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Science & Technology Section

The Design Optimization of Multi-Band Microstrip Patch Antennas for GNSS Application

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Abstract

This study simulates and analyses a dual-band microstrip patch antenna designed to be optimal for Global Navigation Satellite System usage in the L2 (1227.60 MHz) and L5 (1176.45 MHz) bands. This research focuses on designing a single antenna element to receive signals from multiple Global Navigation Satellite System (GNSS) constellations operating over the L2 and L5 frequency bands. The antenna design presented herein utilizes a novel technique that combines a slotted patch configuration with a defective ground plane to achieve dual-band functionality while maintaining the miniaturization and low-profile characteristics of the structure. Full-wave numerical simulations were performed using a finite element-based electromagnetic solver to fine-tune various performance parameters, such as S_{11} bandwidths, radiation patterns, and realized gain of this proposed microstrip slot-patch antenna structure implemented on a high-frequency electronic material substrate. The effects of different design factors, including substrate selection and characteristics, as well as variation in the length-width ratio of the rectangular patch strip, are also investigated, and their influence on key antenna performance metrics is analysed. This study contributes to the field of GNSS antenna design by presenting a cost-effective and efficient dual-band solution that can be easily integrated into modern navigation devices. In addition, this study explains how much more gain the antennas in the L2 and L5 bands of the GNSS provided in the antenna array with different feeding techniques.

Keywords: GNSS, GPS, microstrip patch antenna, dual-band, antenna design.

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1. Introduction

The main objective of this study is to explain the benefits of an antenna array compared to a single antenna, the differences that occur, and their importance according to the locations where they are applied (Pozar, 1992). Microstrip patch antennas are widely used in radar, communication, and navigation systems on aircraft platforms. In addition, this type of antenna is preferred for use in satellite communication and remote sensing radars. Moreover, in almost all mobile satellite telephones, microstrip patch antennas are chosen to use. (Garg, Bhartia & Bahl, 2001; Kraus,1988; Pandey, 2019). The microstrip antenna was first invented during the 1960s and 1970s (Deschamps, 1953; Munson, 1974). The concept of the microstrip patch antenna was first introduced by Deschamps in 1953. However, its widespread development and practical implementation were largely realized in the 1970s, primarily due to advancements in substrate materials and fabrication techniques, as demonstrated in the pioneering works of Munson (1974).

From the 1980s to the present, significant advances have been achieved in phased array antennas, smart antennas, and Multiple-Input Multiple-Output (MIMO) systems (Balanis, 2008). Microstrip antenna arrays investigated to date have generally employed the inset-feed technique and have operated at 2.4 GHz using substrates with a dielectric constant of 2.2. Singh et al. (2014) proposed 2×1 and 4×1 inset-fed antenna arrays for Global Positioning System (GPS) applications, utilizing a substrate with a dielectric constant of 2.2 and a thickness of 1.588 mm. Notably, the S_{11} values reported by Singh et al. (2014) are approximately 50% lower than those reported by Balanis (2008), indicating improved impedance matching performance.

Similar to Singh et al. (2014), Khraisat (2012) demonstrated 2x1 and 4x1 inset feed microstrip antenna arrays operating at 2.4-2.5 GHz using the same substrate material and thickness. The proposed antenna (Joshi et al., 2020) is characterized as a dual-band apparatus, functioning at 2.45 GHz for WLAN (Wireless Local Area Network) functionalities and 1.575 GHz for GPS, augmented by incorporating an artificial magnetic conductor plane. Furthermore, a realized gain of around 2 dBic at 1.575 GHz and 1.9 dBi at 2.45 GHz were obtained from the functioning of the AMC plane at 2.45 GHz. Additionally, Zhong et al. (2019) have proposed another antenna for GPS applications that also operates within dual frequency bands. In Zhong's design, the gain value of the antenna is not exceeded 3.15 dBic, which means almost 6 dBi.

In a recent study, Dündar and Ateş (2024) proposed an L5-band microstrip antenna design. However, the specific feeding technique used in the antenna structure was not described in detail. In this study, the antenna designed with dimensions of 77x63.56x1.6mm achieved 6.07dBm directivity and -38.85dB S_{11} values (Dündar & Ateş, 2024). The dimensions of the antenna designed by Dündar and Ateş are slightly larger than the one in this study, and its directivity value is lower, reaching around 15%.

Ayad et al. (2022) designed a microstrip patch antenna for use in GPS applications in the L1 band. After numerous optimizations, they achieved a maximum S_{11} value of -24.80 at 1.575

GHz. To achieve these values, they required an antenna measuring 95x82x2.1mm made from FR-4 material with a relative permittivity of 4.3 (Ayad et al., 2022). After numerous optimizations, they achieved a maximum S_{11} value of -24.80 at 1.575 GHz. To achieve these values, they needed an antenna measuring 95 mm x 82 mm x 2.1 mm made from FR-4 material with a relative permittivity of 4.3. Although the S_{11} value obtained in this study is satisfactory, the antenna dimensions require twice the volume.

In a recent piece of research, Basar et al. (2023) designed an antenna with a slot measuring 56x56mm, operating in the L1 band, using FR-4 material with a thickness of 1.6 mm. With this design, the researchers achieved an S_{11} value of up to -35dB and measured the resonant frequency as 1.590 GHz instead of 1.575 GHz (Basar et al., 2023). Compared to the work that achieved a maximum directivity value of 8.64 dBi with a 22.725 mm slot, this study required more than three times the transmission line for the values included in this work and also required a wide antenna slot.

Concerning these studies, the one presented here differs in terms of the feed type of the antennas, the substrate material chosen, and the operating frequency. The innovative aspect of this study is the comparison of two different feed antennas operating at the same frequency in terms of gain, bandwidth, S_{11}, and Voltage Standing Wave Ratio (VSWR). Furthermore, unlike other studies, this work is designed to operate in the L2 and L5 bands of GNSS systems with more gainful antennas. The L2 band in GNSS systems is used for high-precision positioning. Furthermore, antennas operating in the L2 band, which is used in military radar applications, can largely eliminate ionospheric errors. This paper compares the performance of antennas that use the same feeding method but operate at different frequencies. It also discusses the different behaviour of the antenna array compared to a single antenna using the same frequency and feeding method.

2. Methodology

Numerous crucial considerations and computations are needed to construct a microstrip patch antenna. These criteria must be considered to ensure the best performance for the intended application. Prioritizing the selection of the operating or resonant frequency and substrate material is essential. The substrate's primary role in microstrip antennas is to support the antenna structurally. To be effective, the substrate must be composed of a dielectric material, which can influence the circuits, the electrical efficiency of the antenna, and the transmission line impedance. The substrate should possess the minimal thickness. In this context, a height between $0.01\lambda_0$ and $0.05\lambda_0$ is deemed optimal. A height of $0.01\lambda_0$ to $0.05\lambda_0$ is regarded as ideal in this regard. After that, the feeding type is selected. Then, with the knowledge of resonant frequency and substrate material values, the width of the antenna is calculated. To calculate the width, the free space wavelength and dielectric constant need to be used. Equation (1) is utilized for this purpose (Balanis, 2016).

$$W = \frac{\lambda_0}{2\sqrt{0.5(\varepsilon_r+1)}} \quad (1)$$

Where λ_0 and ε_r are the wavelength in free space and the dielectric constant of the substrate, respectively. λ_0 is the division of c_0 by f_0, resonant frequency. In the next step, the effective dielectric constant, ε_{eff}, can be calculated. The effective dielectric constant is directly proportional to the dielectric constant and inversely proportional to height of the dielectric material. The aim is to design and optimize using 1.6mm thick FR-4 dielectric material, both because it is the primary material used in PCB designs and because it offers mechanical durability, lower losses up to 1-2 GHz levels, and cost advantages for prototypes. This parameter has an important place in the calculation of the effective width of the antenna. ε_{eff} can be calculate by using the following Equation (2) (Balanis, 2016).

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

After that, the length of the rectangular patch can be calculated using Equation (3) (Pandey, 2019).

$$L = \frac{c_0}{2f_0\sqrt{\varepsilon_{eff}}} \quad (3)$$

with c_0 = 2.998 $\times 10^8$ meter/second being the velocity of the electromagnetic wave in free space. The extension of the patch length due to the fringing effect, fringe factor, can be calculated using the following Equation (4) (Pandey, 2019).

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)} \quad (4)$$

Hence, using Equation (3) and the line extension, the effective length, $L\ e\ f\ f$, of a rectangular antenna element by using Equation (5) (Pandey, 2019).

$$L_{eff} = \frac{c_0}{2f_0\sqrt{\frac{\varepsilon_{eff}+1}{2}}} - 2\Delta L \quad (5)$$

The impedance of an antenna defines the relationship between the voltage and current at its input. The usual impedance at the border of a resonant rectangular patch varies between 100 and 400 **Ω**, and the radiation impedance of a patch at the border can be estimated in Equation (6) (Pandey, 2019).

$$Z_a \approx 90\frac{{\varepsilon_r}^2}{\varepsilon_r - 1}\left(\frac{L}{W}\right)^2 \quad (6)$$

Input impedance Z_{in} is matched with a 50-ohm microstrip feed line impedance Z_0 (Pandey, 2019). The specific type of antenna and whether it is functioning at its resonant frequency influences the input or feed point impedance of an antenna. When the antenna is at resonance, its input impedance is ideally purely resistive, meaning it effectively accepts and transmits all the power from the source and behaves like a purely dissipative load. However, when operating off resonance, the impedance generally increases as reactive components come into play. If the edge impedance of the patch antenna is Z_a, then the input impedance seen from the beginning of the quarter-wavelength line is calculated in Equation (7) (Pandey, 2019).

$$Z_{in} = Z_0 = \frac{{Z_l}^2}{Z_a} \quad (7)$$

Input impedance Z_{in} can be changed by the selection of Z_l, so that Z_{in}= Z_0 and the antenna is matched by impedance. The impedance Z_l,load impedance or transition impedance, value varies with the width of the quarter-wavelength strip.

When *W/d* <1, the characteristic impedance of the line is Equation (8) (Huang & Boyle, 2008)

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{8d}{W} + \frac{W}{4d}\right) > \frac{126}{\sqrt{\varepsilon_r}} \quad (8)$$

It decreases monotonically to $126/\sqrt{\varepsilon_r}$ as *W/d* increases to 1.

When *W/d* >1, the characteristic impedance of the line is Equation (9) (Huang & Boyle, 2008)

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_r}(\frac{W}{d} + 1.393 + 0.667\ln(\frac{W}{d} + 1.44)} < \frac{126}{\sqrt{\varepsilon_r}} \quad (9)$$

It also decreases monotonically from $126/\sqrt{\varepsilon_r}$ W/d as it increases. From Equation (9), 70.71 Ohm is obtained to reach the 50 Ohm input line with two parallel 100 Ohm antenna input lines as illustrated in Figure 1. For the inset feed technique, 6 mm on the x-axis and 3.6 mm on the y-axis are cut from the patch using nickel material. The main reason for cutting is adjusting and obtaining targeted level of gain. Arranging multiple patch elements in an array can significantly increase directivity. The array factor combines with the element pattern to produce a more directive overall pattern (Pozar & Schaubert, 1995). λ /4 is more advantageous than the tapered line because of its straightforward structure, lesser volume, production which is very easy, and also it is good for single-frequency systems. Tapered line may be utilized over broader bands but will need longer physical dimensions (Pozar, 2011).

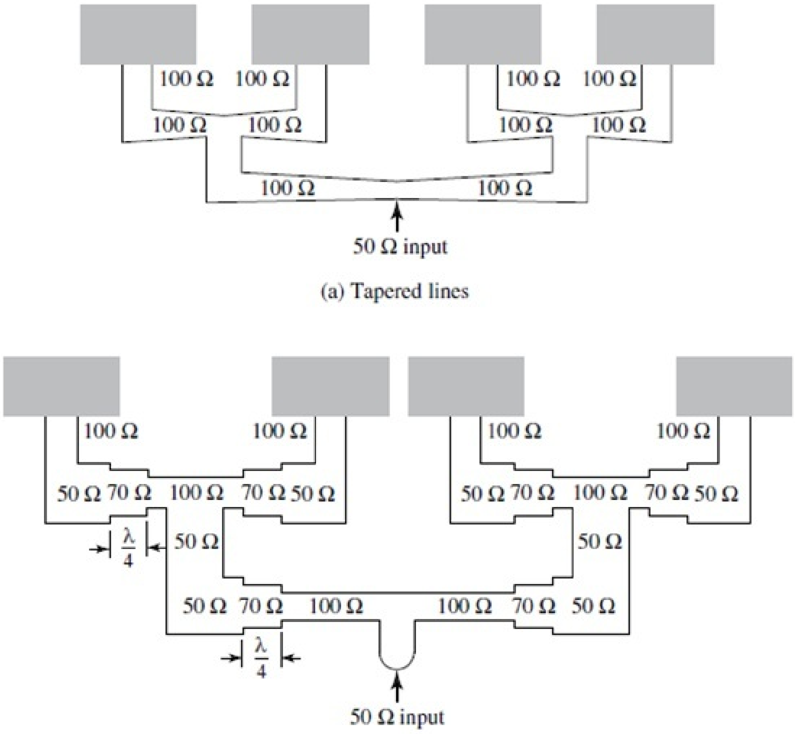

Figure 1. Tapered and λ/4 impedance transformer lines to match 100-ohm patches to a 50-ohm line (Balanis, 2016).

Table 1. Designed antennas parameter data.

	L2 Band Edge Feed	L5 Band Edge Feed	L2 Band Inset Feed	L5 Band Inset Feed
Substrate	FR-4	FR-4	FR-4	FR-4
Substrate Thickness (mm)	≈1.6	≈1.6	≈1.6	≈1.6
Patch Width (mm)	75.0604	78.3539	75.0604	78.3539
Patch Length (mm)	56.6500	58.8571	56.6500	58.8571
50 Ohm Feedline Width (mm)	3.13	3.1355	3.137	3.137
Single Patch Obtained Gain (dBi)	6.99	7.02	≈6.11	6.09
Single Patch S_{11} Value (dB)	-16.562	-17.172	-20.672	-22.168
Single Patch VSWR	1.3674	1.3231	1.2255	1.1875
50 Ohm Feedline Length For 2x1 Antenna Array (mm)	33.805	35.2749	33.8051	30.37
70.71 Ohm Feedline Width For 2x1 Antenna Array (mm)	1.641	1.606	1.641	1.641
100 Ohm Feedline Width For 2x1 Antenna Array (mm)	0.7235	0.7237	0.7235	0.7235
2x1 Array Obtained Gain (dBi)	8.988	8.984	8.987	8.979
2x1 Array S_{11} Value (dB) (Without magnitude)	-40.112	-41.456	-18.634	-20.783
2x1 Array VSWR	1.0218	1.0171	1.2655	1.2016
2x1 Array Current Distribution (dB)(A/m)	26.7455	25.2166	27.6212	25.1225

The work carried out up to this stage has been on the design and simulation of antennas at the specified frequencies in an electronic environment. In future studies, it is aimed to compare the results obtained from prototype production with simulation results.

3. Results

Many parameters need to be evaluated in designed antennas. First of all, S_{11}, the input reflection coefficient, values should be considered. The main reason for considering the S_{11} parameter affects the reflection coefficient, Voltage Standing Wave Ratio (VSWR), and also insertion loss values. The second important parameter of an antenna is the level of gain. The level of gain plays an important role in determining whether an antenna is sufficient for the intended use.

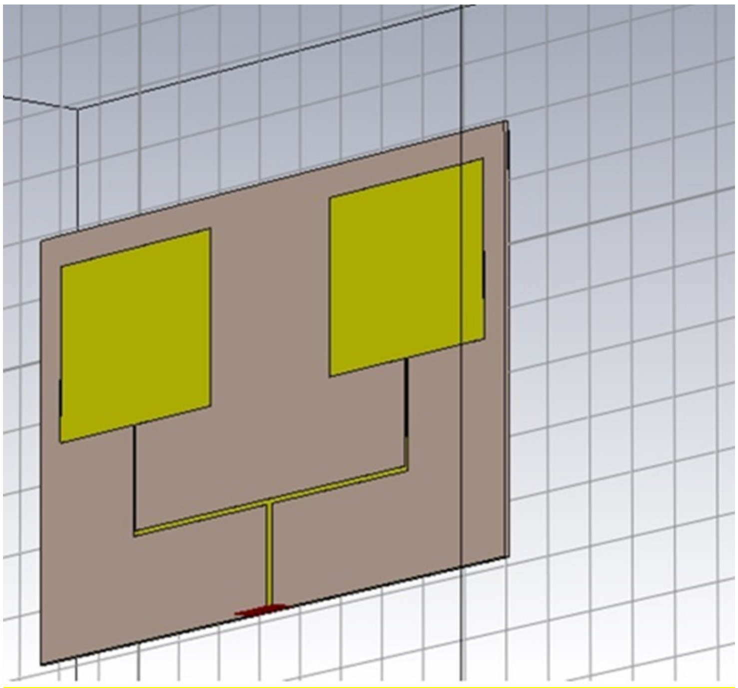

Figure 2. L2/L5 band edge feedline 2x1 microstrip patch antenna array.

According to the 2x1 antenna array shown in Figure 2 and the table and graph obtained in Figure 3, the L2 band edge feed antenna array has -40.112 S_{11} at 1224.4 MHz. This operating frequency is obtained after optimizing the patch length. If patch length is reduced, then frequency and bandwidth are increased. In this array, bandwidth is calculated around 32 MHz. These values are proof of having lower insertion loss. Furthermore, the gain of this feeding array is almost 9 dBi; even a single microstrip patch antenna with the same feeding cannot exceed 7 dBi. In addition, VSWR is 1.0218 and this value shows that this design is closer for impedance matching.

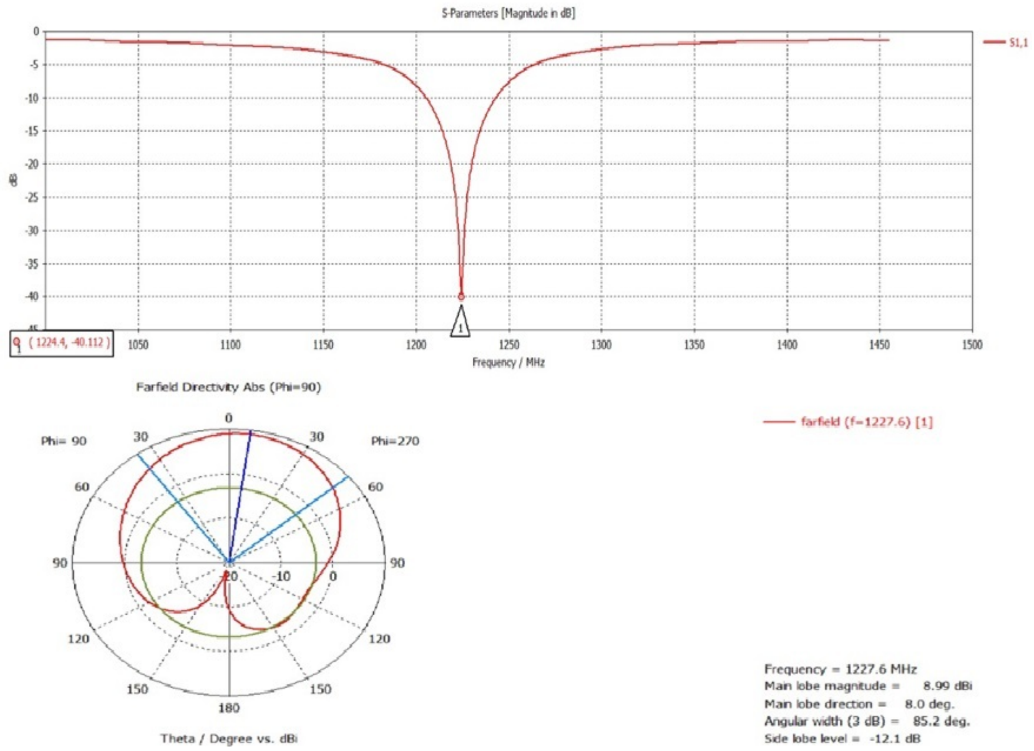

Figure 3. L2 Band edge feedline 2x1 microstrip patch antenna array S_{11} graph and directivity.

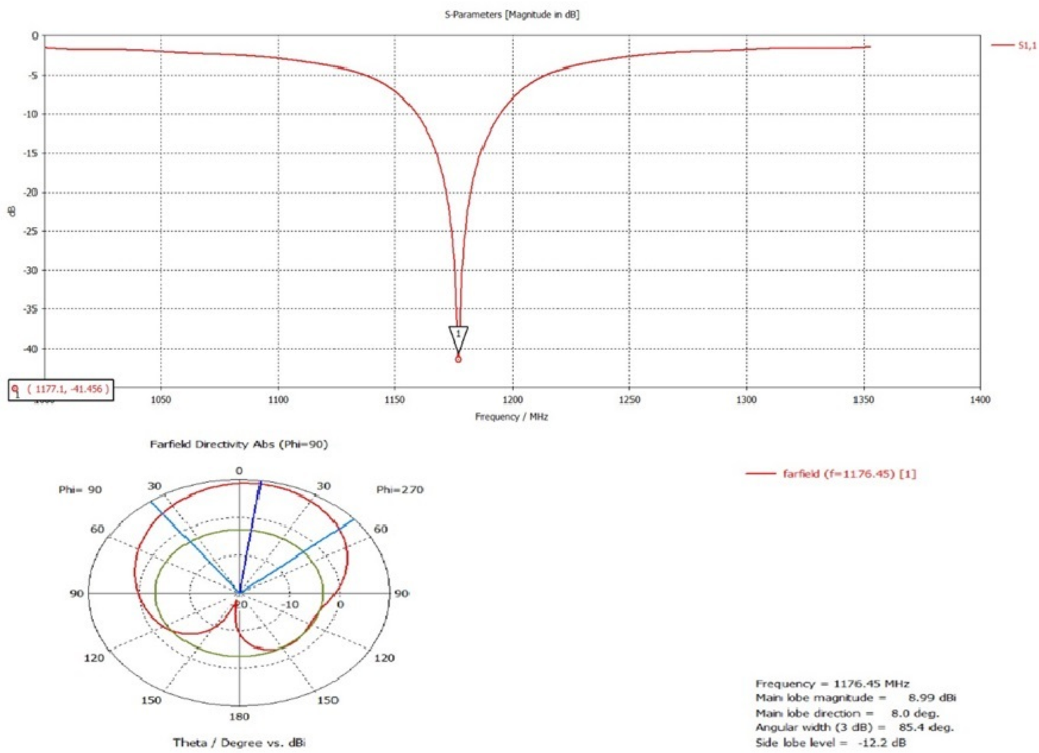

Figure 4. L5 band edge feedline 2x1 microstrip patch antenna array S_{11} graph and directivity.

The L5 band edge feed antenna array has a -41.456 S_{11} at 1177.1 MHz, as exhibited in Figure 4. This operating frequency is also obtained after optimizing the patch length. If patch length is reduced, then frequency and bandwidth are increased. VSWR for the L5 band array is 1.0171, and this band is much closer for impedance matching. The L5 band edge feed antenna array's bandwidth is roughly 35 MHz. Besides, the L5 band antenna array has almost the same gain as the L2 band application. This provides an upper limitation of this feeding method in terms of gain.

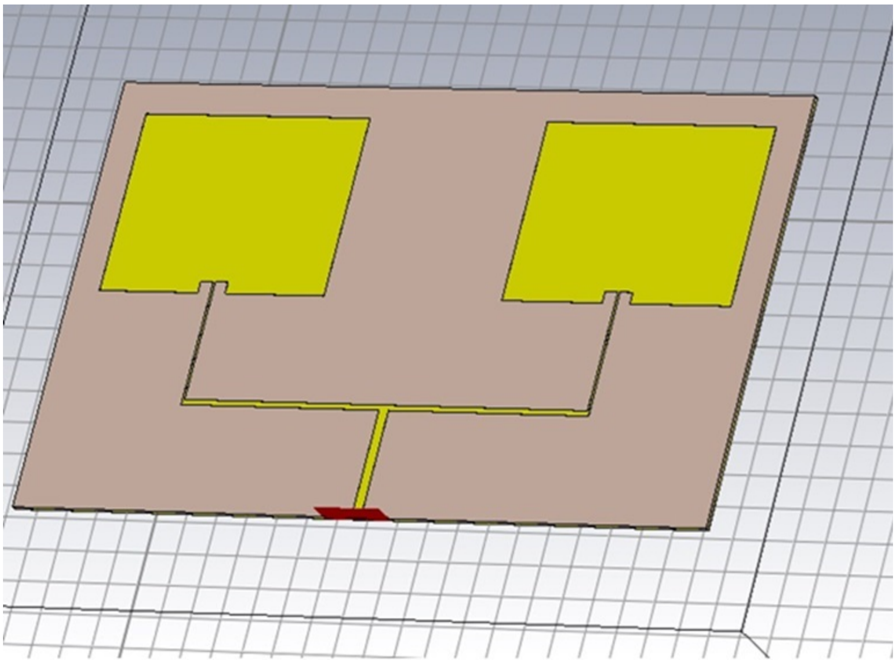

Figure 5. L2/L5 band inset feedline 2x1 microstrip patch antenna array.

Inset feedline is a feeding technique used in microstrip patch antennas. The feedline is recessed (inset) a certain distance into the antenna to match the antenna's input impedance to the feedline. This method ensures efficient antenna operation and low reflection loss.

Based on the 2x1 Inset feedline antenna array illustrated in Figure 5, along with the data and graph presented in Figure 6, the effect of changing the patch length on the S_{11} value can be clearly observed. The figure presents many different curves. The very small differences between the curves represent the S_{11} value at the frequency at which the antenna is intended to operate within the bandwidth. The L2 band inset feed antenna array has an S_{11} of -18.634 at 1226.7 MHz. At this frequency, the bandwidth is calculated to be approximately 31.3 MHz and the VSWR is 1.2655.

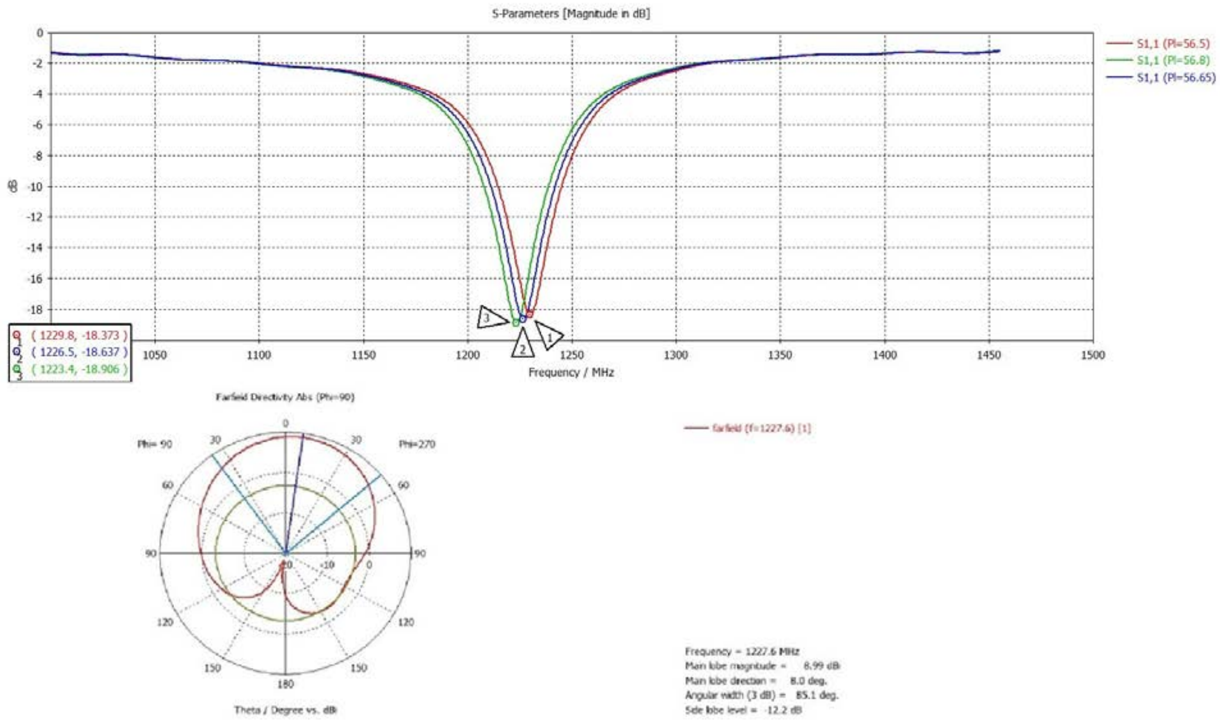

Figure 6. L2 band inset feedline 2x1 microstrip patch antenna array S_{11} graph and directivity.

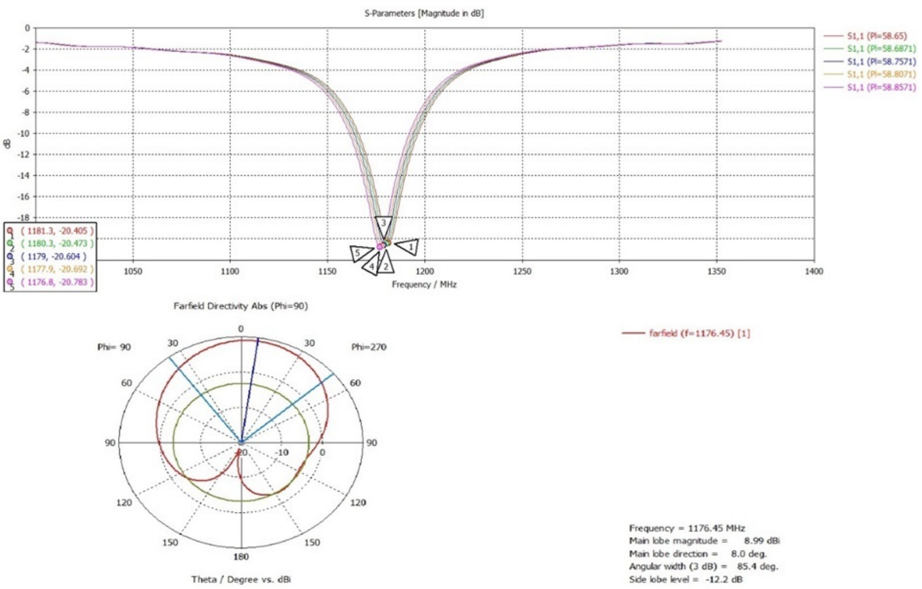

Figure 7. L5 band inset feedline 2x1 microstrip patch antenna array S_{11} graph and directivity.

As illustrated in Figure 7, one can distinctly discern the impact of varying the patch length on the S_{11} parameter. In the same illustration, numerous distinct curves are shown. The minimal variations among these curves are utilized to ascertain the S_{11} value at the frequency for which the antenna is designed to operate within the specified bandwidth. The L5 band inset feed antenna array has an S_{11} of -20.783 at 1176.8 MHz, and the VSWR is 1.2016. At this frequency, the bandwidth is calculated to be nearly 35 MHz.

4. Discussion

When the current distribution values and graphs of the designed antennas are examined, it is observed that the antennas exhibit similar characteristics and produce values that are close to each other. The antennas operating in the L2 band have the current distribution values of 26.7455 dB and 27.6212 dB for edge feed and inset feed, respectively, while those operating in the L5 band have values of 25.2166 dB and 25.1225 dB. After using the formulas required for antenna design and optimization through the Computer Simulation Technology Microwave Studio (CST MWS), it is noted that the antenna array with edge feed has greater gain. CST MWS is the application that does the simulation. The CST MWS that simulates the antenna design can display the antenna's return loss, VSWR, gain, directivity, radiation pattern, and efficiency. Additionally, the optimum width of the patch for the L2 band is obtained as 75.0604 mm, and the optimum length of the antenna at the same frequency is 56.650 mm. Furthermore, the optimum length for the L5 band is 58.8571 mm, while the optimum width is 78.3539 mm. For all antenna array designs, the VSWRs remain less than 2 (VSWR $\leq$ 2), despite the various gain values.

The results of the above-mentioned designs show that similar results are obtained in terms of both S_{11} values and gain values without using the slots that will increase the gain as in the antennas designed by Joshi et al. (2020). In addition, the S_{11} values of the 2x1 antenna array designed using the edge feed technique also indicate that although the gain values are similar to the antenna array designed by Yahya, they are transmitted more depending on the operating frequency. Ayad et al. (2022) showed that a larger and thicker antenna was required, yet a similar gain was achieved despite obtaining a worse VSWR value. In this context, it was demonstrated that this could be achieved with a smaller antenna size, even though there was not much difference in gain. Although the values in the study by Basar et al. (2023) appear to be close to those in this study, they prevent the slot antenna used to obtain the maximum directivity value from being reduced to smaller dimensions. As long as small antenna dimensions are required in GNSS applications, the antenna dimensions obtained as a result of this study are shown to be more efficient and preferable.

In the study conducted by Dündar and Ateş (2024), no feedline information was provided for the antenna designed in the L5 band. The performance and characteristic properties exhibited by an antenna, depending on the type and features of the feedline, play a critical role in GNSS systems that typically employ a 50-ohm feeding impedance. All parameters of the antenna to be selected for the intended system or application are significant. Therefore, the selection of an antenna with well-defined feedline characteristics and performance should be prioritized. Considering that the feed characteristics presented in this study were developed under the assumption that GNSS antennas operate with a standard 50-ohm input impedance, their application is considered more appropriate for ensuring consistency and reliability in system design.

5. Conclusion

In this study, edge feed and inset feed at the L2 band and L5 band were designed for 2x1 microstrip patch antenna arrays. While designing the antenna, the initial parameters were determined using the formulas from the previous chapter, and then optimizations were performed with the CST MWS. According to the results, the edge feed method at the L2 and L5 bands for a single patch antenna provides nearly 7 dBi gain, even when different feeding techniques are applied. However, with the same parameters, inset feed ensures around 6.1 dBi gain. In some applications, these gain levels are not considered sufficient. In global navigation satellite systems, it is crucial that the gain level is as high as possible for the system to function more effectively. By carefully selecting the substrate material, optimizing the patch geometry, and implementing effective impedance matching strategies, designers can create microstrip patch antennas that operate with high performance in the L2 and L5 bands. For this reason, a 2x1 antenna array configuration is applied using inset feed and edge feed techniques. The inset feed L2 band 2x1 microstrip patch antenna achieves 47 percent more gain, while the edge feed technique provides 28 percent more gain. Additionally, for the L5 band, the inset feed L5 band 2x1 microstrip patch antenna achieves the same gain percentage as the L2 band inset feed application. Furthermore, the values and corresponding VSWR measurements indicate that the antenna array technique brings the antennas closer to an impeccable design. The closer the VSWR value is to 1, the more optimal the design becomes regarding impedance matching. Based on the S_{11} values of the antennas designed in this study, it is observed that nearly 100% of the power supplied to the antennas is utilized by the antennas, indicating very high efficiency. When the bandwidths, S_{11} values, and VSWR values obtained from the simulation results are evaluated together, the designs are considered suitable for GNSS systems. Upon analysis of the designs' properties, including frequency, S_{11}, voltage standing wave ratio, and gain, it is determined that the designs satisfy the required standards for GPS bands.

Conflict of Interest

The authors have no conflicts of interest to declare.

Author Contributions

Both authors contributed equally to the preparation of this paper.

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Ethical Statements

I declare that I have obtained the data, information, and documents contained in this scientific article, which I prepared in accordance with the rules set forth by the *Journal of Defence and Security Industries: Strategy and Technology*, in accordance with academic and ethical principles. I have presented all information, documents, evaluations, and results in accordance with scientific ethics and moral principles. I have not made any changes to the data used.

Data and Code Availability

There are no available data and code.

Supplementary Materials

There are no supplementary materials.

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