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Slot Loaded Square Microstrip Patch Antenna for Dual Band Operation

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Abstract In this paper, a design to obtain dual band performance in square microstrip patch antenna has been proposed. This high directive probe feed antenna has only 30 mm × 30 mm patch. It provides dual-band operation by means of three narrow slots close and parallel to the patch radiating edges. It shows quiet analogous and satisfactory radiation pattern at both frequencies in the face of using a relatively facile feeding technique named co-axial feeding. The directivity of proposed antenna is above 6.5 dB at both bands. The dual band results and their radiation performances are observed using 'CST Microwave Studio' based realistic simulations. In short, realistic numerical simulation of a novel design is presented in this paper, considering losses and the presence of the antenna feed, showing how a practical realization is foreseeable.

Keywords Microstrip antenna, Dual-band, Radiation pattern

1. Introduction

The dual-frequency microstrip patch antennas are widely used to meet the need of frequency reuse often required in wireless communication, satellite systems, radar, Synthetic Aperture Radar (SAR), Global Position System (GPS) applications. Microstrip patch antennas are also extensively employed in many practical applications due to inherent advantages of low-profile, light weight, simple planar structures, conformability, ease of fabrication and integration with RF devices [1-7]. Though multi-frequency operations can be obtained by using wide band antennas and suitable electronic circuits, this solution has several drawbacks in terms of efficiency and noise performances [8]. Whereas dual-frequency microstrip patch antennas maintain good noise temperature and efficiency.

A perfect dual-band antenna always shows identical radiation properties at its both operating frequencies. Dual-band can be attained by using multilayer structures [9], [10], parasitic elements coupled to the main patch [11], aperture coupled parallel resonators [12], log-periodic or quasi-log-periodic structures [13], [14]. But these structures have some limitations such that overall large size, difficulties in designing and manufacturing. Likewise, stagger-tuned resonators [15], reactively loaded patches with short pins [16], varactor diodes [17] or optically controlled pin diodes [18] have been successfully developed for increasing bandwidth and dual band operation. However the patch size is small for high frequencies and it becomes difficult to put up the diodes or pins underside it. In order to tune resonant frequency an adjustable air gap between substrate and ground plane has also been carried out [19]. Two complications emerge according to this idea; initially the width of air gap has to be changed mechanically and subsequently, an array consisting of large number of element is difficult to design.

These are just some of the attempts already made to accomplish multi-frequency action of patch antennas. Nevertheless in the Antenna Design literature, dual-band microstrip patch antennas are categorized into two types depending upon the number of radiating elements, explicitly, multi-resonator antennas and reactive loading antennas. In multi-resonator antennas double resonant behavior is achieved via multiple radiating elements each supporting strong currents and radiation at its resonance. Aperture-coupled parallel microstrip dipoles [12] as well as the multi-layer stacked-patch antennas using circular [20], annular [21], rectangular [22], and triangular [23] patches are included in this category. The drawbacks of multi-resonator antennas are large size and high cost. In hand-held terminals they face trouble to be installed owing to their large size. They are costly due to multiple substrate layers in their structure.

The reactive-loading microstrip patch antenna consisting of a single radiating element obtain dual frequency action by connecting coaxial [24] or microstrip stubs [25] at the radiating edges of a rectangular patch. Frequency Ratio (FR)

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below 1.2 is the negative aspect of this solution. Although higher values of frequency ratio (around 4 to 5) can be gained by means of two lumped capacitors connected from the patch to the ground plane [26]. In reactive loading antennas dual-band operation can be realized through multiple shorting pins located symmetrically with respect to the patch axes [27] as well.

An additional kind of reactive loading can be introduced by etching slots on a patch. The slot loading on patch permits to robustly modify the resonant mode of a rectangular patch, particularly when the slots cut the current lines of the unperturbed mode. Previously, mode modification in rectangular microstrip patch antenna was performed by using symmetrical rectangular slots closed to radiating edges [28-31], J slot [32] etc. Symmetrical slot loading in elliptical patch antenna also lead to the same result [32]. Symmetrical slots were introduced in those designs to lower the resonant frequency of TM_{030} mode to act like TM_{010} mode and thus dual band antennas were successfully modeled. The simultaneous use of slots and short-circuit vias, allows to obtain an FR from 1.3 to 3 depending on the number of vias as shown in [32].

In this paper, we have proposed a design to obtain dual band performance via mode modification in square microstrip patch antenna with dimension 30 mm × 30 mm. With the help of slots near the radiating edges of the patch, the typical microstrip patch antenna can be twisted for multi-frequency operation. The proposed antenna provides dual-frequency operation by dint of three rectangular slots close and parallel to the patch radiating edges. The slots near radiating edges split the field into two orthogonal modes. At both bands the antenna shows analogous and satisfactory radiation performance. Furthermore, high directivity is a key prerequisite for modern satellite based communication system. The directivities of the antenna are above 6.5 dB at both bands (quiet satisfactory). Thus the antenna can be used in various applications such as SAR, GPS, WLAN, Wi-Fi, WiMAX and various other applications.

In section 2 the design procedures of proposed antenna are discussed. In section 3 and 4 simulation results are conversed for projected design.

2. Antenna Design

To analyze proposed microstrip antenna, several methods and software are available. We employed 'CST Microwave Studio' based realistic simulations to analyze microstrip antenna. The combination of the proprietary PERFECT BOUNDARY APPROXIMATION (PBA) with the unbeatable efficiency of the Finite Integration Technique (FIT) is the basis for CST MICROWAVE STUDIO. This software uses modules based on methods including FEM, MoM, MLFMM and SBR to calculate desired parameters such as s parameter, input impedance, and radiation pattern and so on. Figure 1 shows the basic design of our proposed single-fed (probe fed) microstrip antenna. The square patch has equal side length L= 30 mm. Permittivity of the substrate is 2. The thickness of the substrate is t = 1.5 mm. The dimension of each rectangular symmetrical slot is 28 mm × 1 mm. Other dimensions are given in Figure 1.

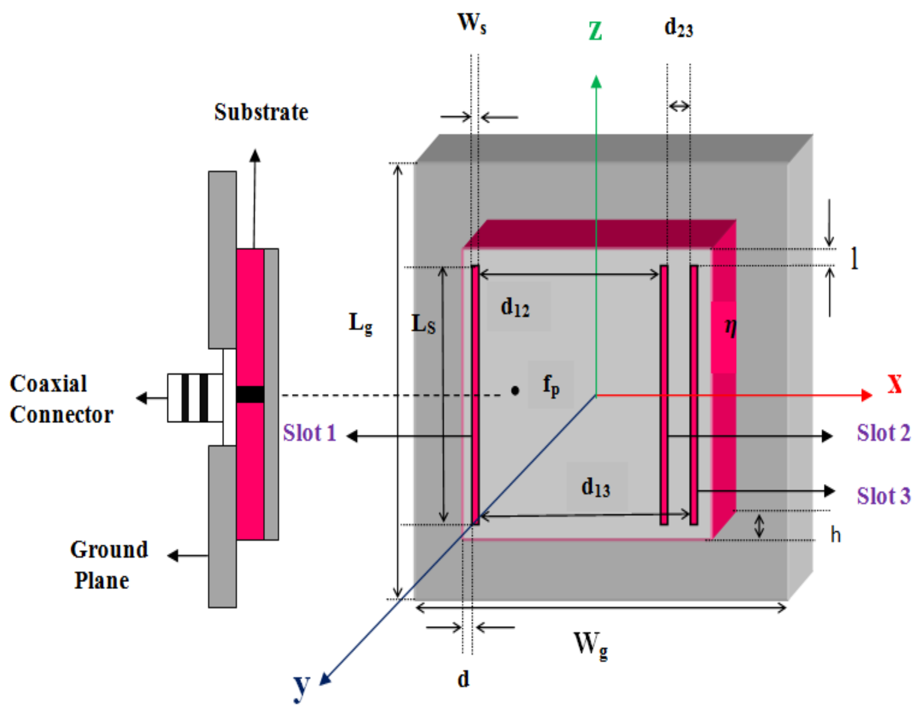

Figure 1. Geometry of proposed slot-loaded square microstrip patch antenna. Detailed information and constitutive parameters are: L_g = 40 mm, W_g = 40 mm, L_s = 28 mm, W_s = 1 mm, d_{12} = 24 mm, d_{13} = 26 mm, d_{23} = 1 mm, d = 1 mm, l = 1 mm, h = 1.5 mm, η = 2 and feed position f_p: (x, y) = (0, - 7.5 mm) considering origin at the centre of the patch

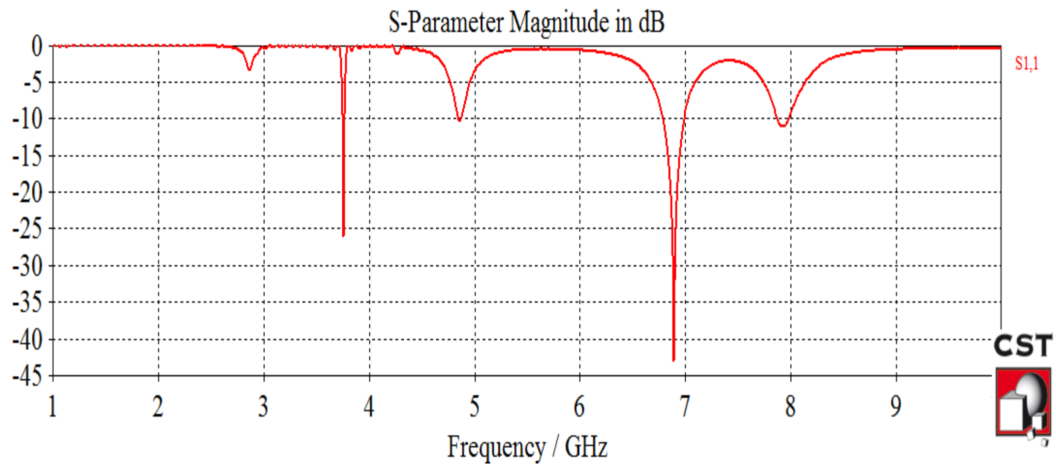

Figure 2. S-parameter performance of the proposed square microstrip patch antenna, TM_{010} mode at 3.754 GHz and $TM_{0\delta 0}$ mode at 4.861 GHz

If we use substrate having permittivity 2 (with thickness = 1.5 mm) and dimension is only 30 mm × 30 mm (with no slot), then the normal resonance frequency is around 3.475 GHz. That means the antenna operates only at single frequency. To get dual band operation, three symmetrical '**I**' slot (Figure 1) with dimension L_S and W_s are etched on the square patch adjacent and parallel to the radiating edges of the antenna. The slots are numbered resembling slot 1, slot 2 and slot 3 as shown in figure 1. The location of the slot 1 and slot 3 with respect to the patch is defined by the dimensions d and l. the distance between slot 1& slot 2, slot 2 & slot 3 and slot 1 & slot 3 are denoted by d_{12}, d_{23} and d_{13} respectively. The thickness of substrate is symbolized by h and the position of probe feed is at f_p. L_g and W_g represents the length and width of ground plane.

Figure 2 shows S-parameter performance of the proposed square microstrip patch antenna. It demonstrates the designed antenna return loss in 3.754 and 4.861 GHZ are -26.087872 dB and -10.301681 dB in that order. In Figure 3 and Figure 4 three dimensional radiation pattern and polar plot of TM_{010} mode at 3.754 GHz are presented respectively. In Figure 5 and Figure 6 three dimensional radiation patterns and polar plot of $TM_{0\delta 0}$ mode at 4.861 GHz are illustrated correspondingly. Other antenna parameters are given below in Table.

Table 1. Antenna Parameters

Mode	Resonant Frequency (GHz)	Directivity (dB)	Gain (dB)
TM_{010}	3.754	6.647	3.493
TM_{030}	4.861	7.693	7.702

3. Theoretical Analysis of Loading Slots on the Patch

The frequency of operation of the patch antenna is determined by the length L. The center frequency will be approximately given by [34],

$$f_c = \frac{v_0}{2L\sqrt{\varepsilon_r}} \quad (1)$$

As the length of proposed antenna, L=30 mm=30×10^{-3} m and the permittivity of the substrate, $\varepsilon_r = 2$ and $v_0 \approx c$ =speed of light so the center frequency of the proposed antenna can be calculated as follows:

$$f_c \approx \frac{3 \times 10^8}{2 \times 30 \ \times 10^{-3} \times \sqrt{2}}$$
$$= 3.54 \times 10^9 \text{ Hz}$$
$$= 3.54 \text{ GHz}$$

Owing to loading three parallel slots in the proposed antenna it operates at two separate frequencies at 3.754 GHz and 4.861 GHz. The effect of slot on the patch can be analyzed using the duality relationship between the dipole and the slot. The Babinet's principle [33] of optics is used to derive the property that the radiation pattern of a slot antenna resembles that of a complimentary metallic strip dipole.

Babinet's principle states that (in optics) that when a field behind a screen with an opening is added to the field of a complementary structure (that is a shape covering the screen hole), then the sum is equal to the field where there is no screen. In the proposed antenna the patch is fed by co-axial cable. Since the slot is thin, the voltage can be sinusoidal with zero voltage across the ends of slot. In this case the voltage across the slot is given as [35]

$$V_g = V_m \sin\left[\left(k\frac{L}{2} - |z|\right)\right], \quad |z| \le 1 \quad (2)$$

Where
L = Length of the slot
K $= \frac{2\pi}{\lambda}$ = Propagation constant in free space
V_m = Maximum input voltage
$|z|$ = Distance along the length of the slot

The current distribution of long dipole given as follows [35]

$$I(z) = I_m \sin\left[k\left(\frac{L}{2} - z\right)\right], \quad z > 0$$
$$= I_m \sin\left[k\left(\frac{L}{2} + z\right)\right], \quad z < 0 \quad (3)$$

Where

I_m=the maximum input current in the dipole antenna.

The total electric field at the far-field point from the antenna is given by [35]

$$E_\theta = \frac{jk\eta_0 e^{-jkr}\sin\theta}{4\pi r}\left[\int_{-L/2}^{L/2} I(z)e^{jkz}\cos\theta\, dz\right] \quad (4)$$

Performing integration yields

$$E_\theta = \frac{jk\eta_0 e^{-jkr}\sin\theta}{4\pi r}\left[\frac{\cos\left(\frac{kL}{2}\cos\theta\right)-\cos\left(\frac{kL}{2}\right)}{\sin\theta}\right] \quad (5)$$

Here

η_0= Characteristic impedance of free space

$= 120\pi\ \Omega$

R= Distance of far-field from center of the dipole

The Poynting vector can be written as [36]

$$P_r = \frac{1}{2}|E_\theta|.|H_\varphi|, \text{ since } H_\varphi = \frac{E_\theta}{\eta_0}$$

$$= \frac{\eta_0 \mathrm{I}_m{}^2}{8\pi^2 r^2}\left[\frac{\cos\left(\frac{kL}{2}\cos\theta\right)-\cos\left(\frac{kL}{2}\right)}{\sin\theta}\right]^2 \quad (6)$$

Therefore, the total power radiated from the dipole antenna is given by [36]

$$W_T = \int p ds = \int_0^\pi P_r 2\pi r^2 \sin\theta\, .d\theta$$

$$= \frac{\eta_0 \mathrm{I}_m{}^2}{8\pi^2 r^2}\int_0^\pi\left[\frac{\cos\left(\frac{kL}{2}\cos\theta\right)-\cos\left(\frac{kL}{2}\right)}{\sin\theta}\right]^2 d\theta \quad (7)$$

If the radiation resistance is defined in terms of maximum current then it may be given as [36]

$$R_r = \frac{2W_T}{I_m{}^2} = \frac{\eta_0}{2\pi}\int_0^\pi\left[\frac{\cos\left(\frac{kL}{2}\cos\theta\right)-\cos\left(\frac{kL}{2}\right)}{\sin\theta}\right]^2 d\theta \quad (8)$$

Solution of equation (8) yields

$$\begin{aligned} R_r &= 60\{C + I_n(kL) - C_i(kL) \\ &+ \frac{1}{2}\sin kL\left[S_i(2kL) - 2S_i(kL)\right] \\ &+ \frac{1}{2}\cos(kL)\left[C + I_n\left(\frac{kL}{2}\right) + C_i(2kL) - 2C_i(kL)\right]\} \end{aligned} \quad (9)$$

Where

C=Euler's constant

$$S_i(x) = \int_0^x \frac{\sin x}{x} dx$$

And

$$C_i(x) = -\int_x^\infty \frac{\cos x}{x} dx$$

The input impedance of the dipole or slot is given by [35]

$$Z_s = \frac{v}{I_m} = -\frac{1}{I_m}\int_{-h}^{h} E_z \sin k(h - |z|)\, dz \quad (10)$$

Where

E_z= the electric field along the z-direction.

4. Antenna Feed

The structure is fed by coaxial probes. The reason behind using this feeding technique is that is the feed can be placed at any desired location inside the patch in order to match with its input impedance (i.e. 50 Ω). Besides, coaxial probe provides low spurious radiation. As seen from Figure 1, the inner conductor of the coaxial connector extends through the dielectric and is soldered to the radiating patch, while the outer conductor is connected to the ground plane. The radius of the inner conductor is 0.3 mm and the radius of outer conductor is 1.2 mm.

Selection of the suitable feed location is a dilemma for dual band operation. Because the radiation pattern regularity is influenced by the symmetry of the feeds. A better procedure (when slot case) can be found for probe feed location using modal matching technique following [30]. But in case of our proposed design, the **'I'** slot will make all these procedures much complex and obviously time consuming. Therefore simulation based iterative process is used by segmenting proposed antenna to choose the suitable feed location. Thus the feed is located at f_p: (x, y) = (0, - 7.5 mm) considering origin at the centre of the patch.

5. Dual Band & Frequency Shifting Operation

The resonant behavior of the slot loaded patch antenna can be explained by initiating from the cavity model description of an unslotted rectangular patch and from cavity perturbation theory. According to cavity model, the first three modes that can be excited in the cavity are usually denoted by TM_{010}, TM_{020} and TM_{030}. These modes correspond to longitudinal currents distributed on the patch which have nulls at the radiating edges. The TM_{010} is the most used in practical applications since the TM_{020} mode has a broadside-null radiation pattern and the TM_{030} produces grating lobes.

While three slots loaded in proposed antenna then the resonant behavior is discussed by cavity perturbation theory. In proportion to cavity perturbation theory, when a resonant cavity is perturbed, i.e. when a foreign object with distinct material properties is introduced into the cavity or when a general shape of the cavity is changed, electromagnetic fields inside the cavity change consequently. The underlying assumption of cavity perturbation theory is that electromagnetic fields inside the cavity after the change differ by a very small amount from the fields before the change. But the change in cavity causes significant change in resonant frequency. The corresponding change in resonant frequency can be approximated as (11) [37]:

$$\frac{\omega-\omega_0}{\omega_0} \cong -\frac{\int_{V_0}(\mu\bar{H}_0{}^2-\epsilon\bar{E}_0{}^2)\, dv}{\int_{V_0}(\mu\bar{H}_0{}^2+\epsilon\bar{E}_0{}^2)\, dv} \quad (11)$$

Here ω_0 is the resonant frequency of the original cavity and ω is the resonant frequency of the perturbed cavity, $\bar{H}_0$ & $\bar{E}_0$ represent the magnetic and electric field of the original cavity correspondingly, μ & ϵ are original permeability and permittivity respectively.

Equation (11) can be written in terms of stored energy as follows [37]:

$$\frac{\omega-\omega_0}{\omega_0} \frac{\Delta W_m - \Delta W_e}{W_m + W_e} \quad (12)$$

Here ΔW_m & ΔW_e are the changes in the stored magnetic energy and electric energy respectively, after perturbation and $W_m + W_e$ is the total stored energy in the cavity.

Due to etching three narrow slots near radiating edges of proposed antenna, the currents of TM_{030} resonant frequency circulate around the slots and become similar to the TM_{010} mode. Thus the slots also modify three lobe shape of TM_{030} mode to regular behavior. But they do not perturb TM_{010} mode significantly. The amount of perturbation on excited mode in loaded slot antenna does not have close form formula to calculate, but there is a relationship between two perturbed frequencies (TM_{010} and TM_{030}) as given in equation (13) [28].

$$f_{TM030} = (1.6\text{-}2)\, f_{TM010} \quad (13)$$

In addition the slots cause minor perturbations of TM_{010} are expected because the slots are located close to the current minima. The radiating mechanism associated with this first mode is essentially the same as that of a patch without slots. As a consequence, its resonant frequency is only slightly different from that of a standard (unslotted) patch. The resonant frequency of unslotted antenna is 3.475 GHz whereas the resonant frequency of slot-loaded antenna for first mode (i.e. TM_{010} mode) is 3.754 GHz.

In loaded slot microstrip antenna, the second mode (TM_{020}) has also good radiation properties. But because of its null effect in broadside direction, it cannot be used as broadside radiator.

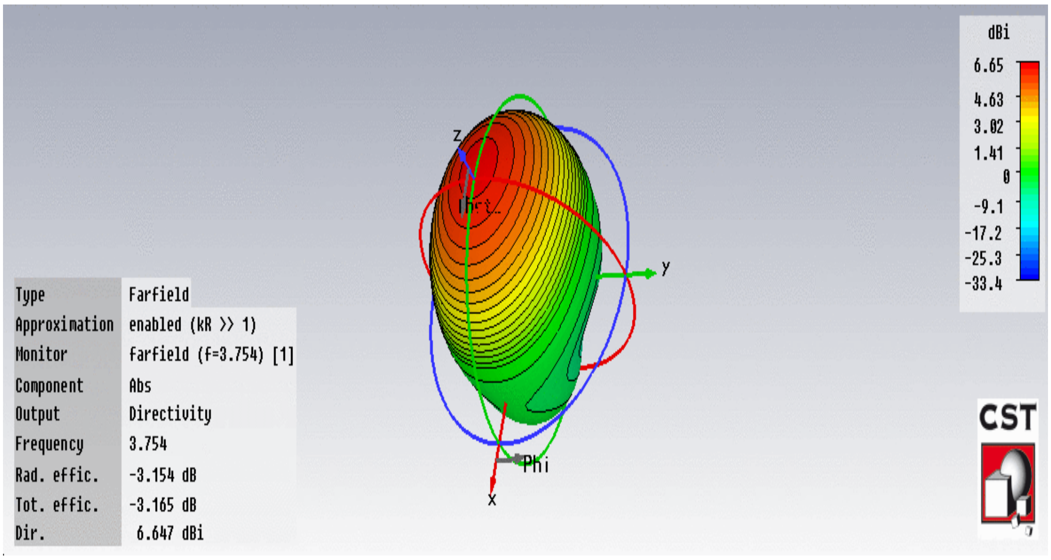

Figure 3. Three dimensional radiation pattern of TM_{010} mode at 3.754 GHz

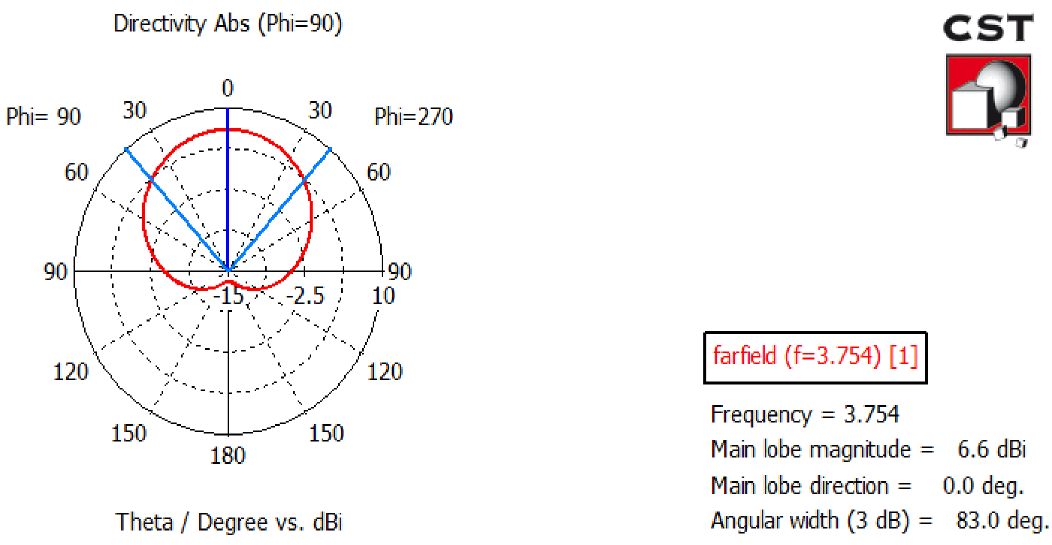

Figure 4. Polar plot of TM_{010} mode at 3.754 GHz

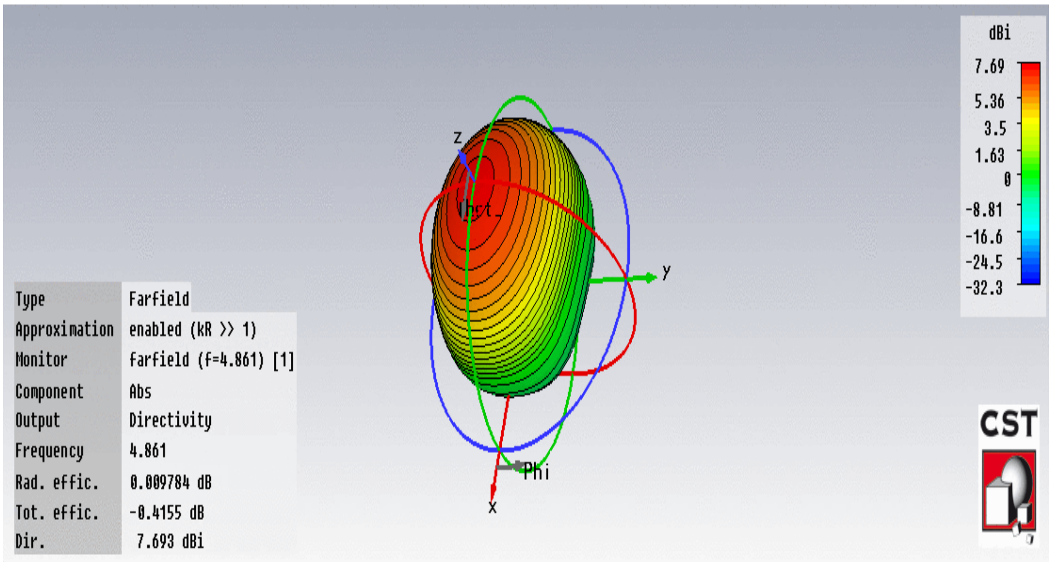

Figure 5. Three dimensional radiation pattern of $TM_{0\delta0}$ mode at 4.861 GHz

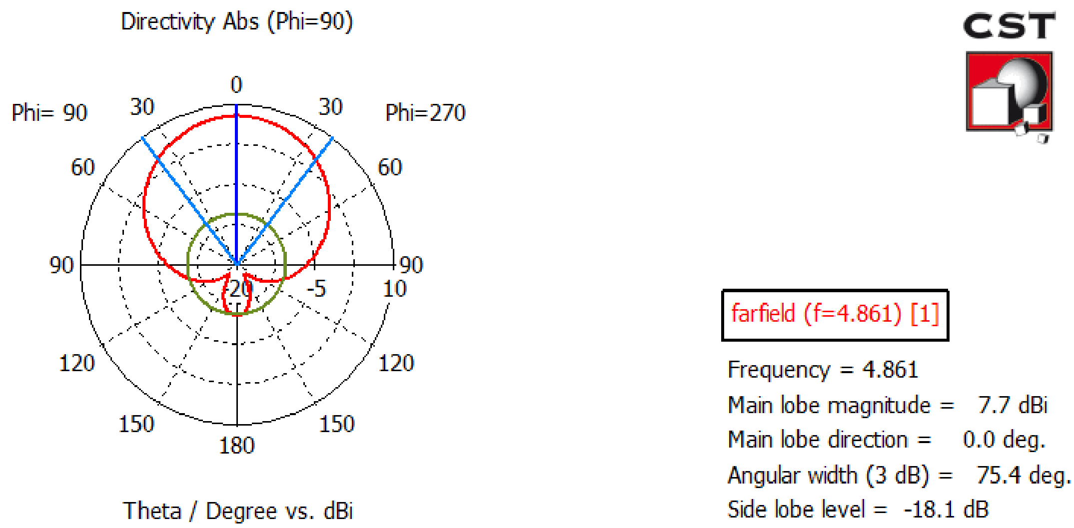

Figure 6. Polar plot of $TM_{0\delta0}$ mode at 4.861 GHz

6. Conclusions

A design of dual band single feed microstrip patch antenna has been proposed and described. The new geometry of the patch has verified to be a high directive and dual band element. This is particularly important for radar systems where directional characteristics, narrow bandwidth are often demanded to determine the range, altitude, direction, or speed of objects. It can also be applied to satellite systems where two channels are needed to provide communication links between various points on Earth. Here, antenna size (30 mm × 30 mm) is reduced compared to the conventional dual-band antenna design. The results show satisfactory radiation pattern, gain & directivity in both frequencies. As a result the proposed antenna is attractive for radar and satellite systems.

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