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Analysis of Radiation Structure of Circular Microstrip Antenna using Characteristic Mode Analysis for ISM Band

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ABSTRAK

Makalah ini bertujuan untuk melihat karakteristik struktur radiasi menggunakan Analisis Mode Karakteristik pada antena sirkular array. Kontribusi utama dari pekerjaan ini adalah menganalisis penyebab masalah antena yang tidak sesuai dengan impedansinya pada frekuensi 2,4 GHz melalui mode distribusi arus pada patch atau radiasi. Pencocokan impedansi dapat dicapai dengan menetapkan slot ke dua patch yang tersusun dan memberikan efek peningkatan bandwidth dan gain. Untuk validasi hasil performansi antena dapat dilihat dari mode aktif pada frekuensi yang sesuai. Ditemukan bahwa antena yang diusulkan memiliki dua mode aktif pada frekuensi 2,4 GHz. Ditemukan bahwa antena yang digunakan cukup akurat. Hal ini dibuktikan dengan nilai S11 sebesar -19,606 dB dan gain sebesar 3,45 pada frekuensi 2,45 GHz.

Kata kunci: *antena, mikrostrip, characteristic mode analysis, ISM Band, 2.4 GHz*

ABSTRACT

This paper aims to see the characteristics of the radiation structure using Characteristic Mode Analysis on circular array antennas. The main contribution of this work is to analyze the causes of the problem of the antenna not matching its impedance at the 2.4 GHz frequency through the current distribution modes on the patch or radiation. Matching impedance can be achieved by assigning slots to the two arrayed patches and increasing bandwidth and gain. It can be seen from the active modes at the appropriate frequency to validate the results of antenna performance. The proposed antenna has two active modes at a frequency of 2.4 GHz. It is found that the proposed antenna is entirely accurate. It is proven by the S11 value of -19.606 dB and the gain of 3.45 at a frequency of 2.45 GHz.

Keywords: *antenna, microstrip, characteristic mode analysis, ISM Band, 2.4 GHz*

1. INTRODUCTION

One of the most popular wireless network developments today is wireless fidelity (Wi-Fi) which operates at a frequency of 2.4 GHz. In addition to wireless technology, sensor device technology and computers are increasingly making it possible to build a communication network of sensors and sophisticated devices through the internet network commonly known as the Internet of Things **(Gardašević et al., 2020) (Philip et al., 2021) (Sabila et al., 2021)**. Internet of Things (IoT) can be defined as a computer network that includes integrated technologies to help devices communicate information in wireless environments and settings. IoT allows these devices to be controlled remotely by providing wireless communication, resulting in several economic benefits and increased efficiency **(Perwej et al., 2019) (Motlagh et al., 2020)**. The internet has now been expanded by the Internet of Things (IoT). It is a vast, quickly expanding network of interconnected things that supports a wide range of sensors, actuators, and input-output devices using defined communication protocols. An antenna that sends and receives radio waves that contain sensor data information is required in order to connect remote sensors using a Wi-Fi network. With the rapid advancement of IoT technologies, antennas will increasingly become crucial in wireless sensor technology. There are more and more applications in many industries, including as security, tracking, agriculture, smart cities, and smart homes **(Haque et al., 2022) (Mohammed et al., 2020)**. Unlicensed transmission of combined communication data in higher frequencies operating in the 2.4 GHz industrial, scientific and medical band. The antenna is considered one of the essential components of a wireless communication system as it helps to improve performance and overall system requirements if appropriately designed **(Jijo et al., 2021) (Al-Gburi et al., 2022) (Sabila et al., 2022) (Sabila et al., 2022)**. Microstrip patch antennas are commonly used in IoT applications due to their compatibility, low profile, lightweight applications and precision in the microwave frequency region. Microstrip antenna is widely developed and used in telecommunication devices, one of which is Wi-Fi, because it has several advantages, including its simple shape and eases to manufacture.

Microstrip antennas with one transmitting element have several benefits; they are cheap, smaller in size and lighter in weight **(Shereen et al., 2022) (Alharbi et al., 2022)**. However, in addition to the advantages of one of the radiation elements, it has several disadvantages, such as narrow bandwidth and limited gain. In this study, we will overcome the lack of gain in microstrip antennas by implementing two beam elements in an array configuration. The author in **(Cramer et al., 2019)** presented a wearable antenna using the slot method and line feeding for matching impedance with dimensions 128.1 x 71.1 mm. Their antenna had S11 under -10 dB at 2.4 GHz and a gain of 7.75 dB. The various antenna is proposed in **(Supriyanto et al., 2018)** the design using array method with e-shaped for the patch to get better performances. The measurement result shows frequency resonant at 2.414 GHz and a gain of 4.33 dB.

The theory of characteristic modes is a relatively recent development in antenna design. It applies this theory without being excited. It is possible to obtain a radiating structure's natural resonance frequencies and gain insight into its behavior from the designer so that it can serve its intended purpose. A compact and broadband CP antenna using the combined monopole and slot structures has been presented in **(Tran et al., 2018)** with dimension $0.29\lambda o \times 0.29\lambda o \times 0.01\lambda o$, where λo is the wavelength at the lowest operating frequency. A systematic design procedure is proposed with the theory of Characteristic Mode Analysis (CMA). A coplanar waveguide-fed ring slot antenna is offered for the generation of circular polarization, as presented in **(Saraswat and Harish, 2018)**. It is demonstrated that including a stub can increase bandwidth. Understanding wideband behavior and circular polarization creation in various antenna configurations is done via characteristics mode analysis. A frequency reconfigurable patch antenna design based on the characteristic mode analysis is presented in **(Mahlaoui et al., 2019)**. The antenna's ground plane has a slot engraved into it. A metallic rectangular plate measuring 29 mm by 31 mm is used by CMA over a ground plane measuring 35 mm by 50 mm. This demonstrates that at its resonance frequency, there are six modes.

2. METHODOLOGY

2.1 Microstrip Antenna

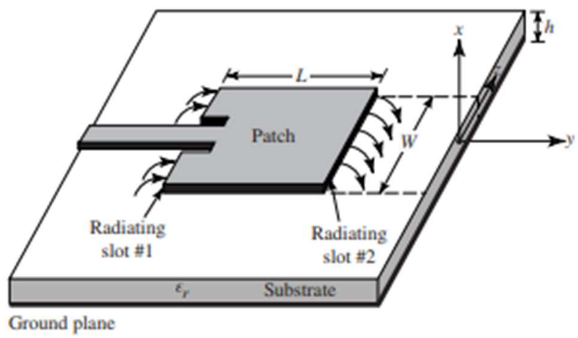

Figure 1. Microstrip Antenna

Low-profile antennas may be necessary in high-performance aircraft, spacecraft, satellite, and missile applications where size, weight, cost, performance, ease of installation, and aerodynamic profile are constraints. Similar requirements can be found in numerous other governmental and commercial uses, including wireless communications and mobile radio. Microstrip antennas can be utilized to satisfy these needs. As depicted in Figure 1, a microstrip antenna is made out of a thin metallic strip (patch) that is elevated slightly above the ground plane. Patch antennas are another name for microstrip antennas. Typically, the feed lines and radiating elements are photoetched onto the dielectric substrate. The radiating patch can be shaped whatever you like: square, rectangular, thin strip (dipole), circular, elliptical, triangular, etc. The feed line feeding technique is also depicted in Figure 1. The microstrip-line feed is simple to model, easy to manufacture, and easy to match by adjusting the inset location.

2.2 Characteristic Mode Analysis

Characteristic Mode Theory (CM), commonly known as Characteristic Mode Analysis (CMA), was first developed by Garbacz in 1968 and later acquired by Harrington and Mautz. The material widely used in this CMA theory is the Perfect Electrical Conductor (PEC). PEC is the conducting part of the antenna body. The presence of an electric field (E) hitting the conductor body on the surface (S) can cause a current (J) on the surface. This current surface will produce a scattered field so that the CMA formula can be used as a current relationship (J) on the surface (S) of the conducting material. Characteristic modes are obtained through the impedance matrix and then solving the generalized eigenvalue problem:

$$Z(J) = R(J) + jX(J) \quad (1)$$

$$X(\overrightarrow{J_n}) = \lambda_n R(\overrightarrow{J_n}) \quad (2)$$

Where λ_n is an eigenvalue, $\overrightarrow{J_n}$ is eigencurrent and R and X are real and imaginary parts of the impedance Z. The eigenvalues are essential because their magnitude provides information about the resonant frequency and transmitter properties of different current modes. In addition, another two parameters of the characteristic mode analysis are modal significance and characteristic angle.

2.2.1 Eigenvalue

In general, the eigenvalues of λ_n range from -∞ sampai + ∞. A resonant mode (J_n) is when the associated eigenvalue is zero. In addition, the eigenvalue sign determines whether the mode contributes to storing magnetic energy ($\lambda_n > 0$) or electrical energy ($\lambda_n < 0$). While $\lambda_n = 0$ is resonant

2.2.2 Modal Significance

Modal significance (MSn) represents the normalized amplitude in the current mode, can be expressed as:

$$MS_n = \left|\frac{1}{1+j\lambda}\right| \tag{3}$$

2.2.3 Characteristic Angle

The characteristic angle is defined as:

$$\alpha_n = 180° - tan^{-1}(\lambda_n) \tag{4}$$

The mode is resonant when λ_n = 0, i.e. when the characteristic angle λ_n is 180º. Therefore, when the characteristic angle is close to 180º, the mode is a good radiator, while when the characteristic angle is close to 90º or 270º, this mode is mainly energy saving.

2.3 Specifications and Initial Design

Table 1. Spesifications Antenna

Parameter	Spesification
Frequency range	2.4 GHz – 2.484 GHz
Resonant frequency	2.422 GHz
Bandwidth	84 MHz
S_{11}	≤ -10 dB
Gain	≥ 2 dBi
Radiation pattern	Directional

Table 2. Nominal Size of Antenna

Factor	Size
Radius Patch (r)	13.5 mm
Slot Width (Ws)	0 mm
Slot Height (Ls)	0 mm

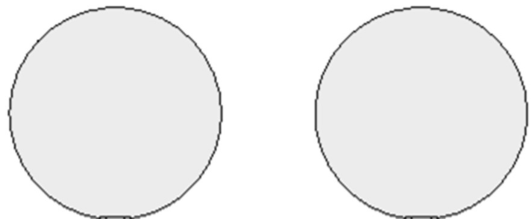

Figure 2. Initial Design

The antenna specifications have been created before the design process began, as shown in Table 1. CST Microwave Studio was utilized to simulate the antenna design. The board thickness for this antenna is 1.6 mm, the FR dielectric material has a dielectric constant of 4.3, and the copper layer is 0.035 mm thick. The microstrip antenna's nominal size was estimated using the design procedures in Table 2. Figure 2 depicts the antenna's original design. An antenna array with a circular structure is set up in a 2x1 array. The advantage of the circular structure is that it is simple to create. In the initial step, all that needs to be done is determine the patch circle's radius based on the desired frequency.

3. RESULT AND DISCUSSION

3.1 Characteristic Mode Analysis of Initial Design

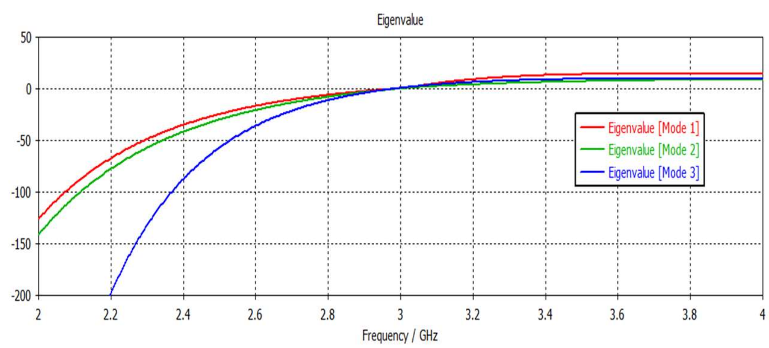

Figure 3. Eigenvalue Initial Design

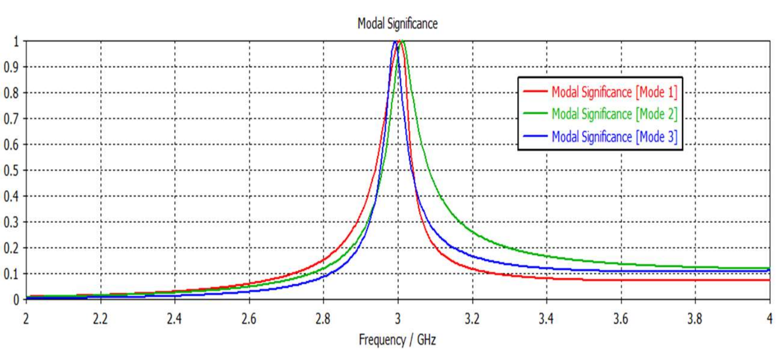

Figure 4. Modal Significance Initial Design

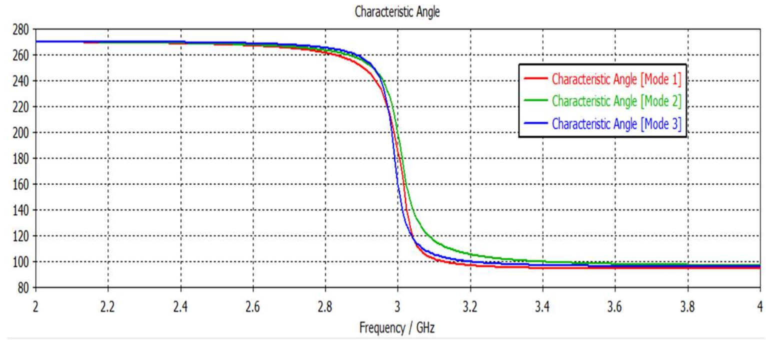

Figure 5. Characteristic Angle Initial Design

From the antenna design in Figure 2, CMA can be studied on the radiating structure. Figure 3 to figure 5 shows the first three mode eigenvalue, modal significance and characteristic angle. The x-axis shows the frequency and the y-axis shows the CMA value in three modes (J_n). It can be seen that the first mode (J_1), second mode (J_2) and third mode (J_3) have values that coincide. J_1, J_2, and J_3 in Figure 3 have a value of λ_n=0 at a frequency of 3 GHz. From Figure 4, the resonance of each mode can be identified with a maximum value of one on the modal significance curve. J_1, J_2, and J_3 have a capital significance value close to one at the 3 GHz frequency. While Figure 5 presents the variation in the frequency of characteristic angles (α_n). The mode is resonant when λ_n = 0, when the characteristic angle is 180º, i.e. at a frequency of 3 GHz.

3.2 Characteristic Mode Analysis of Optimization Antenna Design

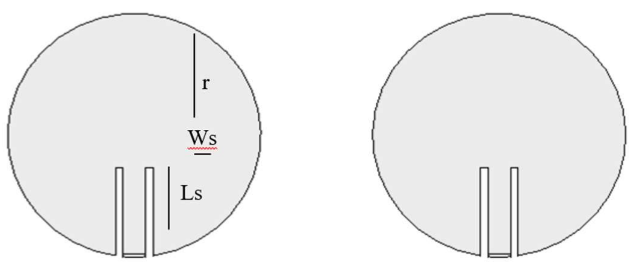

Figure 6. Design Antenna Optimization

Table 3. Final Size of Antenna

Factor	Size
Radius Patch (r)	17 mm
Slot Width (Ws)	1 mm
Slot Height (Ls)	12 mm

Figures 4 to 5 show that the resonant frequency does not match the required specifications, namely 2.4 GHz. Therefore, optimization of the antenna design is carried out. The optimization variation is done by changing the size of the antenna radius and adding slots. The optimization of the antenna design is shown in Figure 6. The final size of the microstrip antenna was calculated directly from its design formulas in Table 3. The antenna design in Figure 6 produces the eigenvalue, modal significance and characteristic angle, which can be seen in Figures 7 to 9.

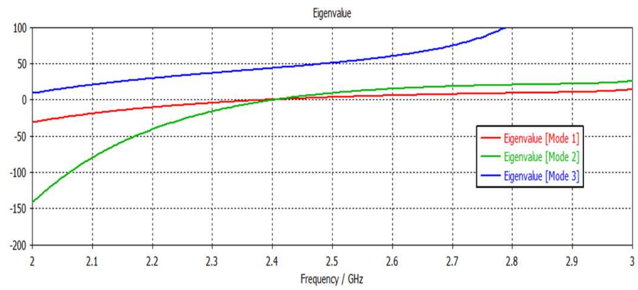

Figure 7. Eigenvalue

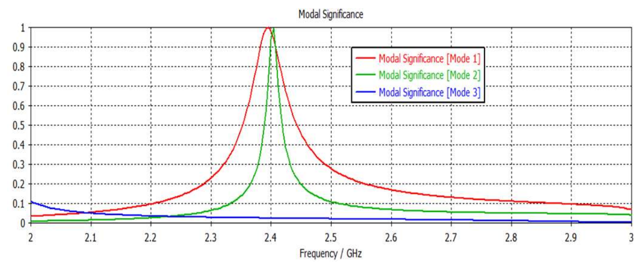

Figure 8. Modal Significance

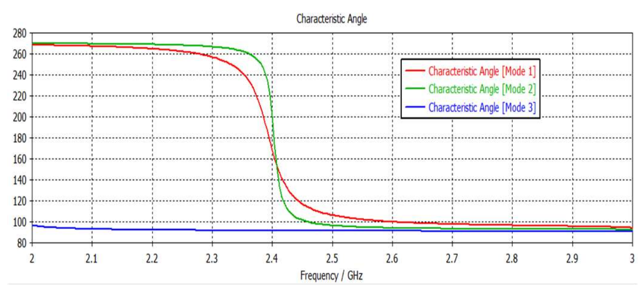

Figure 9. Characteristic Angle

In optimizing the antenna design, Figure 7 shows that J_1, J_2 and J_3 show different graphic results from the initial antenna design. J_3 looks separate from J_1 and J_2. J_1 and J_2 have a value of $\lambda n=0$ at frequencies around 2.4 GHz while J_2 has a value of $\lambda n=0$ at frequencies below 2 GHz. Based on Figure 7, J_1 and J_2 have a capital significance value close to one at a frequency of 2.4 GHz. In Figure 8, the capital significance chart shows a change where J_1 and J_2 which initially coincided became separated and there was a shift in frequency. J_1 and J_2 have a modal value of sinificance close to one at frequencies around 2.4 GHz, while J_3 has a modal value of sinificance close to one at frequencies below 2 GHz. Likewise for the characteristic angle results in Figure 9. Similar to Figures 7 and 8, J_1, J_2 and J_3 experienced changes from being close together, becoming separated and experiencing a frequency shift. J_1 and J_2 have a characteristic angle of 180° at frequencies around 2.4 GHz and J_3 at frequencies below 2 GHz.

From the eigenvalue, modal significance and characteristic angle in Figures 7 to 9, it can be concluded that there are only two modes that resonate at a frequency of 2.4 GHz. This indicates the presence of a resonant frequency by the desired specifications.

3.3 Simulation Result

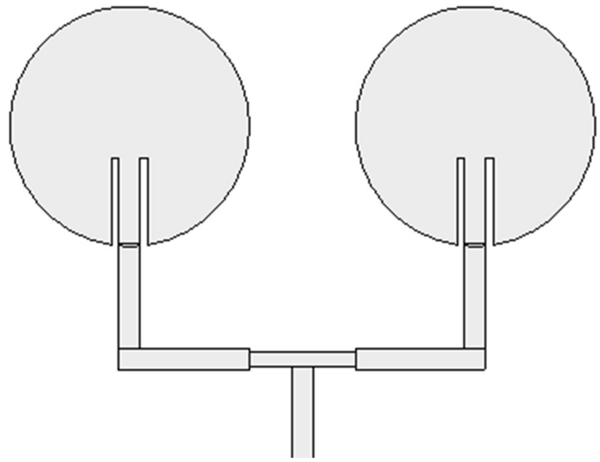

Figure 10. Final Design

The results in Chapter 2 have been by the resonant frequency. Are continued by giving the distribution of the antenna design. Finally, the feed is carried out using the feeding line technique with an array arrangement using an impedance of 50 ohms, as shown in Figure 10.

3.3.1 S11 and Bandwidth

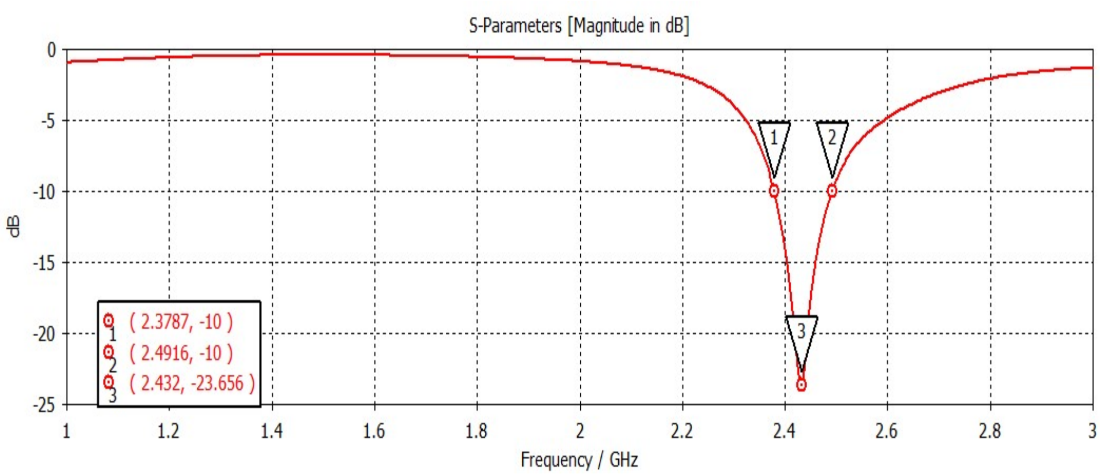

Figure 11. Final Result S11

Figure 11 shows the S11 result of -23.66 dB at a frequency of 2.432 GHz. The value shown in graph S11 is the antenna reflection coefficient. The smaller the value of S11, the less power will return to the transmitter. The bandwidth indicated is 112.9 MHz with an upper limit of 2.3787 GHz and a lower limit of 2.4916 GHz.

3.3.2 Gain and Radiation Pattern

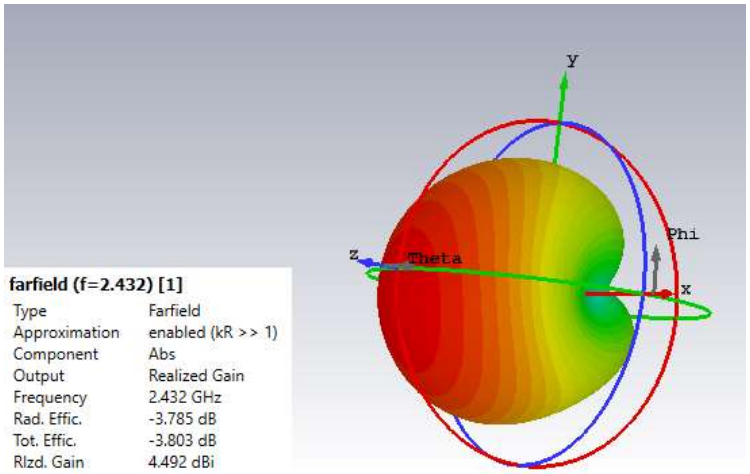

Figure 12. Gain simulation

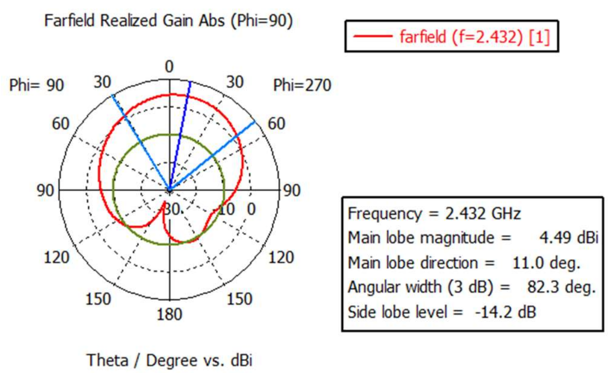

Figure 13. Elevation radiation pattern

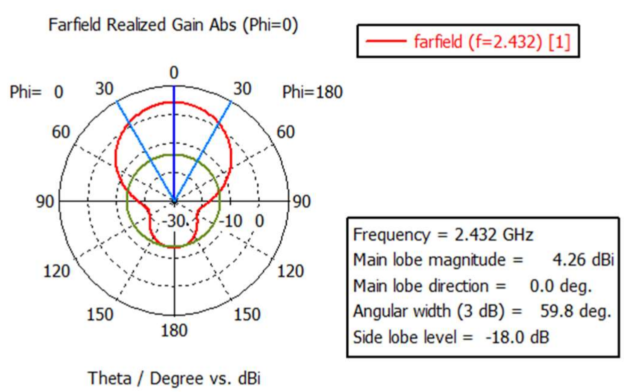

Figure 14. Azimuth radiation pattern

Figure 11 shows the antenna has a gain value of 4.492 dBi. Based on Figures 13 and 14, it can be seen that the antenna has an elevation and azimuth radiation pattern, which proves that the radiation pattern is directional.

3.4 Measurement result

The measuring instrument used in the measurement is a Vector Network Analyzer (VNA) model SAA-2 to measure coefficient reflection (S11) and gain using mutual coupling (S21).

3.4.1 S11

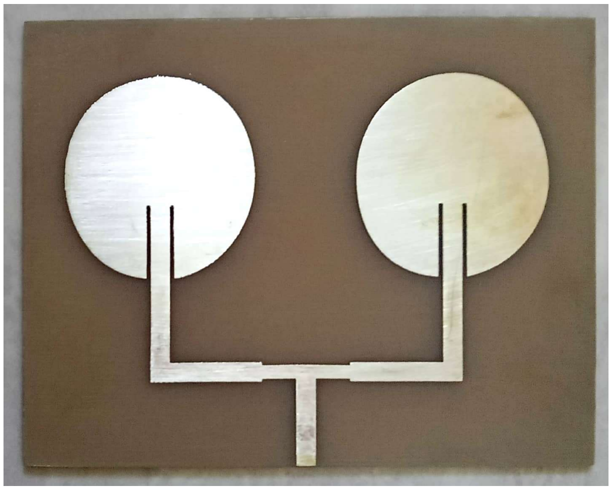

Figure 15. Fabricated antenna

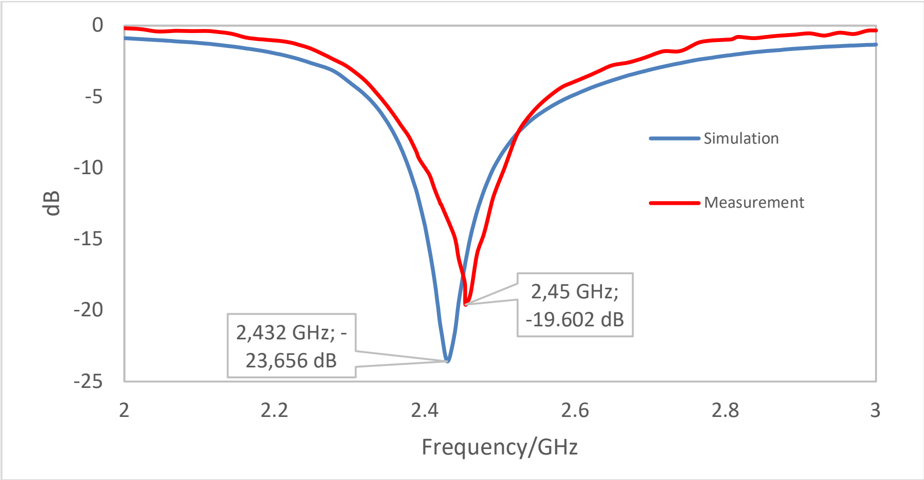

Figure 16. Graph of Simulation and Measurement

Vector Network Analyzer SAA-2 was used to measure S11 on the antenna. Figure 15 depicts the constructed antenna. The antenna measures 9,5 x 7,5 cm when fully assembled. An image of the frequency relationship with the S11 findings acquired in decibels (dB) between the simulation and measurement is obtained based on the simulation results using CST Microwave Studio 2019, S11 measurements, and the SAA-2 Network Analyzer, as shown in Figure 16. The frequency range of 2 to 3 GHz is displayed on the horizontal axis, while the S11 value in decibels is displayed on the vertical axis.

Table 4. Comparison of Measurement and Simulation at The Resonant Frequency and S11

Factor	S11 (dB)	Frequency (GHz)
Simulation	-23.656	2.432
Measurement	-19,602	2,45

Table 4 displays the difference between simulation and observations for the resonant frequency and S11 value. The difference in S11 values between simulated results and measurements, as well as the shift in resonant frequencies. The intended microstrip is most likely the result of fabrication-related antenna size error.

3.4.2 Gain

Table 5. Comparison Gain of Measurement and Simulation

Factor	Gain (dBi)	Frequency (GHz)
Simulation	4,492	2.432
Measurement	3,54	2,45

In this measurement, two identical antennas are used, namely the designed antenna. The two antennas are connected to the SAA2 Network Analyzer. Antenna 1 is connected to port one, and antenna two is connected to port 2, which helps measure each frequency. The gain value is taken from the measurement results of S21 or port two.

In this case, the values of Gtx and Grx are the same because they use identical antennas. The distance between the transmitting and receiving antennas is 1 m. The antenna gain measurement results are shown in Table 5. The measurement results have a gain value of 3,54 dBi, and the simulation results have a gain value of 4,492 dBi. There is a difference in the gain value between the simulation and measurement results, nevertheless still close to the gain value of the simulation results.

4. CONCLUSION

This paper presents a microstrip antenna design with a circular patch shape. Characteristic Mode Analysis was used as the radiation structure analysis. It can be seen that there are differences in characteristics that affect the performance of the antenna at the start and when the antenna slot is given. Furthermore, two modes in the final antenna design play a significant role. As a result, there is a difference in the measurement results with the simulation. However, these differences can still be tolerated because the results are still by the specified specifications.

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