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Design of Compact Monopole Antenna with U-Shaped Defected Ground Structure (DGS) for UWB Application

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Abstract

This paper described the design of a compact printed monopole antenna with U-shaped Defected Ground Structure (DGS) for ultrawideband (UWB) application. The implementation of DGS facilitates in reduction of size and increases in antenna performance. The DGS and antenna design parameters are simulated using CST Microwave Studio 2020, and the measurement is carried out using R&S Vector Network Analyzer (VNA). The optimized design of the proposed UWB antenna with U-shaped DGS presented smaller in size (23.88mm x 29.10mm x 0.813mm) with a reduction of 32% compared to the conventional design, which fabricated on Rogers RO4003C substrate with a relative permittivity, $\varepsilon_r = 3.38$. Simulation results show that the proposed antenna provided a very wide range of frequency (3.2 - 20GHz), 144.8% of BW. The simulated and measurement results show good agreement.

I. INTRODUCTION

The antenna is considered an ultrawideband (UWB) antenna if the operational bandwidth exceeds 500MHz or 20% of the centre frequency. Nowadays, the potential of the UWB antenna for imaging communication is high in future communication, and microwave imaging applications since the Federal Communications Commissions (FCC) has allowed UWB bands from 3.1 to 10.6 GHz for commercial usage [1, 2]. To achieve miniaturization of microwave devices, researchers focus on size reduction of the antenna and integration of multiband or UWB antennas into a unit. Antennas that are compatible with microwave circuit integration, such as multiband [3], broadband, wideband [4][5][6][7], and ultra-wideband antennas[8][9], are recommended.

Recently, a slotted hexagonal monopole antenna having an ultra-wideband of 123% (3.1-13 GHz) has been proposed [9]. It used printed round-slot geometry and DGS to achieve a broader bandwidth. Besides, a U-slot monopole antenna with 19.2 x 28.8 mm2 was presented with a 109.4% (4.1 - 14 GHz) fractional bandwidth [3]. A rectangular monopole antenna with a truncated ground plane was designed with a feeding mechanism, and the researcher achieved a 118.3% (3.8 - 14.8 GHz) bandwidth [12]. Other research also proposed a spanner shape monopole antenna with a rectangular slit [13]. This design has a UWB bandwidth of 112.5% (2.98-10.64 GHz). Rather than an elliptical radiating shape monopole antenna with fractional bandwidth of 116.5% (2.9 - 11GHz), an egg-like shape was used for the design instead to see if there is an improvement in the system. The egg design is generated based on Newton's diverging parabolas curve formula [14].

Monopole antennas are commonly selected as they are compact, simple, low-cost, and lightweight [15]. Such characteristics make monopole antennas that can be integrated into microwave imaging easily [16]. Recently, several types of monopole antennas have been designed to achieve wide bandwidth, such as circular [17], U-shape [11], square [18], elliptical [19], octagon shape [20], spline-shaped monopole [21] and egg [14].

Researchers have proposed several techniques, such as feeding line modification [22], meander line structures, and defected ground structures(DGS), to broaden the impedance bandwidth and optimize the characteristics of the antenna. DGS is the slots with various shapes implemented in the antenna's ground plane. Recent research proved that DGS does improve antenna performance, such as size reduction, radiation efficiency, bandwidth, and gain enhancement [23].

This paper describes a UWB monopole antenna with a U-shaped DGS capable of operating at ultra-wide bandwidth. U-shaped DGS is implemented to improve the impedance bandwidth and reduce the antenna size. To simulate an ideal situation, impedance matching is required to minimize return loss for the device; thus, a quarter waveguide transformer is used. The operating frequency for simulation is in the range of 3.2GHz to approximately 20GHz, while the measurement takes place in the range from 3.9GHz to about 8GHz.

II. DESIGN

In this research, a compact UWB monopole antenna is proposed and designed. First, a simple UWB antenna without DGS was designed. After that, DGS was implemented into the design in the second phase. The proposed UWB monopole antenna design with U-shaped DGS is shown in Figure 1 and Figure 2. The substrate used for the proposed antenna is Rogers RO4003C with a relative permittivity, ε_r of 3.38 and thickness of 0.813mm, respectively. The proposed antenna is shown in Figure 1.

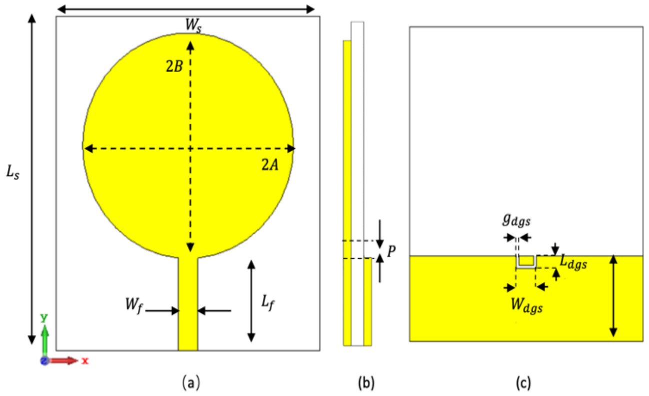

Figure 1. The proposed design of monopole antenna (a) front view (b) side view (c) back view

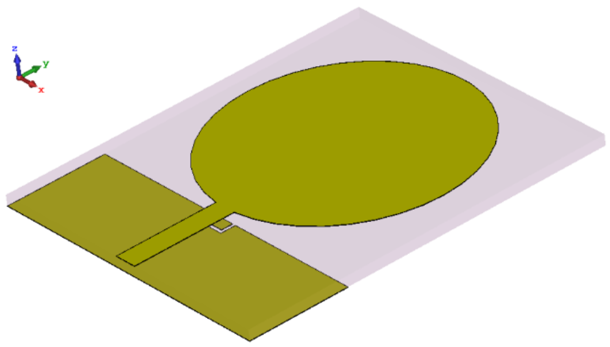

Figure 2. The proposed monopole antenna design (3D view)

A. *Patch Size (A & B)*

With modification, the estimation of lower band edge frequency corresponding to $|S11| \leq -10$ dB is calculated based on cylindrical monopole antenna formulae. L in cm corresponds to the height of the equivalent cylindrical monopole, while r in cm is the antenna's radius, which is equivalent to the effective radius of the cylindrical monopole [24].

$$f_L = \frac{c}{\lambda} = \frac{7.2}{L + r + P} GHz \qquad (1)$$

$$L = 2B \qquad (2)$$

$$r = \frac{A}{4} \qquad (3)$$

where f_L is the lowest limit frequency, A and B are the radius of the patch antenna on the X and Y-axis, respectively. The design of the 50 Ω feedline is optimized to 0.1 mm, represented by unit P for the patch. L and r are the length and radius of the antenna, respectively. For simplicity, all the parameters L, r, and P in the formulas are all in centimetres.

Using the value of the proposed antenna will result in f_L = 1.982 GHz to be an estimated working lower limit frequency.

B. *Ground Plane Layer Length (Lg)*

The ground plane length has the design of a quarter wavelength of lower band-edge frequency, which is at 3.1 GHz. As for its width, it will follow the existing width of the substrate.

$$L_g = \frac{\lambda}{4} = \frac{c}{4\,k\,f_L} \qquad (4)$$

where Lg is the lower plane layer length, c is the speed of light, $k=\sqrt{\varepsilon_{eff}}$, while f_L is the lowest limit frequency calculated in (1).

C. *Substrate Dimensions*

The width of the ground plane controls the width of the substrate. However, the roll-off pattern is highly dependent on the back radiation produced by the ground plane [22]. The proposed design of the antenna will be wider than the patch but still fall within the antenna patch's specification. It should be able to yield a rapid roll-off pattern with the proposed antenna design. The parameters and dimensions of the proposed design are shown in Table 1.

Table 1
Proposed Design's Dimension

Parameters	Values (mm)
A	15
B	13
L_s	30
W_s	34
g_{dgs}	0.388
W_{dgs}	1.5
L_{dgs}	1
W_f	1.795
L_f	8
P	0.1

III. RESULTS

The presence of DGS on the ground plane is responsible for the generation of ultra-wide bandwidth and miniaturization. With commercial-based Finite-Integration Technique (FIT) electromagnetic virtual simulation software, CST-Microwave Studio-2020, the antenna was simulated with dimensions as calculated. The following sections discussed the improvement of the antenna's performance, such as optimized antenna characteristics and size reduction. A parametric study of U-shape DGS was also conducted.

A. *Effect of DGS on the Ground Plane*

The effect of the existence of DGS on the ground plane has been studied in this section. The comparison of return loss characteristics, S_{11} (dB), between the existence of DGS on the ground plane of the antenna is shown in Figure 3. The antenna with DGS shows simulated impedance with the bandwidth of 13.3 GHz (2.97 – 16.3 GHz) (defined by -10 dB), while the antenna without DGS has an impedance bandwidth of 5.03 GHz (2.97 – 8 GHz). From the simulation result in Figure 3, the bandwidth of the antenna with DGS is comparatively wider (164.41% improvement) due to the existence of DGS on the ground plane. The simulated S_{11} (dB) shows that the antenna falls into the microwave class as it covers the frequency range's S-band, C band, and X band. Therefore, the designed antenna falls in the frequency range Ultra-Wide Band (UWB), which makes it a UWB-type antenna.

The function of DGS is to change the transmission line characteristics by disturbing the ground plane current distribution with the presence of DGS on the ground plane [25]. That is, the presence of a microstrip line will directly influence the value of slot capacitance, inductance, and resistance [23]. Thus, the resonance frequency for the antenna can be predicted. Changes in the area for the slot will directly change the property of effective inductance and its capacitance, although it is made of the same substrate. The decrement of the slot area led to the increment of effective inductance, and, as a result, the effective capacitance will decrement, and the resonance frequency will increase because of the increase of the slot area [23].

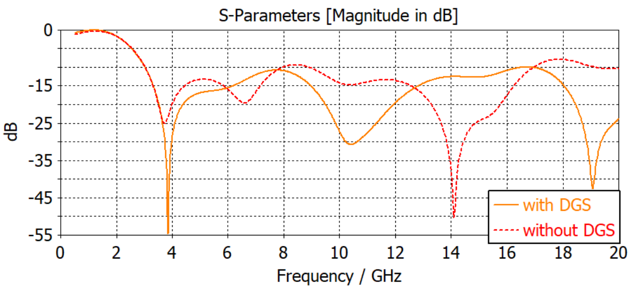

Figure 3. Result of S_{11} (dB) with and without the presence of DGS

B. Effect of Various Dimensions of DGS on Antenna Response

This section indicates the parametric study for the DGS width (W_{dgs}), length (L_{dgs}), and gap (g_{dgs}). The dimension of DGS heavily influences the frequency response characteristic of the antenna etched on the ground plane. The simulated result was produced by using the parameter shown in Table 1. The back side of the microstrip line was being etched with U-shaped DGS after its dimension was selected as the dimension will affect the matching bandwidth of the feedline.

Bandwidth is obtained by taking the difference of frequency that starts to fall below -10dB range until the frequency rises above -10dB. The first parameter is the width of the slot on the ground plane is represented by 'Wdgs'; its parametric study with Wdgs being slightly adjusted and the results were as shown in Figure 4(a). From the simulated result, when Wdgs increase from its proposed value, its bandwidth reduces. When W_{dgs} is 1.5mm, the largest bandwidth is 13.43 GHz (2.97 – 16.4 GHz).

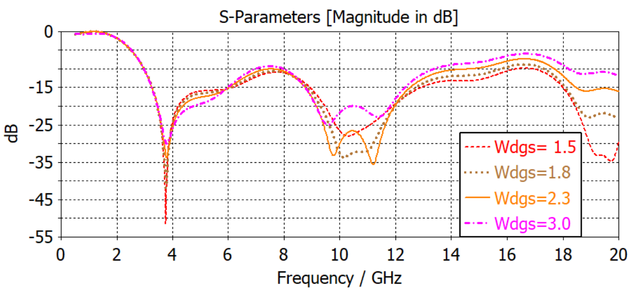

Figure 4(a). Variation of S11 (dB) with the width of DGS, W_{dgs}

The second parameter is the ground plane's length, denoted by 'L_{dgs}', as indicated in Figure 4(b). The simulated result proved that the proposed value is the optimum value, while the introduction of value aside from the proposed 'L_{dgs}' will compromise its bandwidth and performance.

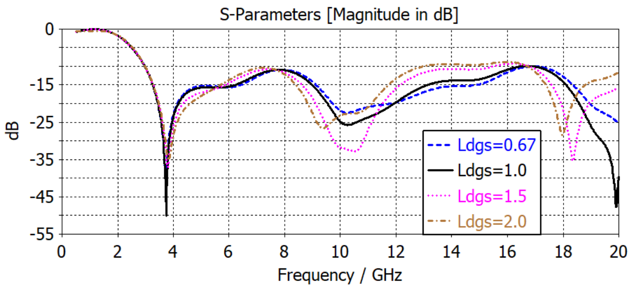

Figure 4(b). Variation of S11 (dB) with the different lengths for DGS structure, L_{dgs}

The thickness of the slot will be the third parameter, denoted by 'g_{dgs}', as indicated in Figure 4(c). The simulated result also proved that parameters aside from the proposed value would reduce bandwidth. When the value of g_{dgs} is increased, the bandwidth is also reduced.

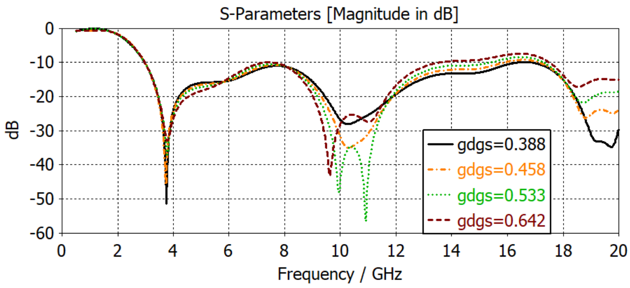

Figure 4 (c). Simulated result of S11 (dB) by using tweaking the parameter g_{dgs} of DGS structure

C. Effect of DGS on Antenna Size

This section discusses the effect of DGS on antenna size design. The existing antenna size is then optimized to a smaller, more compact with a 51.8% reduction in size for the antenna patch area. With the addition of DGS to the reduced antenna size design, the simulated result yields a satisfying result, as shown in the black line in Figure 5. The simulated result of the reduced size antenna without DGS does not produce a desirable result as S11 raises to above -10dB mark for the simulated frequency at about 5GHz to 6.3GHz and 9GHz to 11GHz.

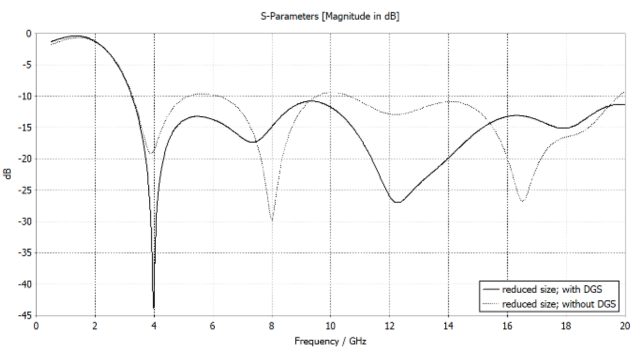

Figure 5. S_{11} (dB) comparison of the reduced size antenna with DGS and without DGS

The comparison of the dimension of the original values with the optimized value is shown in Table 2. This shows that the addition of DGS does improve the result. Thus, with the addition of DGS, the overall antenna design can be further optimized to be 32% smaller than the normal size antenna with DGS.

Table 2
Optimize Design

Parameters	Original Values (mm)	Optimized value (mm)
A	15	9.6
B	13	9.8
L_s	30	29
W_s	34	24
g_{dgs}	0.388	0.388
W_{dgs}	1.5	1.5
L_{dgs}	1	1

D. Radiation Pattern

The polarization of an antenna is loosely defined as the direction of the electromagnetic fields produced by the antenna when energy radiates out. These directional fields influence the direction in which an antenna radiates or receives energy. Figures 6 and 7 show the antenna's co-polarization type and cross-polarization type radiation patterns at 4 GHz and 7 GHz, respectively. Investigation of radiation patterns falls in the UWB frequency spectrum. Figures 6 and 7 show that the proposed UWB monopole antenna with U-shaped DGS has an omnidirectional radiation pattern.

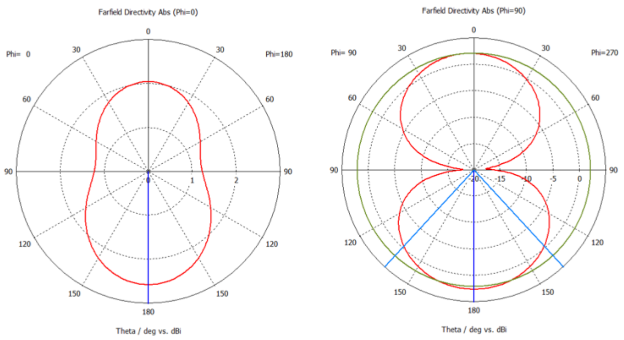

Figure 6. Simulation E-plane and H-plane radiation pattern at f =4 GHz

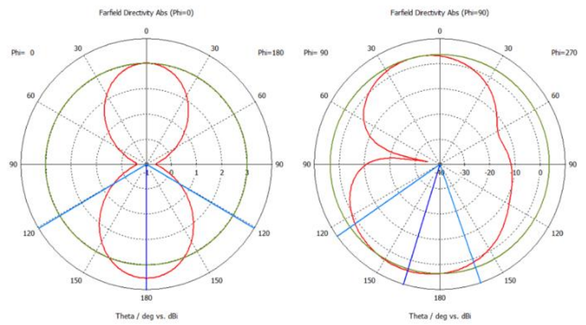

Figure 7. Simulation E-plane and H-plane radiation pattern at f =7 GHz

E. Simulated Gain of The Proposed Antenna

The simulated realized gain of the proposed monopole antenna is presented in Figure 8. The gain of the proposed monopole antenna was more than 1 dB over the UWB operating band. It can be observed that the proposed antenna gain gradually enhanced towards the upper frequencies for the entire BW of UWB (3.1–10.6 GHz).

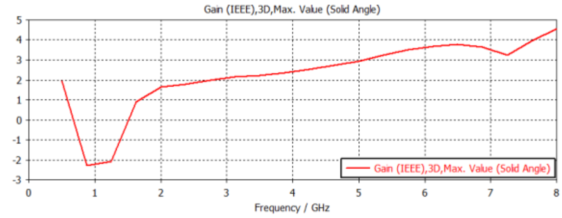

Figure 8. Simulated realized gain of the proposed antenna

F. Measurement Results

Figure 9 shows the dimension of the fabricated antenna with a U-shaped DGS. The fabrication of the proposed antenna uses a photo-fabrication process. The antenna layout was drawn using AutoCAD software based on the designed antenna specification in CST Microwave Studio 2020 and printed onto the transparent plastic film. Then, a photoresist film is rolled onto substrate sheets using a heating machine. The printed layout of plastic film is imaged to the substrate sheets after exposure to UV light. The antenna is then etched and soldered with an SMA connector.

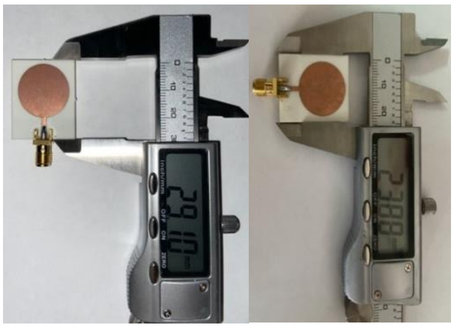

Figure 9. The dimension of Fabricated Antenna (a)Length (b)Width

The measurement of S11 (dB) of the antenna is performed by using an R&S vector network analyzer (VNA). Based on Figure 10, the S11 (dB) for simulation and measurement results are compared and illustrated. As shown in Figure 10, there is a slight difference between S-parameter in simulation and the actual measured value; this could be due to the fabrication tolerance of the material. The operating frequency of the measured antenna starts from 3.9 GHz, which is shifted by 0.7 GHz from the simulation value. However, the S11 (dB) of the measured and simulated result of the antenna continues to be under −10 dB throughout the 8GHz frequency. The measurement result can only reach a maximum of up to 8GHz due to the limitation of R&S VNA. Generally, the measured monopole UWB antenna with U-shape DGS shows an acceptable result to operate in radar and microwave imaging applications. Some significant measured such as ripple occurred due to the calibration of the equipment itself and the uncontrollable environment. From [27], the type of SMA connector used is also one factor that affects the measurement result. Besides, different simulation solvers such as ADS and CST (selected simulation tool) also cause the simulated return loss slightly due to different solvers [28].

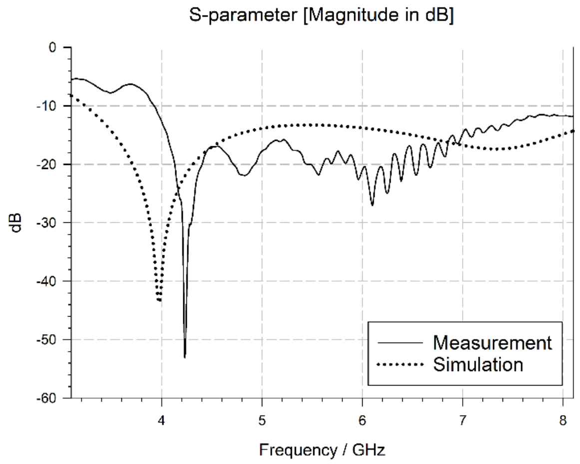

Figure 10. Simulated versus measured results of return loss (dB) against frequency (GHz)

IV. CONCLUSION

A compact monopole antenna with a U-shape DGS that is capable of an ultra-wide bandwidth and high efficiency has been designed in this paper. The dimensions of the antenna with 3.2 GHz - 20 GHz, which is 23.88mm x 29.10mm x 0.813mm, are smaller than the conventional design. Due to VNA equipment limitations, the measured result will only provide a frequency range of up to 8GHz. Regardless, the simulated result and measured result do not differ much from each other. U-Shaped DGS does improve the antenna performance in terms of bandwidth and size reduction. The monopole antenna with U-shaped DGS is simple and easy to fabricate at a low cost.

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