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Impact of Substrate Material on The Performance of Circular Loop Patch Antenna with Partial Ground

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Abstract
This articles outline the design of a circular loop antenna aimed to millimetre wave applications operating within the frequency range of 20 GHz to 55 GHz. A multi-objective function for the antenna has been established on a substrate measuring 14mm x 14mm x 1.6mm to optimize both its bandwidth and gain. The antenna design utilizes Rogers RT/duroid 5870 dielectric material, which has a dielectric constant (ε_r) of 3.55 and a loss tangent (δ) of 0.0027. Following the successful optimization of the antenna, its performance is evaluated through the assessment of return loss is -29.8 dB, VSWR is 0.56 dB and Gain is 6.62 dB characteristics with a partial ground plane. Finally, after achieving the specified objectives, a radiation characteristics analysis is performed to explore the antenna's radiation properties. This study illustrates how the choice of substrate material influences the performance metrics of the antenna, including radiation pattern, gain, directivity, and VSWR [8].

Keywords: *Substrate material, Return loss, VSWR, Gain, Roger, FR4*

1. Introduction
The advent of fifth-generation (5G) wireless communication has brought about a paradigm shift in the field of antenna design, particularly in relation to millimetre wave applications [1]. Millimeter waves, operating in the frequency range of 24 GHz to 300 GHz, offer vast bandwidths and high data rates, making them a key component of 5G networks [2]. As a result, there is a growing demand for antenna systems capable of efficiently transmitting and receiving millimeter wave signals in 5G applications [3]. The unique characteristics of millimeter waves pose both opportunities and challenges in antenna design [6]. On the one hand, the availability of large bandwidths allows for substantial data transmission rates, enabling applications such as ultra-high definition video streaming, virtual reality, and Internet of Things (IoT) connectivity. On the other hand, millimetre waves have a limited range and are susceptible to atmospheric attenuation and blockage by physical obstacles, necessitating the development of highly directive and efficient antenna systems. The substrate material in a patch antenna is a critical component that significantly influences its performance. It is the dielectric layer positioned between the radiating patch and the ground plane. Several factors must be considered when selecting a substrate. The dielectric constant (ε_r) determines the impedance, efficiency, and bandwidth of the antenna, with lower values (f_l) preferred for better radiation and broader bandwidth. The thickness of the substrate affects bandwidth and efficiency, with thicker substrates improving bandwidth but potentially increasing surface wave losses. A low loss tangent (δ) is essential to minimize energy dissipation and

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enhance efficiency. The thermal stability and mechanical robustness of the substrate are vital for maintaining consistent performance under varying environmental conditions, such as temperature fluctuations or mechanical stress. Additionally, the substrate material should have good frequency compatibility, ensuring minimal signal degradation at the operating frequency. Common materials include FR-4, which is cost-effective but has moderate losses; Teflon, known for its low-loss properties at high frequencies; and Rogers/Duroid, premium options offering low loss and high performance for advanced applications [4]. The choice of substrate is dictated by factors such as operating frequency, desired efficiency, size constraints, manufacturing ease, and budget considerations. Modern advancements include 3D-printed substrates with tailored properties, bio- sourced environmentally friendly options, and meta-substrates that enhance performance [5]. Selecting the right substrate is vital to ensuring the antenna meets the specific requirements of its application while achieving a balance between performance and cost.
The effective dielectric constant ε_{eff} is derived from Eq. (1)

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2} \quad (1)$$

2. Geometry of Antenna

The dimensions of circular patch antenna is calculated for the dominant TM_{110}^{Z} mode, where z is the vector perpendicular to the circular patch. The substrate the height h is much smaller than the resonant wavelength λ. The ground plane is assumed to be infinite and all the metallic surfaces are lossless. Due to the fringing of fields the electrical size of the circular patch is larger than its physical radius a and it is calculated a_e is derived from Eq. (2) and (3)

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

$$a_e = a\left\{1 + \frac{2h}{\pi a \varepsilon_r}\left[ln\left(\frac{\pi a}{2h} + 1.7726\right)\right]\right\}^{1/2} \quad (3)$$

The geometry of partially grounded florescent shaped circular loop patch antenna is shown in figure.1 & 2. The dimensions of the substrate are 14mm x 14mm, the thickness of the substrate is 1.6mm. Ground is partially structured and the dimensions are shown in table 1. The antenna uses the microstrip line feeding technique. It is the dielectric layer positioned between the radiating patch and the ground plane. Several factors must be considered when selecting a substrate operating frequency, desired efficiency, size constraints, manufacturing ease, and budget considerations Figure 1 shows Structure of Proposed Circular Loop Patch Antenna, Figure 2 shows Proposed Partial Ground Plane

Table 1 Dimension of Proposed Circular Loop Patch Antenna

Parameter	Dimension (mm)
L1	8
W1	12
R1	2
R2	1.2
R3	0.5
R4	0.3
F1	2x0.75
F2 & F3	0.2x2

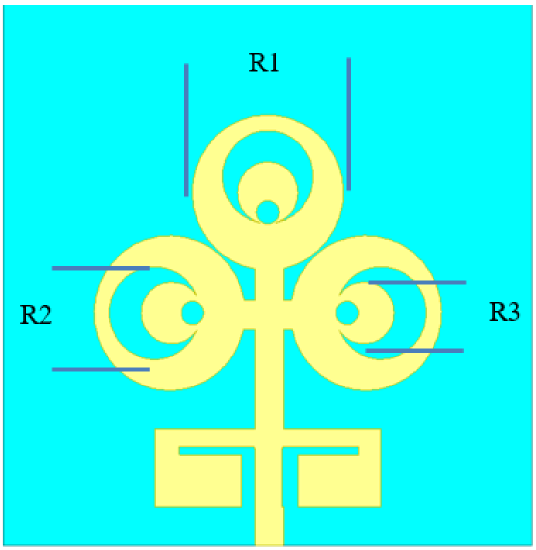

Figure 1 Structure of Proposed Circular Loop Patch Antenna

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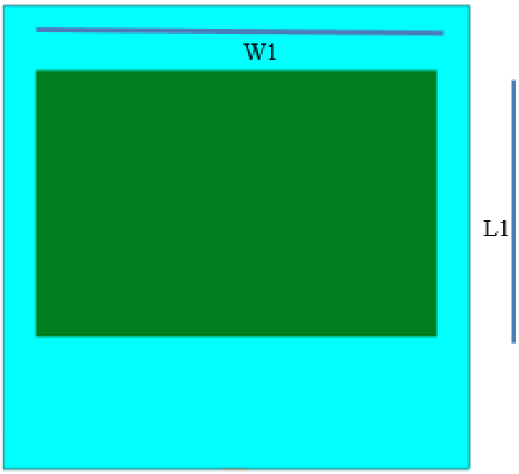

Figure 2 Proposed Partial Ground Plane

3. Results and Discussion

The result of the return loss is shown in fig. 3. From the result RT Duroid 5870 shows the better result than FR4 substrate material [9]. It obtains -29.8 dB at 27.17 GHz where FR4 value is -15.4 dB at 22 GHz values are listed in table 2. The result of VSWR measurement is shown in the fig. 4. From the result RT Duroid 5870 shows the better result than FR4 substrate material [10]. It obtains 0.56 dB at 27.17 GHz where FR4 value is -2.99 dB at 2.89 GHz values are listed in table 2. Figure 3 shows Return Loss of Different Substrate for Proposed Circular Loop Antenna, Figure 4 shows VSWR Measurement of Different Substrate for Proposed Circular Loop Antenna

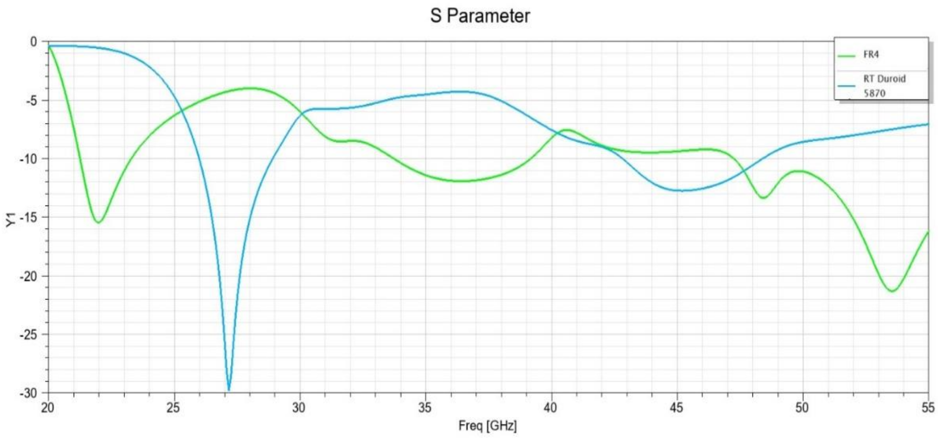

Figure 3 Return Loss of Different Substrate for Proposed Circular Loop Antenna

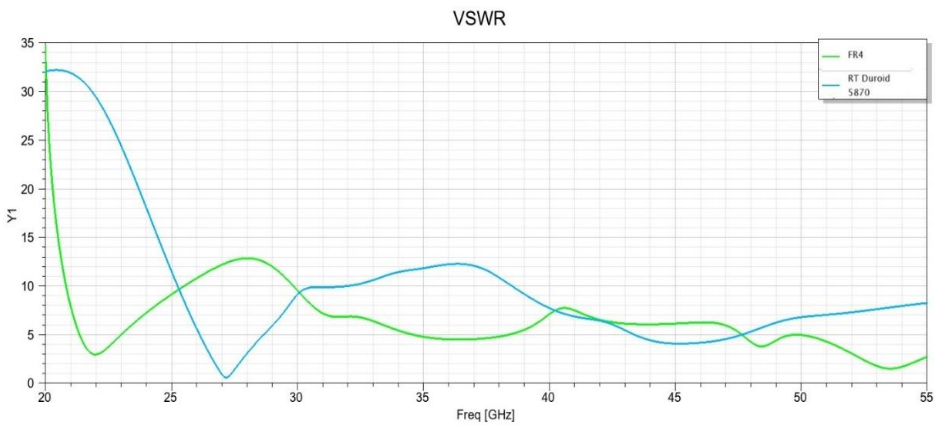

Figure 4 VSWR Measurement of Different Substrate for Proposed Circular Loop Antenna

The result of gain is shown in the figure 5, 6. From the result RT Duroid 5870 shows the better gain than FR4 substrate material. It obtain 6.62 dB where FR4 is 2.43 dB values are listed in table 2.

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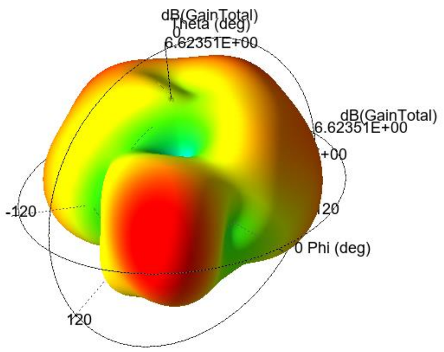

Figure 5 **Gain of RT Duroid 5870 Substrate for Proposed Circular Loop Antenna**

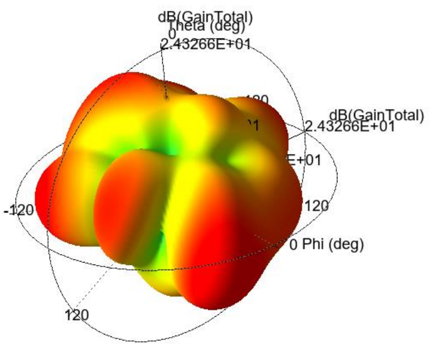

Figure 6 **Gain of FR4 Substrate for Proposed Circular Loop Antenna**

Table 2 **Result of Proposed Circular Loop Patch Antenna at Frequency 53.2 GHz**

	Return Loss	VSWR	Gain
FR4	-15.4 dB	2.99 dB	2.43 dB
RT Duroid 5870	-29.8 dB	0.56 dB	6.62 dB

Conclusion

Various parameters of desired proposed circular loop patch antenna have been studied by using different substrates [12]. It is found that by selecting a suitable substrate specific antenna requirement can be met. It can be concluded that Rogers RT/duroid 5870 is the most efficient amongst the other substrate material used in circular loop and has a satisfactory value of return loss is -29.8 dB, VSWR is 0.56 dB and Gain is 6.62 dB. This proposed circular loop antenna is suitable for millimetre wave applications [13].

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