substrates of this design are widened to 0.47 mm from the initial design. The outer frame-shaped DGS has the same width as its substrate, 57.47 mm, whereas the inner boundaries are 41.57 mm and 31.1 mm. The rectangular patch is constantly the same as the initial design. The details of the frame shape are shown in Fig. 6. The frame-shaped DGS provides a resonant frequency of 2.1 GHz. The simulation obtains the magnitude of the reflection coefficient, S_{11} of –23 dB at the resonant frequency. The device has an impedance bandwidth of 533 MHz, which is shown in Fig. 7.

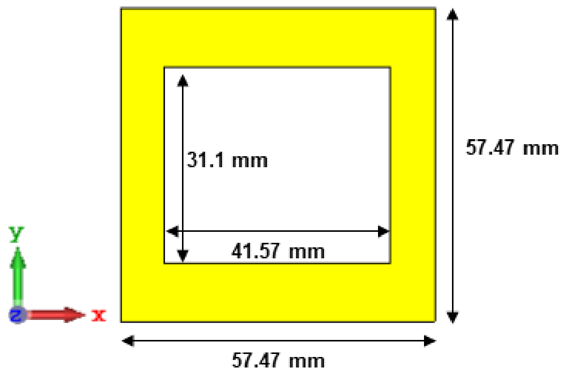


Fig. 6. Frame-shaped DGS design.

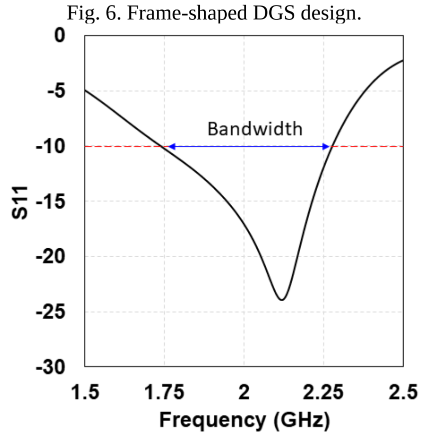


Fig. 7. S_{11} of frame-shaped DGS.

B. Rectangular Antenna with Rectangular Slot-Shaped DGS

The second DGS design has two slots on the edge side of the ground with the ground plane exactly behind the patch in the rearview. This detailed design is shown in Fig. 8. Generally, the size of this substrate is enlarged by 22.8% compared to the initial design, in order to obtain the resonant frequency of 2.1 GHz. The ground plane has a width of 34 mm and a length of 70 mm. The rectangular slot-shaped DGS gives an impedance bandwidth of 118 MHz. This shape is shown in Fig. 9.

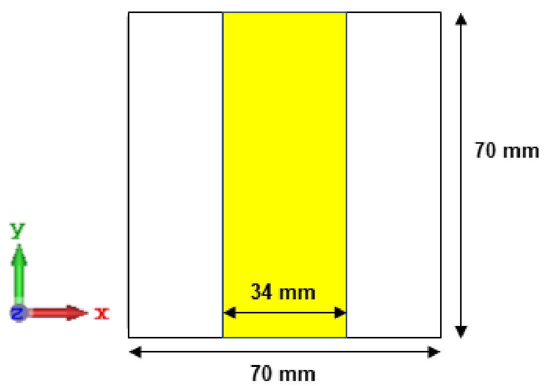


Fig. 8. Rectangular-shaped DGS design.

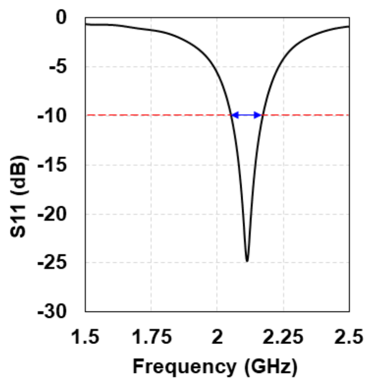


Fig. 9. S_{11} rectangular-shaped DGS.

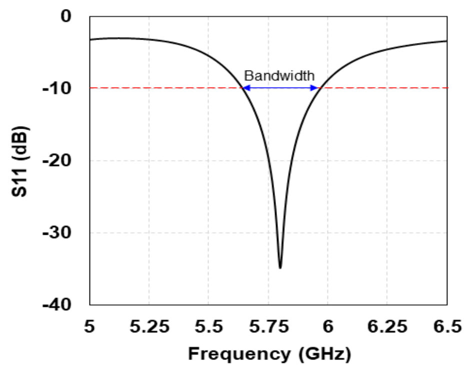


Fig. 12. S_{11} rectangular slot-shaped DGS.

C. Array Circular Antenna with Rectangular Slots of DGS

The initial design of the ground plane has a width of 250 mm and a length of 205 mm. The ground plane is modified using two rectangular slots of DGS. To obtain the resonant frequency of 5.8 GHz, the size of the antenna is minimized. The miniaturized antenna has dimensions of 75.20 mm × 54.93 mm with detail of DGS shown in Fig. 10. Two slots of DGS are at the back side of the patches. The front view of the array circular antenna is shown in Fig. 11. The circular slots on the patches are shifted toward the top edge of the patches. The result of this modified antenna demonstrates suitable antenna performance for LTE applications. The impedance bandwidth is obtained at 327 MHz and shown in Fig. 12.

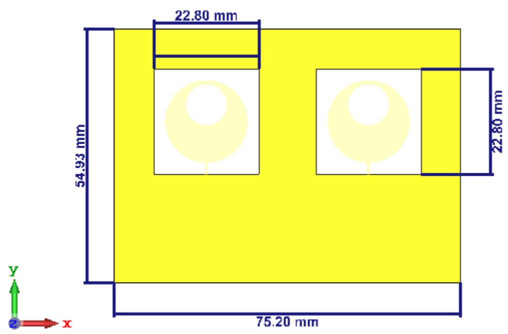


Fig. 10. Rectangular slot-shaped DGS design.

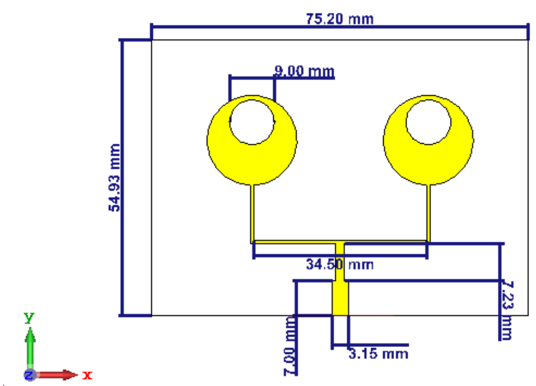


Fig. 11. Front view of the array circular antenna.

IV. Results and Discussion

This section discusses the antenna performance before and after using DGS.

A. Antenna with DGS

The results of rectangular DGS models are shown in Tables IV–V. Table IV shows the rectangular antenna properties in detail. The rectangular DGS with a frame shape is better than the rectangular DGS. The impedance bandwidth of the frame-shaped DGS is 533 MHz, which is 9.25 times wider than that of the initial rectangular antenna without DGS. The fractional bandwidth of this model achieves 25.38% and its gain reaches 3.24 dB. These properties are improved from the initial rectangular antenna without DGS. The rectangular patch design is minimized from the initial. Nevertheless, the minimized rectangular patch obtains a gain enhancement approximately 1.2 dB from the initial design. The rectangular frame-shaped DGS is shown in Fig. 13.

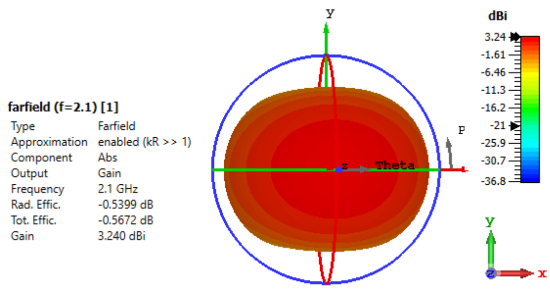


Fig. 13. Rectangular with frame-shaped DGS gain.

TABLE IV. Rectangular Antenna

Antenna Properties	Design		
	Rectangular	Rectangular with frame-shaped DGS	Rectangular with rectangular-shaped DGS
Impedance Bandwidth	52 MHz	533 MHz	118 MHz
Gain	2.44 dB	3.24 dB	3.3 dB
Fractional Bandwidth	2.48%	25.38%	5.62%
Antenna dimension	57 × 57 mm	57.47 × 57.47 mm	70 × 70 mm
Patch design	44 × 33 mm	41.57 × 31.1 mm (miniaturized)	44 × 30 mm (miniaturized)

TABLE V. CIRCULAR ARRAY ANTENNA

Antenna Properties	**Design**	
	Circular Array	**Circular Array with Rectangular Slots of DGS**
Resonant Frequency	5.85 GHz	5.8 GHz
Impedance Bandwidth	497 MHz	327 MHz
Fractional Bandwidth	8.57%	5.64%
Gain	–11.14 dB	5.34 dB
Gain improvemen t	–	16.48 dB
Antenna dimension	250 × 205 mm	75.2 × 54.39 mm (miniaturized)
Patch design	58.59 mm circle diameter	18 mm circle diameter (miniaturized)

The antenna properties of the circular array antenna are shown in Table V. A circular array with rectangular slots of DGS gives better gain than the initial design. Moreover, this model is miniaturized in width and length by 69.92% and 73.47%, respectively; nonetheless, the antenna gain is improved up to 16 dB. The gain of the circular array with rectangular slots of the DGS antenna is shown in Fig. 14. Figs. 13–14 are the results of antenna designs using CST (Computer Simulation Technology) Studio Suite software.

According to the antenna properties with DGS, better performance in impedance bandwidth or gain can be achieved using a slot of DGS on the back side of patches. The rectangular with frame-shaped DGS is modeled using a rectangular slot at the back side of its patch and gives wider impedance bandwidth. Moreover, the circular array with rectangular slots of DGS gives a gain improvement in the miniaturized antenna. These two models of DGS rely on the same concept of DGS design, example to put a slot at the back side of its patches.

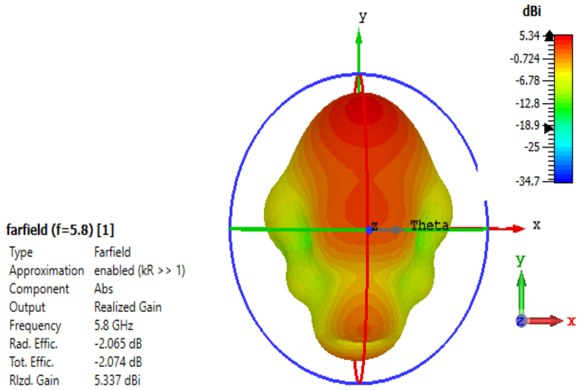


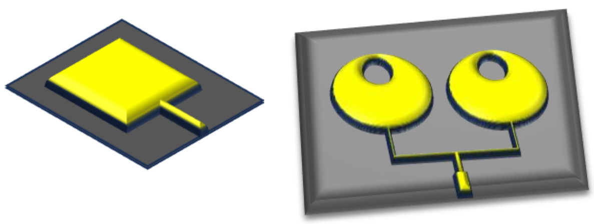
Fig. 14. Gain of the circular array with rectangular slots of DGS.

B. Feasibility DGS Models with Others

The rectangular with frame-shaped DGS reaches the fractional bandwidth of 25.38% and this value is better than the fractional bandwidth reported in [12–14], [20]. For a resonant frequency of 5.8 GHz, the circular array with rectangular slots of DGS has better gain than [25] in the gain. We compare our designed antenna with another antenna, as shown in Table VI. The final antenna designs are also shown in Fig. 15, where Fig. 15(a) depicts the final patch design of the rectangular antenna and Fig. 15(b) being the final design of the circular array antenna.

TABLE VI. ANTENNA DESIGN COMPARISON

Antenna Properties	**References of A Single Antenna**				**References of An Array Antenna**	
	Chen *et al*. [12]	Liu *et al*.[13]	Astuti *et al*. [14]	This work	Qian *et al*.[25]	This work
DGS Design	Rectangular at the left side of the ground	L-shaped stub and DGS	cross-dumbbell DGS	Rectangular frame-shaped DGS	Three DGS etched between the antennas	Rectangular Slots of DGS
Resonant frequency	3.5 GHz	5 GHz	3.5 GHz	2.1 GHz	2.45 GHz	5.8 GHz
Impedance Bandwidth	200 MHz	1.01 GHz	490 MHz	533 MHz	200 MHz	327 MHz
Fractional Bandwidth	5.71%	20.1%	13.37 %	25.38%	8.16%	5.64%
Gain	Not mention	–	–	–	reduction	16.48 dB
Antenna dimension	14 × 14 mm	45 × 45 mm	90 × 90 mm	57.47 × 57.47 mm	84 × 84 mm	75.2 × 54.39 mm
Patch design	U-shaped design 14 × 14 mm	9 × 34.5 mm	Bowtie 26 × 20 mm	Rectangular 41.57 × 31.1 mm	2 × 2 rectangular arrays	2 × 1 array of 18 mm circle diameter



(a) (b)

Fig. 15. Final patch antenna design, (a). rectangular, (b). array.

V. CONCLUSION

A study on designing DGS models is reported here. The results show that the ground plane at the back side of the substrate should have a slot of DGS to perform a wider bandwidth or enhanced gain over the full ground plane design. The rectangular antenna with a frame-shaped DGS improves the fractional bandwidth by almost 10x. The array antenna enhances the antenna gain of 16 dB using

DGS. The patch rectangular antenna is miniaturized by 10% from the initial patch, while the array patch antenna is miniaturized by 73% in the DGS model. The miniaturized patch antenna with DGS can achieve properties suitable for broadband applications.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All the authors have contributed to this work. Riva, Yosi, and Yus designed the antenna. Riva and Yosi simulated the program and optimized the antennas' parameters. Yus analyzed the simulation and wrote the paper. Dian and Dwi analyzed the data and reviewed the paper. Yudi and Catur reviewed the paper to the final version. All the authors approved the final version of the paper.

Funding

This research has been funded by Universitas Telkom for number 184/S.KEP/PPM/TELU-JKT/IV/2023.

References

[1] C. A. Balanis, *Antenna Theory Analysis and Design*. 2016.
[2] B. Dwivedy, "Consideration of engineered ground planes for planar antennas: Their effects and applications, a review," *IEEE Access*, vol. 10, no. July, pp. 84317–84329, 2022.
[3] R. S. Elliott, *Antenna Theory & Design*, Los Angeles, California: John Wiley & Sons, Inc, 2003.
[4] M. K. Khandelwal, B. K. Kanaujia, and S. Kumar, "Defected ground structure: Fundamentals, analysis, and applications in modern wireless trends," *Int. J. Antennas Propag.*, vol. 2017, 2017.
[5] Y. H. Chen and C. N. Chiu, "An ultrawideband bidirectional absorptive common-mode filter with all-pass signal transmission," *IEEE Access*, vol. 10, pp. 50000–50007, 2022.
[6] X. Luo, J. G. Ma, and E. P. Li, "Hybrid microstrip/DGS cell for filter design," *IEEE Microw. Wirel. Components Lett.*, vol. 21, no. 10, pp. 528–530, 2011.
[7] T. Huang, H. Liu, C. Guo, L. Feng, and L. Geng, "3-D Printed mm-wave filter using increased-height DGS resonator for spurious suppression," *IEEE Trans. Circuits Syst. II Express Briefs*, vol. 69, no. 11, pp. 4293–4297, 2022.
[8] K. Z. Hu, B. C. Guo, S. Y. Pan, D. Yan, M. C. Tang, and P. Wang, "Low-profile single-layer half-mode SIW filtering antenna with shorted parasitic patch and defected ground structure," *IEEE Trans. Circuits Syst. II Express Briefs*, vol. 70, no. 1, pp. 91–95, 2023.
[9] D. Tang and X. Luo, "Compact filtering balun with wide stopband and low radiation loss using hybrid microstrip and substrate-integrated defected ground structure," *IEEE Microw. Wirel. Components Lett.*, vol. 31, no. 6, pp. 549–552, 2021.
[10] S. K. Tseng, C. N. Chiu, Y. C. Tsao, and Y. P. Chiou, "A novel ultrawideband absorptive common-mode filter design using a miniaturized and resistive defected ground structure," *IEEE Trans. Electromagn. Compat.*, vol. 63, no. 1, pp. 66–73, 2021.
[11] B. Chen, R. K. Pokharel, S. K. Thapa, N. Jahan, and A. Barakat, "Design of 50-GHz low phase noise VCO employing two-branches DGS resonator in 0.18-μm CMOS technology," *IEEE Microw. Wirel. Components Lett.*, vol. 32, no. 10, pp. 1203–1206, 2022.
[12] C. Chen, Y. F. Mao, S. Tao, and M. Guo, "Compact dual-band monopole antenna with defected ground plane for Internet of things," *IET Microwaves, Antennas Propag.*, vol. 12, no. 8, pp. 1332 – 1338, 2018.
[13] Y. Liu *et al.*, "A pattern-reversal wideband antenna integrating metal rings, diodes-loaded stubs and defective ground," *IEEE Open J. Antennas Propag.*, vol. 3, no. July, pp. 722–731, 2022.
[14] D. W. Astuti, R. Fadilah, Muslim, D. Rusdiyanto, S. Alam, and Y. Wahyu, "Bandwidth enhancement of bow-tie microstrip patch antenna using defected ground structure for 5G," *J. Commun.*, vol. 17, no. 12, pp. 995–1002, 2022.
[15] D. Kumar, Candrakanta; Guha, "Communications asymmetric geometry of defected ground structure for rectangular microstrip: A new approach," *IEEE Trans. Antenna Propag.*, vol. 64, no. 6, pp. 2503–2506, 2016.
[16] M. Ayyappan and P. Patel, "On design of a triple elliptical super wideband antenna for 5G applications," *IEEE Access*, vol. 10, no. July, pp. 76031–76043, 2022.
[17] D. Gopi, A. R. Vadaboyina, and J. R. K. K. Dabbakuti, "DGS based monopole circular-shaped patch antenna for UWB applications," *SN Appl. Sci.*, vol. 3, no. 2, pp. 1–12, 2021.
[18] Y. Chang, N. Li, J. Zhao, Y. Wang, and Z. Yang, "A novel ultrasonic guided wave-based method for railway contact wire defect detection," *IEEE Trans. Instrum. Meas.*, vol. 71, 2022.
[19] S. Zhu, H. Liu, P. Wen, Z. Chen, and H. Xu, "Vivaldi antenna array using defected ground structure for edge effect restraint and back radiation suppression," *IEEE Antennas Wirel. Propag. Lett.*, vol. 19, no. 1, pp. 84–88, 2020.
[20] S. Nej, A. Ghosh, S. Ahmad, J. Kumar, A. Ghaffar, and M. I. Hussein, "Design and characterization of 10-Elements MIMO antenna with improved isolation and radiation characteristics for mm-Wave 5G applications," *IEEE Access*, vol. 10, no. October, pp. 125086–125101, 2022.
[21] P. Kumar *et al.*, "Design of a six-port compact UWB MIMO antenna with a distinctive DGS for improved isolation," *IEEE Access*, vol. 10, no. October, pp. 112964–112974, 2022.
[22] M. Kim and S. Ahn, "Analytical approaches for effects of edge-located EBG structure with defected ground structure on cavity-mode resonances of power/ground planes," *IEEE Trans. Microw. Theory Tech.*, vol. 70, no. 12, pp. 5405–5417, 2022.
[23] S. Chakraborty, M. A. Rahman, M. A. Hossain, A. T. Mobashsher, E. Nishiyama, and I. Toyoda, "A 4-element MIMO antenna with orthogonal circular polarization for sub-6 GHz 5G cellular applications," *SN Applied Sciences*, vol. 2, no. 7. 2020.
[24] B. Maity and S. K. Nayak, "Compact quad-band CP series-fed circular slit microstrip array antenna using machine learning," *IEEE Access*, vol. 10, no. June, pp. 116650–116661, 2022.
[25] B. Qian, X. Huang, X. Chen, M. Abdullah, L. Zhao, and A. Kishk, "Surrogate-assisted defected ground structure design for Reducing mutual coupling in 2 × 2 microstrip antenna array," *IEEE Antennas Wirel. Propag. Lett.*, vol. 21, no. 2, pp. 351–355, 2022.
[26] S. Kuzu and N. Akcam, "Array antenna using defected ground structure shaped with fractal form generated by apollonius circle," *IEEE Antennas Wirel. Propag. Lett.*, vol. 16, pp. 1020–1023, 2017.
[27] International Telecommunication Union (ITU)-R, "ETSI TS 134 121-1 V13.0.0 (2016-08)," 2016.