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An Integrated T-Structure within a U-Shaped Loop Antenna: Design and Performance Analysis

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Abstract—

Loop antennas have become an important part of current wireless communication systems because of their small size, simple design, and constant radiation. In this study, a T-structured loop antenna was designed and analyzed for C-band applications using the ANSYS HFSS. The proposed antenna uses a modified loop geometry with a T-shaped extension to enhance the matching of the current distribution and the impedance.

The design relies on the basic electromagnetic theory and is optimized by simulation. The results show a loss of approximately -15 dB at 5 GHz, a VSWR of less than 2, and a consistent radiation pattern with moderate gain. The operation of the proposed antenna was compared with that of current loop antenna designs, and it was found to have better impedance properties and size than the latter. Antenna is simulated on low cost FR4 substrate material. The compactness of design is achieved by following dimension 26mm x 15mm x 1.6mm, which is suitable for 5G application.

I. Introduction

With the ever-changing nature of wireless communication systems, there is a growing need to design small and effective antennas that can operate in several frequency bands. One potential solution is the loop antenna, specifically microstrip loop antennas, which have a low profile, are easy to manufacture, and can retain stable radiation characteristics. Compared to traditional patch antennas, loop antennas are mainly magnetic current distribution-based, and thus less sensitive to the surrounding objects and can fit in small wireless equipment. Nonetheless, traditional loop antennas are usually characterized by low bandwidth and impedance mismatch, limiting their usefulness in high-frequency applications. [1] .

To overcome these drawbacks, scientists have attempted various structural alterations to improve antenna performance. Methods such as the addition of parasitic elements, defected ground structures, and loading metamaterials have been extensively investigated. For example, adding geometrical elements to an existing path can effectively reduce the resonant frequency and enhance impedance matching and gain. Likewise, loop antennas in combination with enhanced geometries, such as metamaterials and fractal geometries, have proven better bandwidth and miniaturization properties than planar antennas. [2].

Other modified loop designs, such as L-shaped and multi-arm loops, have been promising with respect to the improvement of antenna performance among other configurations. One study reported that a loop antenna is much better when L-shaped arms are added to the antenna to enhance the bandwidth and allow this antenna to operate in more than one band by changing the current distribution. Based on these strategies, this study proposes a T-structured loop, in which the loop is supplemented with a vertical arm to create a better electrical length and increase the impedance properties. [3]

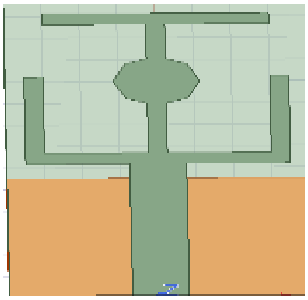

FIG 1. (a) Front Face of Antenna

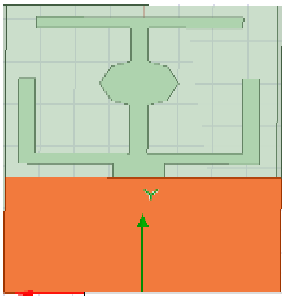

FIG 1. (b) Ground Plane of Antenna

In this study, a T-structured loop antenna for C-band operation is designed and analyzed using HFSS. The design aims to enhance the performance of the return loss, VSWR, and radiation while retaining structural simplicity. The effectiveness of the antenna was tested using simulations and compared with existing loop antenna designs to ensure its effectiveness. [4]

II. Literature Review

Loop antennas are a popular research topic owing to their small size, ease of design, and stability of radiation, which are desirable in current wireless communication systems. However, traditional loop antennas have been noted to have low bandwidth and impedance mismatch, thus limiting their use in high-frequency applications. Initial studies have determined that the performance of antennas is highly sensitive to the loop geometry and current distribution, and that resonance is predominantly controlled by the effective electrical length of the loop [1]. To counter these constraints, several researchers have suggested structural adjustments to enhance the properties of antennas. Alkanal proved that the introduction of new arms and loop geometry changes can increase the bandwidth and enable multiband operation by changing the current paths [3]. Similarly, Poorgholam-Khanjari et al. mentioned that compact wideband loop antennas are possible through the extension of the current path and enhancement of electromagnetic coupling, leading to improved return loss and radiation efficiency [2]. These studies indicate that geometric optimization is an important tool for improving antenna performance.

Other modified loop designs, such as L-shaped and multi-arm loops, have been promising with respect to the improvement of antenna performance among other configurations. One study reported that a loop antenna is much better when L-shaped arms are added to the antenna to enhance the bandwidth and allow this antenna to operate in more than one band by changing the current distribution. Based on these strategies, this study proposes a T-structured loop, in which the loop is supplemented with a vertical arm to create a better electrical length and increase the impedance properties. [3]

Moreover, other sophisticated methods, such as metamaterials, defected ground structures, and optimization using simulations, have been considered to further enhance the efficiency and miniaturization of antennas. Naser-Moghaddasi and others demonstrated that metamaterials can be used effectively to increase electrical length without size, resulting in better impedance matching [5]. Additionally, recent research has highlighted the relevance of simulation tools, such as HFSS, for optimizing antenna properties, such as return loss, VSWR, and gain [4]. The current work is based on these findings; it is a T-structured loop antenna design that improves its performance by geometric adjustment without increasing its complexity and size.

III. Methodology

I. Antenna Design Process

The proposed T-structured loop antenna is designed to operate in the C-band with a target frequency of approximately 5 GHz. The design process begins with the calculation of the basic parameters based on the desired resonant frequency. The approximate wavelength was derived using standard electromagnetic relations, and the dimensions of the loop were chosen such that the effective current path was in resonance conditions. An antenna was designed on an FR4 material with a dielectric constant of 4.4 and thickness of 1.6 mm. The general size of the substrates was selected to be 16 mm × 16 mm (W_s = 16 mm, W_g = 16 mm), which is a small structure that can be utilized in practice.

The antenna geometry is a loop structure with a T-shaped extension that is incorporated to increase the effective electrical length of the antenna. The parameters used to define the loop segment included the loop size (Ls = 26 mm), ground length (Lg = 10 mm), and central structure dimensions (C = 14 mm, Cc = 1 mm). The feed line had a width of 2.5 mm (W_f = 2.5 mm) and was located at a length of 11.35 mm (L_f = 11.35 mm) to attain an appropriate impedance matching. The addition of the T-shaped component changes the distribution of the current by adding more lines that enhance the resonant characteristics of the antenna and minimize the loss of reflections. This dimensional tuning has turned out to be very important in the regulation of parameters such as return loss and VSWR as evidenced by the former studies in the antenna design.

The ANSYS HFSS was used to model and simulate the antenna, and parametric optimization was performed by varying the key dimensions to optimize the performance of the antenna. The simulation measures crucial attributes such as return loss (S11), VSWR, gain, and radiation pattern. The resultant dimensions yielded a resonant frequency of approximately 5 GHz with reasonable impedance matching. The surface current distribution analysis confirms that the T-structure improves the distribution of current across the antenna, resulting in increased radiation efficiency. This dimension-based design approach guarantees that the antenna is small, simple, and effective for operation in the C-band wireless.

The proposed T-structured loop antenna design is a variant of a traditional microstrip loop antenna, in which a T-shaped addition is incorporated into the radiating structure to improve its electrical performance. Based on the provided design, it is clear that the geometry was designed with special care to maximize the current path with minimal effect on the physical size of the antenna. This extension modifies the surface current distribution by providing new current flow paths into the resonant, which subsequently enhances impedance matching and reorients the resonant frequency to the desired C-band region. This type of structural change is often employed in the design of compact antennas to achieve miniaturization without significant radiation compromise, as the resonant behavior of loop antennas is highly sensitive to the total electrical length of the current path.

Moreover, the symmetry of the antenna structure indicates that it is designed to ensure a predictable and consistent radiation pattern. The T-shaped component probably helps to even out the current distribution in the loop, preventing unwanted reflections and increasing radiation efficiency. The results of the simulation support this claim, with a return loss of approximately -15 dB and a VSWR of less than 2, which shows a strong impedance match. The geometry also seems to enable improved coupling between the radiating element and the feed line, which is important for the efficient transfer of power in microstrip-based antennas. These enhancements can be attributed to the principles of antenna design, where geometric changes have a direct impact on other parameters, such as S11 and bandwidth.

Table1: Dimension Of Proposed Antenna

S.No.	Designed Antenna Parameter	Value (Mm)
1.	L_f	11.35
2.	W_f	2.5
3.	L_p	10
4.	W_p	15
5.	L_s	26
6.	W_s	15
7.	H_s	1.6
8.	W_g	15
9.	L_g	10

Moreover, the design also presents a feasible performance/simplicity trade-off. Although more sophisticated methods, such as metamaterials or multilayered designs, can be used to further increase the gain and bandwidth, they may come at the cost of more complex fabrication and higher costs. The proposed T-shaped loop has moderate gain and stable radiation properties with a simple planar structure, making it applicable in the real world, including wireless communication and small devices. Generally, the design is indicative of a good design for enhancing the performance of antennas by way of geometrical optimization, which is in line with the tendencies in recent antenna research.

II. Antenna Dimension Equations

Antenna mathematical equation

1. PATCH HEIGHT: -

The patch's height (h) is determined as follows: -

$$h = \frac{0.3c}{2\pi f\sqrt{\varepsilon_r}}$$

2. PATCH WIDTH: -

The patch's width (W) is calculated as follows: -

$$w = \frac{c}{2f}\sqrt{\left(\frac{2}{\epsilon_{r+1}}\right)}$$

3. EFFECTIVE DIELECTRIC CONSTANT: -

The effective dielectric constant is calculated as follows: -

$$(\varepsilon_{\text{eff}} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}[1+12\frac{h}{w}]^{-\frac{1}{2}}$$

4. PATCH LENGTH: -

Extension of the patch length (Δ L) is calculated as follows: -

$$\Delta \mathrm{L} = 0.412\frac{[\varepsilon_{eff}+0.3][\frac{w}{h}+0.264]}{[\varepsilon_{eff}-0.258][\frac{w}{h}+0.8]}$$

5. EFFECTIVE LENGTH: -

Effective length of the patch (L_{eff}) is calculated as follows: -

$$L_{eff} = \frac{c}{2f\sqrt{\varepsilon_{eff}}}$$

6. PATCH REAL LENGTH: -

calculated as follows: -

$$L = L_{eff} - 2\Delta L$$

7. GROUND PLANE DIMENSION'S: -

Calculation of the ground plane dimensions is calculated as follows: -

$$Lg = L + 6h$$

$$Wg = W + 6h$$

IV. RESULTS AND DISCUSSION

S parameter

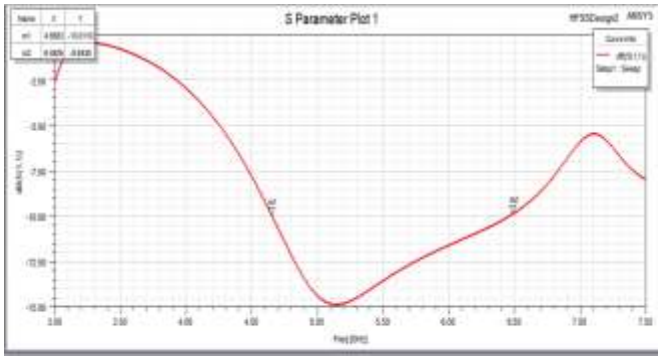

FIG 2. 1 S Parameter of proposed Antenna

The S11 results show that the antenna resonates at approximately 5 GHz with a return loss of approximately −15 dB, indicating good impedance matching and efficient radiation. The Bandwidth of proposed antenna 4.6 to 6.4 Ghz which is best suitable for satellite communication, wifi (partial overlap), defense and military application.

This performance is achieved owing to the T-structured geometry, which improves the current distribution and reduces reflection losses.

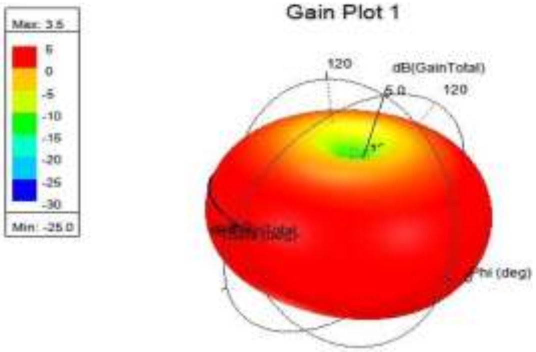

FIG 2. 2 3 D Gain of proposed Antenna

The gain plot shows that the proposed antenna achieves a maximum gain of approximately 3.5 dB, which is suitable for compact-antennas.

The radiation pattern was stable and nearly omnidirectional, ensuring consistent signal coverage.

This moderate gain performance is typical of microstrip loop antennas and confirms their suitability for C-band applications.

VSWR Plot

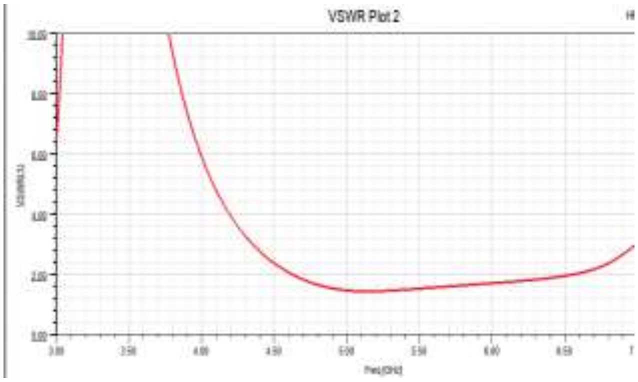

FIG 2. 2 VSWR Graph of proposed Antenna

The VSWR plot shows a minimum value of approximately 1.5 at a resonant frequency of approximately 5 GHz, indicating good impedance matching.

Because the VSWR is below 2, it confirms efficient power transfer with minimal reflection losses [1].

This result demonstrates that the antenna performs effectively within the desired C-band frequency range

Radiation Pattern

The graphical depiction of the distribution of radiated power (or field strength) in space as a directional function is known as a radiation pattern of an antenna.

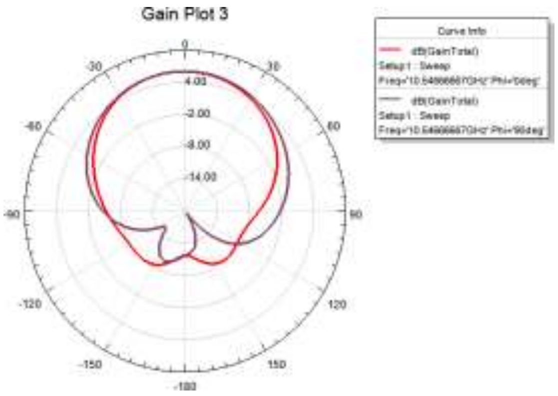

FIG 2. 3 Gain Plot of proposed Antenna

Proposed Antenna radiation pattern are unidirectional which shows less amount of energy radiated in back dur to this directivity of antenna improve and front to back ratio also improves.

V. CONCLUSION

In this study, a T-structured loop antenna was successfully designed and analyzed for C-band applications using ANSYS HFSS. The proposed antenna considers the changes in the loop geometry and a T-shaped extension that increases the effective electrical length and improves the distribution of current over the radiating structure. Theoretical computation and optimization through simulations guarantee that the antenna design achieves the desired resonant frequency of approximately 5 GHz with a smaller size and simplified design.

The simulation results demonstrate that the antenna exhibits good performance in terms of key parameters, such as return loss, VSWR, gain, and radiation pattern. The S-parameter analysis indicated a loss of approximately -15 dB at the return-loss port, which is indicative of an effective impedance match, and a VSWR of less than 2, indicating effective power transfer. Furthermore, the antenna has a moderate gain of 3-5 dB with a constant radiation pattern, which is applicable in practical wireless communication. The enhancement in performance is largely credited to the T-structured change, which boosts the current flow and minimizes the reflection loss.

In general, the new antenna design is a good compromise between simplicity, size, and performance and can be considered a viable candidate for C-band wireless systems. The design shows satisfactory performance compared to larger and more complicated antenna structures without making the fabrication more complex and expensive. Future research may aim to enhance the gain and bandwidth further by using advanced methods such as antenna arrays, metamaterials, or defected ground structures and testing the design in practice by fabricating and experimentally measuring it.

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