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RESPONSE STUDY OF IMPACT OF SLOT AREA VARIATION IN MINIATURE ANTENNA FOR KURTZ-ABOVE BAND APPLICATIONS IN 5G/6G WIRELESS COMMUNICATION

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ABSTRACT

Modern fifth-generation/sixth generation (5G/6G) wireless demand for efficient miniature antenna. To fulfill these demands here efforts have been made using high frequency structure simulator software (HFSS) to design a compact microstrip patch antenna (MPA). The design of the antenna consisted of two slots- one located near the feed line and the other one at the opposite side of the feed line. The volumetric dimension of the proposed antenna was 13.2 mm x 11.4 mm x 1.6 mm, designed at resonant frequency 33 GHz, employing 1.6 mm thick Rogers RT Duroid 5880 substrate having dielectric constant 2.2 and loss tangent 0.0013. A transmission line having a length of 5.7 mm and a width of 2 mm was used to excite the antenna for electromagnetic radiation fields. Antenna parameters simulation results were obtained for different slot areas, keeping other design parameters like dimensions of ground, patch, substrate, and feed port fixed. Different slot areas were selected by changing slot width, keeping its length constant. A gain of 7.7 dB with voltage standing wave ratio (VSWR) of 1.9 and return loss (S11) -19.23 dB was obtained for slot width 3 mm and area 1.5 mm^2. The directivity of the antenna was reported as 5.7dB, with a very good surface current density of 104.94 Amp/m, considered sufficient in the fringing fields breaking situation. Bandwidth was found to be inversely proportional to slot width. VSWR, S11, and 3D gain showed inverse dependence on slot area. Gain and S11 change in direct proportion to feed width whereas VSWR changes inversely with feed length. The proposed MPA is suitable for satellites, mobile phones, wireless communication systems, and remote sensing applications.

Keywords: patch antenna, wireless communication, return loss, gain, miniature antenna.

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1. INTRODUCTION

The remarkable success of wireless mobile communications in recent years is a reflection of both the exponential expansion of wireless communication and technological advancement [1-4]. As communication technology advances, antennas must become more sophisticated and able to meet the demands of the newest generation. Due diligence in the study and analysis of antenna systems is vital for researchers due to the significance of antenna systems for wireless technology and the rapid expansion of next-generation communication systems [5-7].

Microstrip patch antenna (MPA) is a tremendous name in the modern communication world. MPA consists of three layers. The top layer is often a metal foil, known as a radiating patch. The ground is the lower part, whereas the dielectric is the middle part. Radiation of electromagnetic waves of the MPA is due to the in-phase addition of bordering E-fields on its perimeter. Microstrip antennas are more small, low profile, inexpensive, and lightweight than typical microwave antennas, allowing them to satisfy miniaturization criteria. Microstrip patches may be of different shapes like rectangular, circular, elliptical, etc. After the excitement of patches through any feedline the waves are generated and reflected by the dielectric substrate. However, due to fringing fields between the ground plane and patch edges, the antennas radiate electromagnetic waves [8]. The patch antenna's qualities may be optimized by a variety of adjustments. Small sized (Rectangular, circular, or any size) apertures formally known as slots, are drawn on a patch or ground plane to enhance the antenna performance. Researchers get reduced return loss, enhanced bandwidth, and gain by applying a slot on a radiating patch or ground plane of a microstrip antenna [9-11].

The idea of slot design on a patch came to influent the fringing fields that control the radiation pattern of the antenna. Many researchers use different shape slots like ‘E’, ‘H’, and ‘L’ but here a rectangular slot is designed [12-14]. Proper impedance matching between feed line and radiating patch width leads to excite the radiating patch efficiently. As a result, efficient result parameters are obtained. Ozgur Dundar *et al.* tried to achieve a more efficient antenna by using suitable, eligible microstrip feed width in their design [15]. But here, the variation of slot area is more impactful to make the antenna more efficient. Applying a slot on a patch is a standard way to make MPA more flexible for modern communication systems. Shivnarayan *et al.* applied a slot on the patch and took VSWR, and bandwidth for different slot widths and slot lengths at 3 GHz, without considering S11 [16]. S11, VSWR, and operating frequencies are changing inversely with various slot lengths at high frequencies. So, the impact of slot area on the communication system is considerable for any operating frequencies (high and low). Here, a new effort at slot area variation has been made at high frequency. Slot area variation plays an important role in the result parameters of compact, miniature antenna performance at any operating frequency.

This is how the rest of the paper is structured. Material selection for the microstrip antenna is discussed in section 2. The design methodology of the suggested antenna is covered in Section 3. Section 4 covers the simulation results with a discussion of the antenna characteristics. The article's closing thoughts are drawn in Section 5 along with an outline of future research.

2. MATERIAL SELECTION

In the case of patch antennas, a dielectric material consists of the top level radiating conducting patch and bottom level ground. For better antenna performance dielectric material should have a low dielectric constant [17-18]. The use of substrate material with a high dielectric constant provides a narrow bandwidth [19-20]. A challenging issue in the construction of microstrip patch antennas is material selection. The conducting materials and the substrates are the two main materials that have an impact on the microstrip antennas' performance. The electrical conductivity of the conducting material determines its selection, whereas the dielectric qualities, mechanical deformation tolerance (bending, wrapping, twisting), durability in the external environment, and miniaturization susceptibility of the substrate material are taken into consideration.

To guarantee that the antenna operates with high efficiency, it is preferable to investigate conductive materials with high electrical conductivity. Antenna performance is greatly affected by the selection of appropriate conductive material for the antenna's ground and patch. The ratio of the surface current per unit length to the decreased DC voltage is known as surface resistivity. To reduce electrical loss and improve antenna performance, materials need to have an extremely low electrical surface resistance.

For the MPA, a substrate material with low dielectric loss, low coefficient of thermal expansion, low relative permittivity, and high thermal conductivity is optimal [21]. The substrate's dielectric constant must be high to reduce the antenna's size. There is a trade-off between efficiency and antenna design size, though, as increasing antenna efficiency would cost more with larger antenna sizes. Dielectric properties are affected by various factors like temperature, frequency, surface roughness, purity, moisture content, and material homogeneity. Lower dielectric constants generally result in lower surface wave losses. As a result, decreasing the dielectric constant causes the antenna's impedance bandwidth and spatial waves to grow, making the antenna suitable for high efficiency and gain. The antenna's efficiency, performance, and bandwidth are determined by its thickness and substrate dielectric constant. Because of the materials' extremely restricted range of permittivity values, the thickness could result in greater fluctuations. As a result, it is essential to the antenna's construction since it establishes the bandwidth, resonance frequency, and input impedance [22]. The antenna's geometric size is determined by the thickness of the substrate material employed in the design. When the substrate is thin and has a low relative permittivity close to 1 or 2, antenna patches are small; when the substrate is thick and has a low relative permittivity, antenna patches are large [23–24].

3. ANTENNA DESIGN

The design procedure for the MPA suggested in this article is described in detail in this section. There were three steps to the design process. The first step involved applying mathematical models through standard equations to obtain the fundamental design. The next step was to improve the radiating patch's matching with the feed line, to improve the return loss value at the resonance frequency. The design was optimized in the third step through additional improvement of return loss, gain, and downsizing of the antenna's size.

The MPA with a rectangular shape is selected to get acceptable antenna properties. The suggested antenna is initially intended to run at 33 GHz. The whole design procedure, analysis, and simulations are done through high frequency structure simulator software (HFSS). High-frequency structure simulation software, HFSS, is used to design, optimize, and simulate gigahertz and terahertz frequency electronic devices. To design through the said software three design parameters resonance frequency, dielectric constant of substrate, and height of substrate are very critical to choose. The proposed dimension of miniaturized MPA is 13.2 mm x 11.4 mm x 1.6 mm an operating frequency of 33 GHz, a substrate height of 1.6 mm, and material RT Duroid (tm) with dielectric constant 2.2. RT Duroid (tm) is preferred over other substrate materials because its low power dissipation factor enhances its utility to Kurtz above band. It is resistant to all reagents and solvents. A substrate was designed on the ground plane and a rectangular radiating element, known as a patch, of dimension 1.8 mm × 3.6 mm was taken on dielectric material. A transmission line having a length of 5.7 mm and a width of 2 mm was used to excite the antenna for electromagnetic radiation fields. The ‘edge effect’, usually known as the ‘fringing effect’, explains the bending of electromagnetic field lines near the edge of a patch [25-26]. This important fringing field affects the dimension of the antenna and the dielectric constant of the substrate. Standard antenna design equations were used to determine the basic dimensions of the antenna.

The resonance frequency is calculated with the equation.

$$f_r = \frac{v_0}{2L\sqrt{\epsilon_r}} \tag{1}$$

Where, ϵ_r = dielectric constant of substrate material
L = Length of the radiating patch

Considering the fringing effect, the effective dielectric constant is determined by the equation.

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

Where, h = thickness of substrate

Extension in the length of the radiator,

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W}{h}+0.8\right)} \qquad (3)$$

Length of the patch,

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{reff}}\sqrt{\mu_0\,\varepsilon_0}} - 2\Delta L \qquad (4)$$

Width of the patch,

$$W = \frac{\upsilon_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \qquad (5)$$

Effective length of patch due to fringing effect

$$L_{eff} = L + 2\Delta L \qquad (6)$$

Using formulae (equations 1-6), the parameters of the proposed antenna were calculated. After that, a rectangular slot of length 0.5 mm and width 3 mm i.e., the slot of area 1.5 mm^2 was drawn on the patch and the parameters like S11, VSWR, gain, and radiation pattern were determined.

However, parameters are simulated for different slot areas, keeping the other design parameters like dimensions of ground, patch, substrate feed, and port fixed. The different slot areas were selected by changing slot width only. First, the slot width was taken at 3 mm for calculating the result parameters at 33 GHz operation frequency. After obtaining the result parameters at 3 mm slot width, the result parameters were compared for slot width 2.8 mm (slot area 1.4 mm^2), slot width 2.6 mm (slot area 1.3 mm^2), slot width 2.4 mm (slot area 1.2 mm^2) and slot width 2.2 mm (slot area 1.1 mm^2). Here, through the desired impedance matching, the microstrip line of length 5.7 mm and width 2 mm was used for supplying energy to the patch at 33 GHz.

Figure-1 shows the different steps taken to simulate the proposed antenna at 33 GHz. In the first step, the slot having a length of 3 mm and width of 0.5 mm and the microstrip feed line having a length of 5.7 mm and width of 2 mm at 33 GHz was designed. Another identical slot was introduced on the patch on the directly opposite side of the first slot in the second step. The introduction of a second slot made patch size look like a well. The second slot took care of breaking the fringing fields from the patch. By the photolithography method, the proposed antenna can be easily prepared.

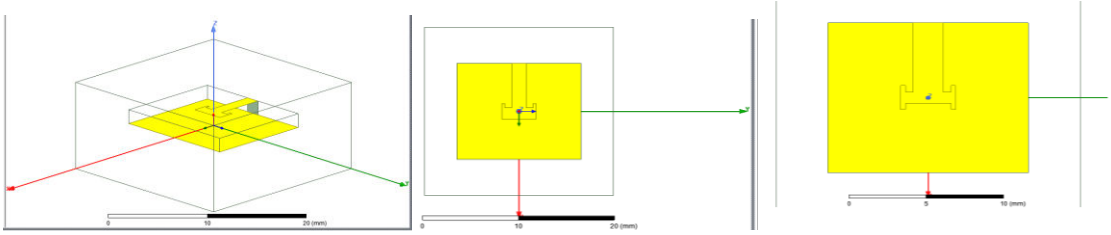

Figure-1. Stepwise HFSS design of the proposed MPA.

4. RESULTS AND DISCUSSIONS

After design and simulation through, HFSS the parameters of the antenna were recorded. By altering the dimensions of particular parameters, the parametric analysis examined how their modifications affect the antenna parameters. The parameter sweep function of the HFSS simulator was used to examine the impact of slot width. A smaller VSWR value enables better antenna matching to the transmission line and greater power provided to the load. Return loss S11 contributes to determining the mismatch from the termination in terms of energy returned to the radiating source. The gain of the antenna is the amount of power transferred in the peak radiation direction as compared to an isotropic antenna.

For slot area 1.5 mm^2, having a slot width of 3 mm, the return loss, VSWR, and radiation pattern are shown in Figure-2, Figure-3, and Figure-4 respectively. Figure-2 shows S11 for slot area 1.5 mm^2 is -19.23 at 33.62 GHz.

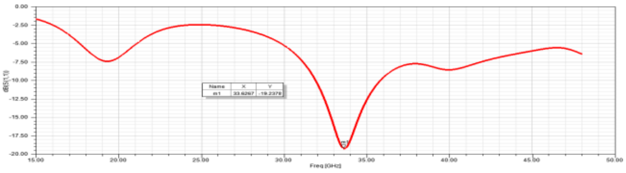

Figure-2. The return loss of the proposed antenna of the slot area 1.5 mm^2.

Figure-3 shows VSWR for slot area 1.5 mm^2. The VSWR value is 1.9169 at 33.70 GHz.

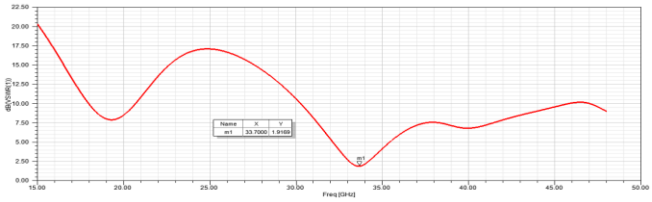

Figure-3. VSWR of the proposed antenna of the slot area 1.5 mm^2.

The Figure-4 shows the real Y parameter for the proposed antenna at 33 GHz. This figure establishes that at this slot length, maximum power can be transmitted with Y parameter conductance 0.0512 and 0.0160.

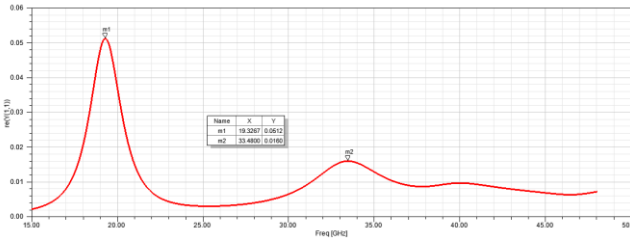

Figure-4. Y parameter (Re).

An antenna's electric field and magnetic field plane patterns are frequently characterized in terms of the plane of polarization of an electromagnetic wave. The 2D radiation pattern of the proposed antenna is shown in Figure-5, which maintains the near isotropic pattern.

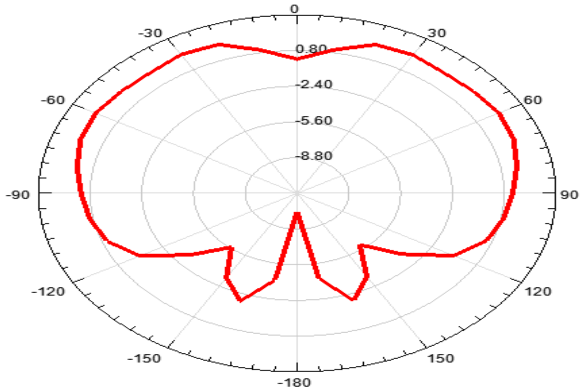

Figure-5. 2D radiation pattern of proposed antenna of slot area 1.5 mm^2.

The amount of power that an antenna's radiation pattern concentrates in a specific direction is known as its directivity. Figure-6 represents the directivity of the antenna and the achieved directivity is 5.7 dB.

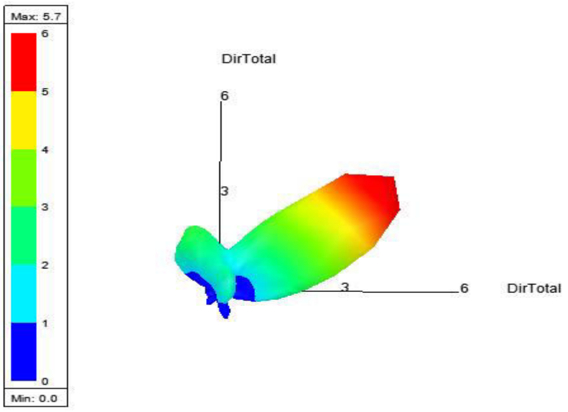

Figure-6. Directivity.

Figure-7 shows surface current density having a value of 104.94 Amp/m which is considered a very good value in the fringing fields breaking situation.

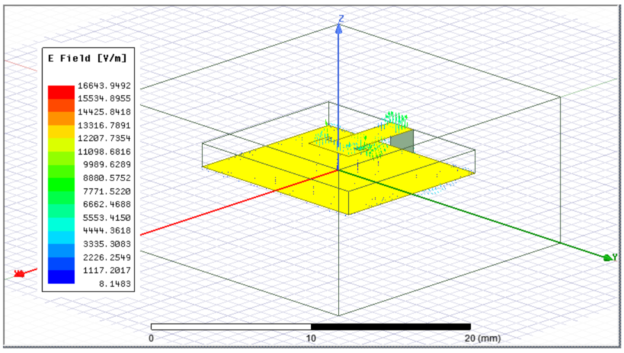

Figure-7. Vector field.

Antenna gain refers to the antenna's capacity for directional emission compared to the ideal antenna. The Figure-8 depicts a maximum gain of 4.02 dB for the two slots antenna at 33 GHz.

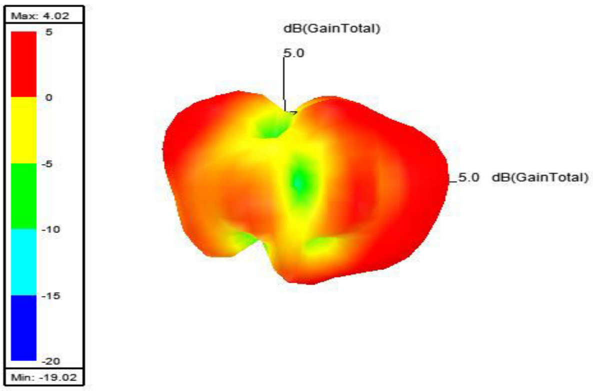

Figure-8. Gain.

Surface current distributions at resonance frequency highlight the electromagnetic radiation properties of the optimized antenna in the operating band. A significant surface current density is observed at the feedline point meeting the patch, and a moderate current distribution over the surface of the active portion of the patch, at the resonant frequency. Figure-9 explains the surface current density for the two-slot antenna at 33 GHz. This figure shows the maximum amplitude of current density is 104.94 Amp/m.

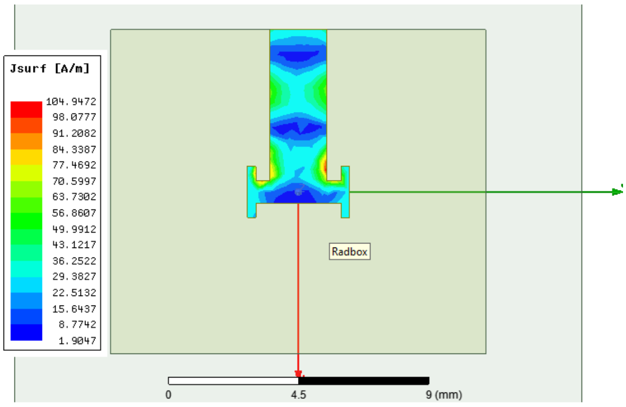

Figure-9. Surface current density.

Henceforth, the different parameters of the designed antenna were calculated by varying slot area only. For slot width 2.8 mm and area 1.4 mm^2, the results of parametric analysis are presented in Figures 10, 11, and 12.

Figure-10 portrays S11 for slot area 1.4 mm^2. The reflection coefficient value of 18.76 dB is obtained at 33.62 GHz.

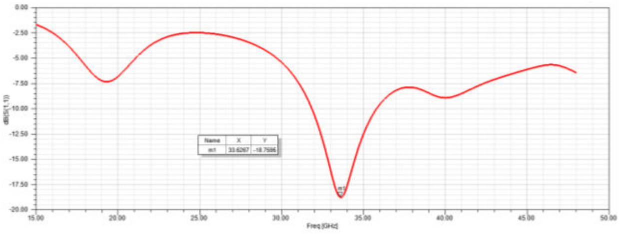

Figure-10. S11 of the proposed antenna of slot area 1.4 mm^2.

Figure-11 shows that a VSWR value slightly greater than 2, i.e. 2.01 is obtained at 33.62 GHz.

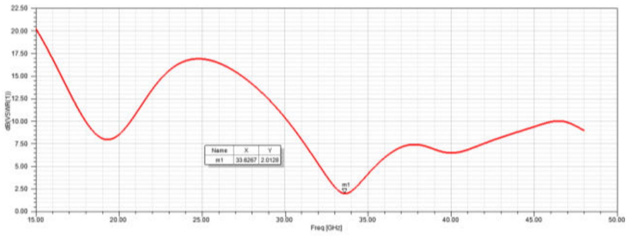

Figure-11. VSWR of the proposed antenna of the slot area 1.4 mm^2.

Figure-12 shows the 2D radiation pattern of the proposed antenna at 33.62 GHz. The radiation pattern is almost isotropic in the forward direction.

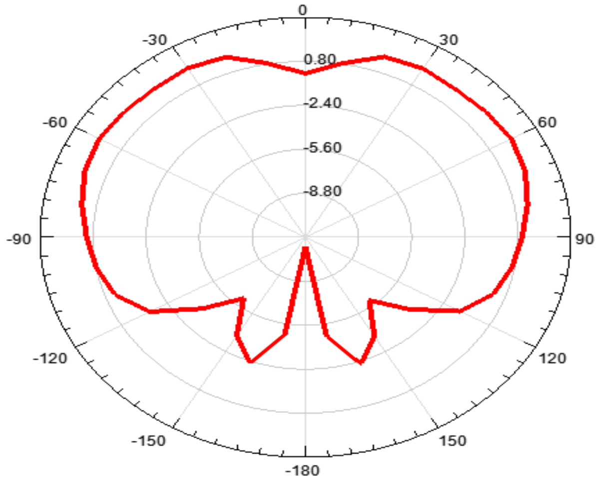

Figure-12. 2D radiation pattern of proposed antenna of slot area 1.4 mm^2

For slot width 2.6 mm that is slot area 1.3 mm^{2,} the parameters are shown in Figures 13, 14, and 15. Figure-13 is the reflection coefficient plot against the operational frequencies, which indicates a value of -18.38 dB at 33.55 GHz.

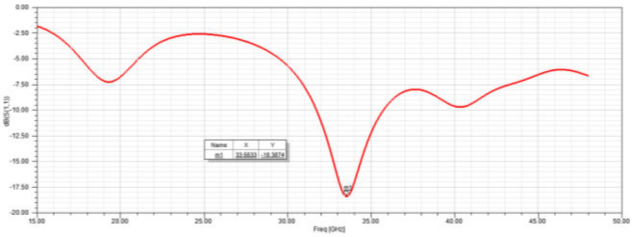

Figure-13. S11 of the proposed antenna of slot area 1.3 mm^2.

Figure-14 shows a VSWR value of 2.1018 for 33.65 GHz, which is 10% worse than the corresponding value due to a slot area of 1.4 mm^2.

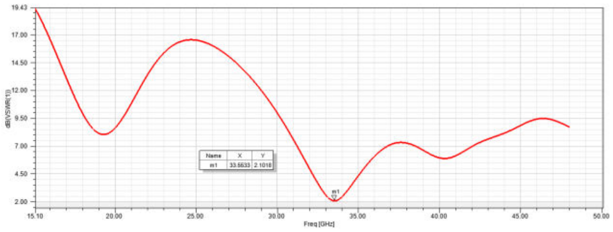

Figure-14. VSWR of the proposed antenna of the slot area 1.3 mm^2.

Figure-15 depicts a 2D radiation pattern, maintaining its isotropy.

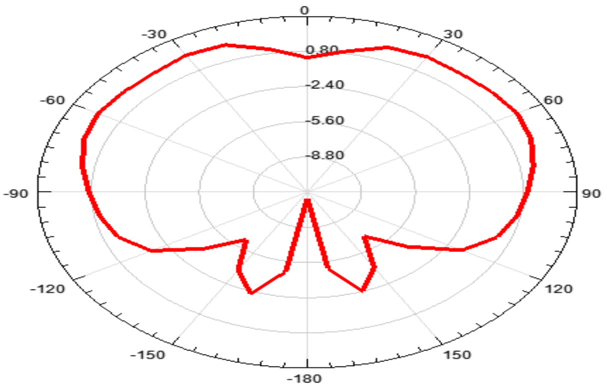

Figure-15. 2D radiation pattern of proposed antenna of slot area 1.3 mm^2.

For slot area 1.2 mm^2 that is slot width 2.4 mm the parametric analysis produces results as shown in Figures 16, 17, and 18. Figure-16 shows an S11 value of -17.72 dB at 33.48 GHz.

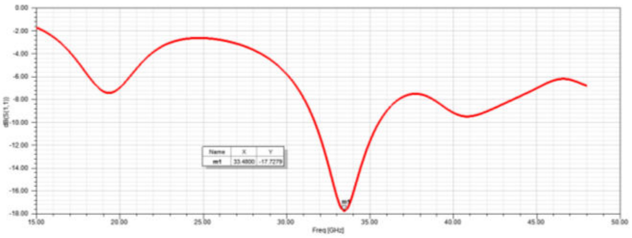

Figure-16. S11 of the proposed antenna of slot area 1.2mm^2.

Figure-17 shows a VSWR value of 2.2694 at 33.48 GHz. This time, a 25% deterioration in the value of VSWR is observed as compared to slot area 1.5 mm^2.

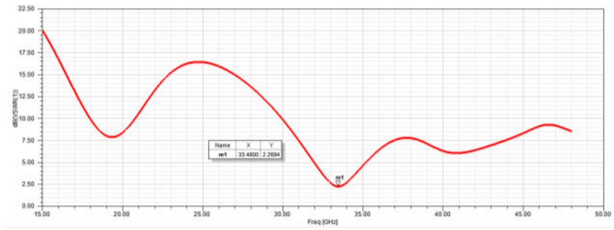

Figure-17. VSWR of the proposed antenna of slot area 1.2mm^2.

Figure-18 is about the 2D radiation pattern, which is again of an isotropic nature.

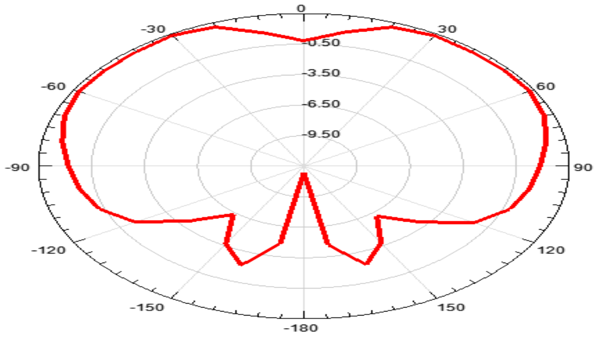

Figure-18. 2D radiation pattern of proposed antenna of slot area 1.2mm^2.

For slot area 1.1 mm^2 that is slot width 2.2 mm parameters obtained are depicted in figures 19, 20, and 21. Figure-19 shows the reflection coefficient variation concerning the operational frequencies. A reflection coefficient value of -16.42 dB at 33.70 GHz is obtained.

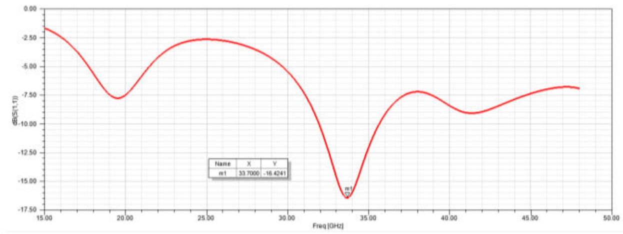

Figure-19. S11 of the proposed antenna of slot area 1.1 mm^2.

Figure-20 shows a VSWR value of 2.6422 at 33.70 GHz, which is an increment over the previous value.

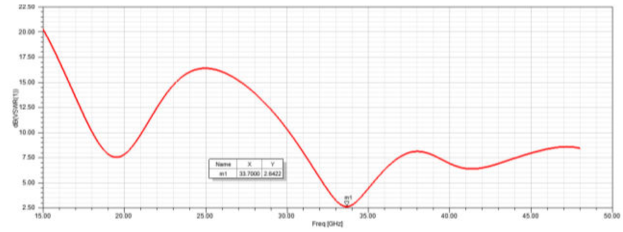

Figure-20. VSWR of the proposed antenna of slot area 1.1mm^2.

Figure-21 shows a 2D radiation pattern. 2D radiation pattern maintains the isotropic character but with reduced range.

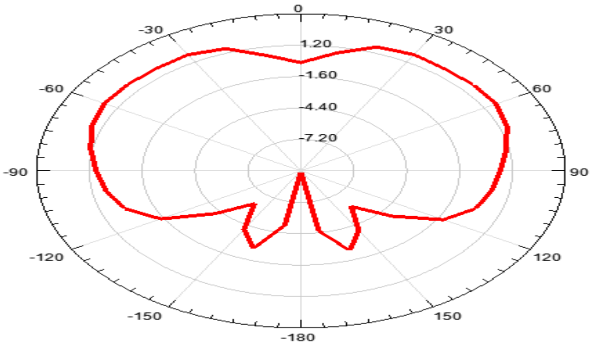

Figure-21. 2D radiation pattern of proposed antenna of slot area 1.1mm^2.

Varying slot widths from 3 mm to 2.2 mm the different antenna parameter values are determined at 33 GHz for a feed width of 2 mm. These different parameters for different slot widths are shown in Table-1.

Table-1. Result parameters for different slot widths at the target resonance frequency 33 GHz.

Slot width (mm)	Area (mm^2)	Gain (dB)		Return loss (dB)
3	1.5	Max 7.7	Min -16.1	-19.23
2.8	1.4	Max 7.8	Min -15	-18.75
2.6	1.3	Max 7.8	Min -15.7	-18.38
2.4	1.2	Max 7.9	Min -15.5	-17.72
2.2	1.1	Max 8.1	Min -15.7	-16.42

The main focus of this paper was to design a miniature microstrip patch antenna at 33 GHz and determine the impact of slot area variation on antenna parameters. The result analysis illustrated the shift of the proposed operating frequency with a variation of slot width or slot area.

Table-1 presents a decrease in S11 with increasing slot width. This table also explains the shifting of operating frequency when the slot width is changed. The slot area or slot width variation has a deep impact on the antenna result parameters. Further, gain also varies with slot width. Maximum gain is obtained for a slot width of 2.2 mm only. Gain increases with decreasing slot width or slot area. The proper dimension of the slot enhances the effectiveness of the antenna. At slot width 2.2 mm the achieved band width becomes maximum and it inversely changes with slot area.

5. CONCLUSIONS

This paper reported a microstrip patch antenna, designed and simulated using HFSS, on a volumetric dimension of 3.2 mm x 11.4 mm x 1.6 mm, designed at resonant frequency 33 GHz, employing a 1.6 mm thick Rogers RT Duroid 5880 substrate and fed with a transmission line having dimension 5.7 mm × 2 mm. Antenna parameters were obtained for different slot areas, keeping other design parameters fixed. Different slot areas were selected by changing slot width, keeping its length constant. A maximum gain of 7.7 dB with a VSWR value of 1.9 and a reflection coefficient of -19.23 dB was obtained for slot width 3 mm and area 1.5 mm^2. The directivity of the antenna turns out to be 5.7 dB, with a very good surface current density of 104.94 Amp/m.

The paper will enrich the designer, student, and researcher of the wireless communication area. The slot area is very important to achieve effective antenna parameters. Feed width is an important parameter to boost the antenna performance. VSWR, S11, and 3D gain showed inverse proportionality on slot area. This observation will play an important role in the design of slot on radiating patch of any shape. Gain, S11 changes directly proportional to feed width, and VSWR changes inversely with the feed length. The slot area plays a vital role in obtaining multiband features of the antenna. Future researchers and antenna designers may be guided by these observations for designing microstrip patch antennae to be used in mm wave wireless applications.

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