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Design and Analysis of Quad Band Antenna for 5G and IoT Applications

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***Abstract*— As there has been a significant increase in the wireless industry, the need for small, efficient and cost-effective devices that stack multiple frequency bands into one solution is at an all-time high. Therefore, designing antennas that operate over multiple frequency bands, without enlarging or complicating the design, is crucial to enabling these solutions. This job involves designing and analysing a compact, quad-band antenna specifically for use in applications such as 5G and IoT devices. This antenna is designed using a typical microstrip patch antenna constructed on an FR-4 substrate and utilizes a slot-loading technique to provide multi-band functionality. This is accomplished by having two rectangular slots cut into the patch in a cross shaped pattern, which affects how much surface current is distributed across the patch by providing multiple current paths with different lengths. When the surface current is affected, multiple resonant frequencies are created due to the different currents. The result is a quad-band antenna with a minimum of four resonant frequencies around 2.4 GHz, 3.775 GHz, 4.64 GHz and 5.315 GHz; each corresponding to a common standard, including Wi-Fi, WLAN, Sub-6 GHz 5G and various IoT devices. The antenna is designed and simulated using CST Microwave Studio, where key performance parameters including reflection coefficient (S11), gain, radiation pattern, and surface current distribution are thoroughly evaluated. The simulations showed good performance of the antenna by providing good impedance matching in all operating bands and having the reflection coefficient values below -20dB. The gain was also in the range which is considered practical for use in wireless communication systems. In addition to the above, the radiation patterns show that the antenna provides stable and directional characteristics for the different operational frequencies. Conclusion drawn from the analysis of surface currents reveals that cross-shaped slots are needed to provide multiple resonating modes by altering how the surface currents operate on the patch. In conclusion, the proposed antenna design is an easy-to-manufacture, low profile, and cost-effective solution for multiband use without the use of complex structures or extra parts. Because it can be manufactured easily, has excellent performance characteristics, and is compatible with current wireless technologies, this antenna would be well suited to be used with future generations of communication devices supporting 5G and IoT.**

***Key words*— 5G, IoT, Microstrip Patch Antenna, Multiband, Slot loading, Cost effective.**

I. INTRODUCTION

In recent years, rapid development of technology has created high demand for efficient and small-size antennas which can operate on multiple frequency bands. According to Balanis et al., there exists an increasing need for advanced antenna systems for current wireless applications, especially in the areas of IoT and 5G [1].

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Moreover, the development of IoT and 5G communications has further contributed to the need for antennas capable of operating at multiple frequency bands. According to Andrews et al., new communication systems require multiple operating bands and wideband antennas [2]. Traditional antennas are usually designed to operate at only one frequency band; thus, they become ineffective when being used at several standards. Pozar et al. indicate that utilization of several single band antennas results in complicated systems, increased costs, and larger sizes [3]. Microstrip patch antennas have gained great popularity as they offer a low-profile and lightweight construction as well as simplicity of manufacturing. According to Garg et al., microstrip antennas provide excellent characteristics for use in integrated communication systems, but their main disadvantages include low efficiency and narrow bandwidth [4]. Several approaches have been suggested to improve the mentioned drawbacks. According to Wong et al., slot loading methods can be used to achieve multi-resonance of the antenna by changing its current distribution [5]. Specifically, rectangular slot configurations have been applied extensively for the purpose of obtaining a multiband antenna without significantly increasing its size. As Deshmukh et al. show, rectangular slots increase the bandwidth of an antenna and allow achieving multi-frequency resonances [6]. However, most current designs are still limited to dual-band or triple-band capabilities and may involve additional size of an antenna or decreased efficiency. Kumar et al. suggest that achieving a quad-band antenna operating in compact dimensions requires substantial efforts in design [7]. To solve the problem, the paper proposes a compact quad-band microstrip patch antenna based on the method of slot loading. The proposed antenna features two rectangular slots which produce resonances at 2.4 GHz, 3.775 GHz, 4.64 GHz, and 5.315 GHz, thus covering communication bands necessary for Wi-Fi, IoT, sub-6 GHz 5G, and WLAN communication. The design and simulation of the proposed antenna will be performed in CST Microwave Studio with analysis of reflection coefficient, antenna gain, radiation pattern, and current distribution.

II. Proposed Patch Antenna Design and Configuration

The design for the proposed quad band microstrip patch antenna was done in a stepwise manner from the basic single band patch, which was modified in geometrical terms to make it multi band capable. The entire design process was carried out using CST Microwave Studio.

A. Substrate Selection

The first stage in the process of design was the choice of suitable substrate material. In this case, the substrate material chosen is FR-4 since it is cost effective and easily available. Though FR-4 shows greater losses than other materials, it is extensively used in actual implementations. The substrate characteristics include Relative permittivity (εr) of 4.4, Substrate thickness of 1.6 mm and Tangent of the loss angle (tanδ) approximately equal to 0.02. The dielectric constant affects the size of the antenna; that is, if the relative permittivity is high, then the antenna size can be reduced slightly.

B. Initial Patch Design (Fundamental Resonance)

The antenna design begins with a conventional rectangular microstrip patch designed to resonate at the fundamental frequency at 2.4 GHz. The standard transmission line model is used to calculate the initial dimensions.

Patch Width (W)

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \qquad (1)$$

Where:

- c= speed of light (3×10^8 m/s)
- f_r= resonant frequency
- ε_r= dielectric constant

Effective Dielectric Constant (εeff)

Due to fringing fields, the patch does not behave like a pure dielectric medium. So, an effective dielectric constant is used:

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

Effective Length (Leff)

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} \quad (3)$$

Length Extension (ΔL)

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

Actual Patch Length (L)

$$L = L_{eff} - 2\Delta L \quad (5)$$

Using these equations, the initial rectangular patch dimensions were calculated to resonate near 2.4 GHz.

C. Feed Line Design

The use of microstrip line for feeding was adopted due to simplicity and easy construction. As seen in Fig. 1, the feed line was constructed in such a way that there was an impedance of 50 ohms to ensure effective impedance matching between the antenna and the feed line. The width of the feed line was adjusted iteratively in CST to obtain minimum reflection coefficient (S_{11}).

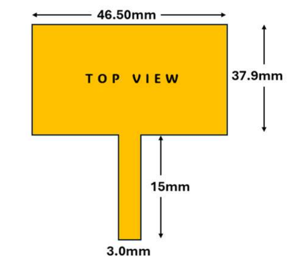

Figure 1. Patch and Feedline Dimensions

D. Slot Loading for Multiband Operation

Having achieved the first resonance using the single-band rectangular patch, the next goal became to add the slot elements to achieve resonances at several frequencies. As seen in Fig. 2, instead of using complicated designs for the slots, a simpler approach was used – two slots were formed on the patch forming a cross shape. The essence of the slot loading consists in changing the currents on the patch. By adding the slots, the current is forced to change its path along the slot edge, thus making it longer. As a result, other resonances appear without increasing the patch size.

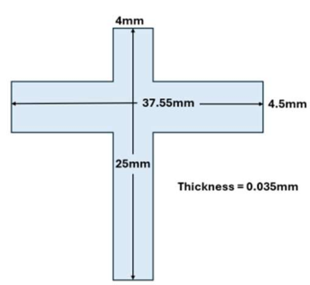

Figure 2. Slot Shape and Dimensions

In this configuration, two rectangular slots are carved in the patch, one along the horizontal axis and the other along the vertical axis. These two slots form a cross (+) shape pattern on the patch. The selection of this geometry is made due to its symmetry nature and for the ability to control different current paths independently. The horizontal slot affects more the current flow from left to right, while the vertical slot impacts more the current flow from top to bottom. Due to this orthogonal configuration, several resonance modes can be generated in this case. This happens because both slots help generate a new or change an existing resonant frequency of the antenna. The interaction of these two slots creates quad-band functionality through multi-paths of currents having various electrical lengths instead of one path, which generates resonance in different frequencies. The major benefit of this configuration, compared to other slot geometries, is its simplicity in geometry, ease of manufacturing, better symmetry of radiation, the possibility of tuning resonant frequencies independently through slot dimensions, and little enlargement in antenna size. Therefore, the implementation of cross-shaped rectangular slots contributes significantly to multiband functionality through the modification of surface currents.

E. Parametric Optimization

Once the slots were introduced, several parameters such as slot length and width, distance between slots and feed position were varied to fine tune the performance of the antenna. Each parameter was adjusted carefully to achieve the desired resonant frequencies, good impedance matching (S11 < -10 dB) and stable radiation characteristics. Fig. 3 shows the 3D design in CST Microwave Studio.

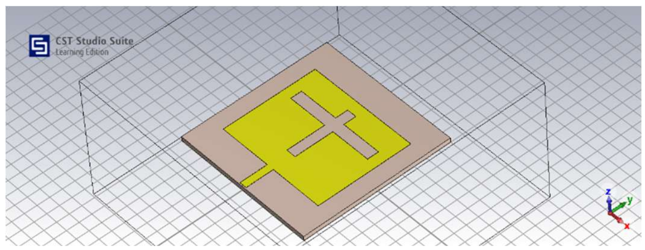

Figure 3. 3D CST Simulation Model

F. Simulation Setup

The antenna was simulated using CST Microwave Studio with appropriate boundary conditions and excitation and the parameters such as reflection coefficient (S11), gain of the antenna, radiation pattern and surface current distribution were analysed.

III. DISCUSSION OF SIMULATION RESULTS

The proposed quad band microstrip patch antenna has been analysed using CST Microwave Studio. The main criteria considered include the Reflection Coefficient (S11), Antenna Gain, Radiation Pattern and Surface Current Distribution. It is evident from the results that the quad band performance is achieved through the cross shaped rectangular slots taken on the patch

A. Reflection Coefficient (S11)

The S11 graph explains how well the impedance matches the antenna between 1GHz and 6GHz frequency. From Fig. 4, it can be observed that the antenna resonates at multiple frequencies, with four prominent bands, the first band is at 2.4GHz with a deep reflection coefficient of approximately -40dB indicating excellent impedance matching. The second band is operated from 3.72GHz to 3.82GHz covering a bandwidth of 100MHz with deep reflection coefficient of approximately -34dB at 3.775GHz. The third band is operated from 4.58GHz to 4.71GHz covering a bandwidth of 130MHz with a deep reflection coefficient of approximately -18dB at 4.64GHz. The fourth band is operated from 5.22GHz to 5.49GHz covering a bandwidth of 270MHz with a deep reflection coefficient of approximately -22dB at 5.315GHz. In all these bands, the S11 value is well below -10 dB, which confirms that the antenna is properly matched and radiating efficiently at these frequencies. The sharp dips in the curve indicate strong resonance, and the presence of multiple dips confirms the quad band nature of the antenna. These resonances are mainly achieved due to the introduction of the cross shaped slots, which create multiple current paths on the patch.

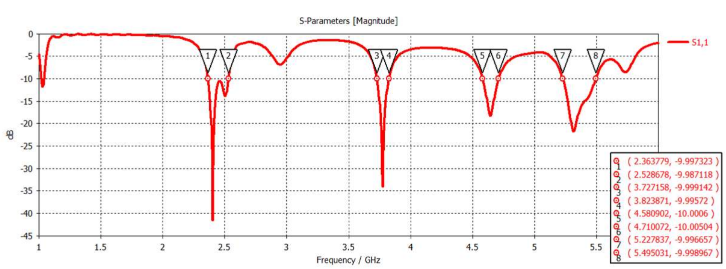

Figure 4. Reflection Coefficient (S11)

B. Gain vs Frequency

The gain of the antenna was evaluated at different resonant frequencies to understand its radiation capability. It can be seen from Fig. 5 that at 2.4GHz, the antenna has a gain of around 2.7dB which will be useful for IoT & WLAN applications. At 3.3GHz the gain is found to be negative which may have occurred due to mismatch loss. At 3.8GHz there is an improvement in the gain value of around 1.8 – 2dB. At 4.6GHz the gain has been observed to be close to 0dB which means moderate radiation. At 5GHz the gain rises to 1.5dB approximately. It can be said that the gain is reduced with an increase in frequency. In general, it is seen that the antenna has adequate gain at all frequency bands, but the lower and mid frequency bands show better gains compared to others.

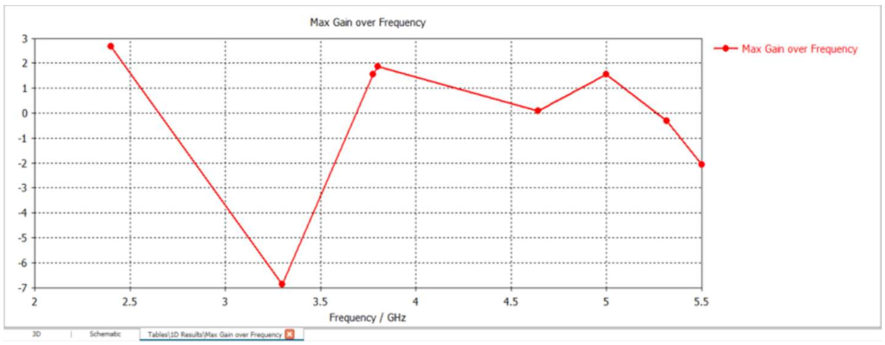

Figure 5. Gain vs Frequency

C. Surface Current Distribution

The Surface Current Distribution gives us a clear understanding of the antenna's radiations at various frequencies. The following current distribution at critical frequencies explains the effect of the cross shaped slot design. For instance, at 2.4GHz as illustrated in Fig. 6, the current is distributed in a larger area of the patch with significant concentration near the feedline portion, the edges of the patch and near the slots. In this case, the current flows along the edge of the slots rather than flowing through the patch which makes its electrical length longer. This explains why resonance is attained without making any modifications in the size of the antenna. As shown in Fig. 7, the distribution of current at 3.775GHz becomes more localized. In this case, the current flows in certain parts of the slots. Hence, the slots play a critical role in the formation of this resonant frequency. The interaction between the two rectangular perpendicular slots leads to many current loops that cause the second and third resonant frequencies. Finally, the current distribution for the fourth resonant frequency at 4.64GHz is less uniform as depicted in Fig. 8. Current is highly concentrated along the edges of the cross shaped slots and near the feedline region. This shows that the slots have a strong influence on the current flow and hence there is a shortening of the current path lengths. As compared to the lower frequencies where the current distributes itself over the whole patch, this shows an excitation of higher order modes. The shortening of the current path tells that the current is excited at a shorter electrical length and thus resonates at higher frequencies. As shown in Fig. 9 at 5.315 GHz, there is a concentration of the current into smaller patches, particularly around the edges and the feed point of the slot. It implies that the current flows through shorter current paths that resonates at higher frequencies. From the above analysis, it can be concluded that the inclusion of cross shaped rectangular slots helps in achieving a quad band behaviour. With the modification of the surface current paths, multiple resonant frequencies can be excited without increasing the size of the antenna. The antenna shows satisfactory impedance matching and acceptable gain in all operating frequencies.

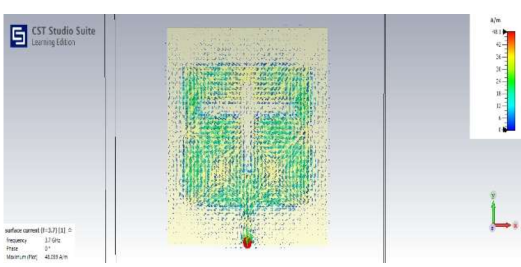

Figure 6. Surface Current Distribution at 2.4 GHz

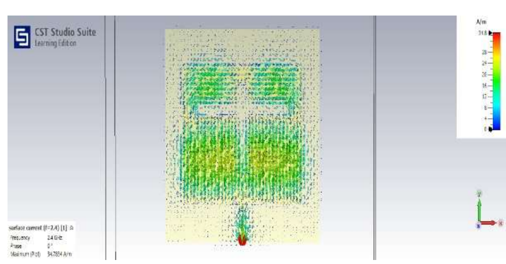

Figure 7. Surface Current Distribution at 3.775 GHz

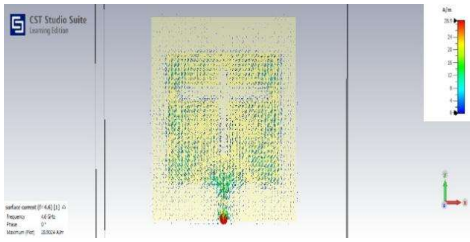

Figure 8. Surface Current Distribution at 4.64 GHz

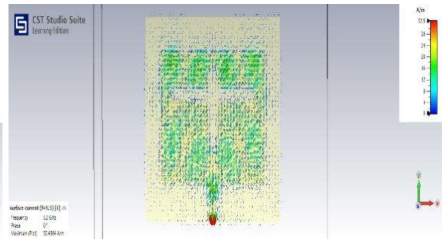

Figure 9. Surface Current Distribution at 5.315 GHz

D. Radiation Pattern

The radiation properties of the designed antenna were studied through far field directivity plots using CST Microwave Studio. The radiation patterns were generated at the important resonance frequencies of 2.4 GHz, 3.775 GHz, 4.64 GHz, and 5.315 GHz to study its directional properties. At 2.4GHz as illustrated in Fig. 10, the antenna radiation shows a directional pattern with a main lobe. The main lobe intensity is about 6.45 dBi. The radiation is oriented at an angle of 7 degrees showing that most of the energy is radiated in a particular single direction. The beamwidth is broad, which contributes positively to the coverage. There is an optimal level of the side lobe that suggests low undesirable radiation. This radiation pattern can be applied in Wi-Fi and IoT technologies where moderate directivity and coverage are required. As can be observed in Fig. 11, at 3.775 GHz, the radiation pattern becomes somewhat directional in nature. The amplitude of the major lobe becomes about 7.47 dBi. The beam tilts due to a change in the radiation pattern. The beam width becomes narrower than in the case of 2.4 GHz. The level of the side lobe is greater in this case, meaning that the side lobes are more dominant here. The gain being higher shows better efficiency of radiation, but side lobes show that energy is radiated in various directions. The radiation pattern at 4.64 GHz from Fig. 12 shows more variations since higher frequencies have been considered for the analysis. The gain in the main lobe is approximately 7.18 dBi. The direction of the main lobe suggests that the radiation is directional in nature. The beam width is moderate in nature. The secondary lobes show more secondary radiation. In this case, the antenna has maintained high gain but with a more complicated radiation pattern. The radiation pattern is observed to be slightly irregular at 5.315 GHz as shown in Fig. 13. The magnitude of the radiation pattern in the main lobe region is about 4.06 dBi. The direction of the radiations is inclined by an angle of 5 degrees. The beamwidth is average, while the level of the side lobe is low. Even though the gain is lower at higher frequencies, the antenna has a stable radiation with low levels of side lobes. It can be used in WLANs and 5G communication at higher frequencies where size is more important than gain. In general, from the radiation pattern, it is clear that the antenna radiates directionally in all bands.

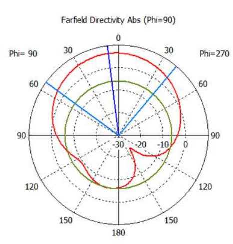

Figure 10. 1D Radiation Pattern at 2.4 GHz

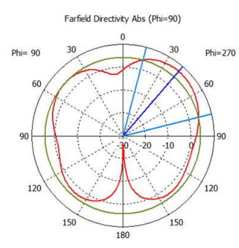

Figure 11. 1D Radiation Pattern at 3.775 GHz

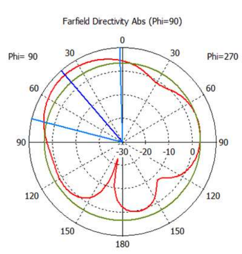

Figure 12. 1D Radiation Pattern at 4.64 GHz

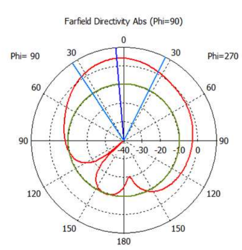

Figure 13. 1D Radiation Pattern at 5.315 GHz

IV. CONCLUSION

In this proposed work, the design of a small-sized quad-band microstrip patch antenna suitable for implementation in 5G/IoT communication networks is discussed. The proposed antenna utilizes a simple and effective method of loading with slots and operates using a substrate of FR-4. Two rectangular slots of cross shape are used to create multi-resonance in the antenna. The design is found to operate at four resonance frequencies including 2.4 GHz, 3.775 GHz, 4.64 GHz, and 5.315 GHz. The reflection coefficient shows good impedance matching with an S11 value of less than -10 dB for all operating frequency bands. Gain characteristics also prove satisfactory for practical use with high stability achieved for most resonance points. Directional nature with acceptable beamwidth and side lobes is observed throughout all frequencies for the radiation pattern of the antenna. The surface currents show the effectiveness of the cross-shaped slot configuration as it allows to create a multi resonant effect without changing the antenna dimensions. The proposed design can serve as a simple but effective way to create multiband antennas with low complexity and low cost. The cross-shaped slot configuration makes the design easier to fabricate and allows to reach multi resonant properties for the relatively easy shape of geometry.

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