JSR Publications

Available Online

J. Sci. Res. **14** (2), 405-417 (2022)

JOURNAL OF SCIENTIFIC RESEARCH

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Effect of Symmetric Shaped Slot on Patch Antenna Design and Performance for 10 GHz 5G Applications

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Received 18 August 2021, accepted in final revised form 25 January 2022

Abstract

A microstrip patch antenna is considered the most suitable radiating and receiving element for millimeter-wave application due to its low cost, simple construction, low weight, and ease with which it is integrated into the circuits. In this paper, we have reported the effects of different symmetric shaped slots on millimeter-wave patch antenna design and its performance at 10 GHz frequency in the X band (8-12 GHZ). The rectangular, circular, and elliptical slots area is kept constant at 11.2 mm^2. The radius of circular and spherical slots is the same. High-frequency simulation software (HFSS) simulation results in parameters like S11 (reflection coefficient), Y-parameter (driving point admittance), Radiation Pattern, 3D Polar plot and illustrate that the results are in good agreement with the desired value. A rectangular slot is found to achieve the target resonance frequency with a low voltage standing wave ratio (VSWR) towards a 'good match.' Circular, spherical, and elliptical-shaped slots have high VSWR values, indicating a larger degree of mismatch. Surprisingly, results are obtained for the spherical-shaped slot, implying that the antenna will work at the target resonance frequency and has a Dual-Resonance. The proposed antenna design is suitable for 5G device applications in the X band.

Keywords: Slot; S11; Y-parameter; Radiation pattern; Resonant frequency; Dual resonance; HFSS.

doi: http://dx.doi.org/10.3329/jsr.v14i2.55209 J. Sci. Res. **14** (2), 405-417 (2022)

1. Introduction

The fifth-generation network requires a higher operational frequency range than fourth-generation mobile telecommunication. Compatible wireless devices and applications will ask for high-speed data transmission and reception in novel applications like the internet of things (IoT), virtual and augmented realities, etc. [1-6] with high bandwidth users in mobile telecommunication [7-9]. 5G wireless communication systems will exploit the use of millimeter-wave spectrum and will call for large bandwidth and high gain compared to the 4G application sets [10,11].

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Microstrip patch antennas work strongly in communication systems accommodating the spectrum limitation and high energy requirement problem. Patch antennas possess the appropriate criteria of wireless communication viz low profile, low cost, easy configuration, and small volume. Slots are designed on a patch to contain the challenges of narrow frequency bandwidth and low efficiency. In today's era of 5G the utilization of patch antenna is most desirable for wireless communication due to its bouquet of properties [12-14].

Every microstrip patch antenna consists of ground, substrate, and patch. The substrate remains between ground and patch. Patch thickness is recommended to be thin and less than the free-space wavelength. During design, the dielectric constant of the substrate is recommended to be in the range of 2.2 and 12.0. Out of the various feeding methods to the patch, the transmission line used in this work is easy to handle and design. A transmission line is of low impedance and splits up the microstrip antenna into two radiating slots. The role of the fringing effect cannot be ruled out in the design of a patch antenna.

In this paper, we have reported the effects of different symmetric shaped slots on millimeter-wave patch antenna design and its performance at 10 GHz frequency in the X band. The rectangular, circular, and elliptical slots area is kept constant at 11.2 mm^2. The radius of circular and spherical slots is the same.

High-frequency simulation software (HFSS) simulation results in parameters like Reflection coefficient (S11), Driving point admittance (Y-parameter), Radiation Pattern, 3D Polar plot and illustrate that the results are in good agreement with the desired value.

A rectangular slot is found to achieve the target resonance frequency with a low voltage standing wave ratio (VSWR) towards a 'good match.' Circular, spherical, and elliptical-shaped slots have a high voltage standing wave ratio (VSWR) value, indicating a larger degree of mismatch. Surprisingly, results are obtained for the spherical-shaped slot, implying that the antenna will work at the target resonance frequency and has a Dual-Resonance. The proposed antenna design is suitable for 5G device applications in the X band

2. Methodology

Microstrip patch antenna consists of conducting and insulating materials divided into three parts. The top and bottom layers are of conducting material (patch and ground, respectively), and a dielectric material (substrate) is in between the two layers. The selection of conducting and insulating material plays an important role in designing an antenna for a specific purpose. Keeping in mind the desired properties of the antenna to work efficiently at 10 GHz frequency cupper is taken as the conducting material and Flame Retardant 4(FR4) dielectric as substrate material. Anys HFSS has been used for the design and simulation and transmission line feed technique for external excitation of the antenna. The antenna patch is of dimension 6.42 × 9.12 mm with a substrate thickness of 1.6 mm. The ground and substrate dimensions are 16.02 × 18.72 mm. A cuboidal radiation box of 28 × 28 × 14 mm has been used. The target resonance frequency of the proposed antenna is set at 10GHz. To the best of our knowledge, no 5G compatible antenna has been designed to work at 10 GHz. The design of the antenna is based on standard design equations [15,16].

Patch width Wp is determined by the equation

$$Wp = \frac{v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

Where f_r is resonant frequency and ε_r is the dielectric constant of the substrate material. Effective dielectric constant addressing the effect of fringing effect can be evaluated from the equation as below-

$$\varepsilon_r^{eff} = \frac{1}{2}(\varepsilon_r+1) + \frac{1}{2}(\varepsilon_r-1)(1+12\ \ \frac{h}{w})^{-1/2} \tag{2}$$

Patch length follows equation (3), where ΔL presents an extension in length arising out of the fringing effect.

$$Lp = \frac{c}{2\sqrt{\varepsilon_r^{eff}}}\left(\frac{1}{f_r}\right)\text{-}2(\Delta L) \tag{3}$$

The equation of extension in length is written at the equation

$$\frac{\Delta L}{h} = \text{o}.412\frac{\left(\varepsilon_r^{eff}+0.3\right)\left(\frac{Wp}{h}+0.264\right)}{\left(\frac{\mathrm{Wp}}{\mathrm{h}}+0.8\right)(\varepsilon_r^{eff}-0.258)} \tag{4}$$

Height of substrate is subject to equation (5):

$$h \le \frac{0.3C}{2*3.14 f_r\sqrt{\varepsilon_r}} \tag{5}$$

The dimensions of various components of patch antenna design are listed in the following Table.

Table 1. Primary data used for the antenna design.

Name	Length along X-axis	Length along Y-axis	Length along Z-axis	Axis
Ground	16.02 mm	18.72 mm		Z
Substrate	16.02 mm	18.72 mm	1.6 mm	
Patch	6.42 mm	9.12 mm		Z
Feed	8.01 mm	3 mm		Z
Port		3	-1.61 mm	X
Radiation box	28 mm	28 mm	14 mm	

The proposed antenna design is based on the values as in Table 1. The antenna patch is of dimension 6.42 × 9.12 mm with Flame Retardant 4(FR4) dielectric substrate thickness of 1.6 mm. The ground and substrate dimensions are 16.02 × 18.72 mm. Design various symmetric-shaped slots like rectangular, circular, elliptical, and spherical are crucial in obtaining the desired resonant frequency. First, an 11.2 mm^2 rectangular slot of 2.88 mm along the x-axis and a width of 4 mm along the y-axis is taken. After completion of design and validation, the simulation operation was performed. This leads to various antenna parameters. Then the rectangular slot is replaced by a circular slot of radius 1.88

mm, with a circular slot area fixed at the previous value of 11.2 mm^2. This patch antenna with a circular slot was simulated, and the result parameters were determined.

Similarly, the circular slot was replaced by the elliptical slot of major radius 2.37 mm and again at the same area of 11.2 mm^2. The design simulation was performed, and result parameters were obtained for the patch antenna. After this, a spherical slot is used to replace an elliptical slot with a similar length as the radius of the circular slot. That is spherical slot also has a radius of 1.88 mm, so its area is 44.39 mm^2. If the area of the spherical slot is 11.2 mm^2, its radius becomes smaller, so the radius of the spherical slot is equal to the circular slot radius. Again, the simulation process and result parameters collection are repeated for spherical slot patch antenna design. After every slot design, the slot is subtracted from the patch, and the feed is united with the patch through HFSS [17,18].

3. Result and Discussion

3.1. *Rectangular slot*

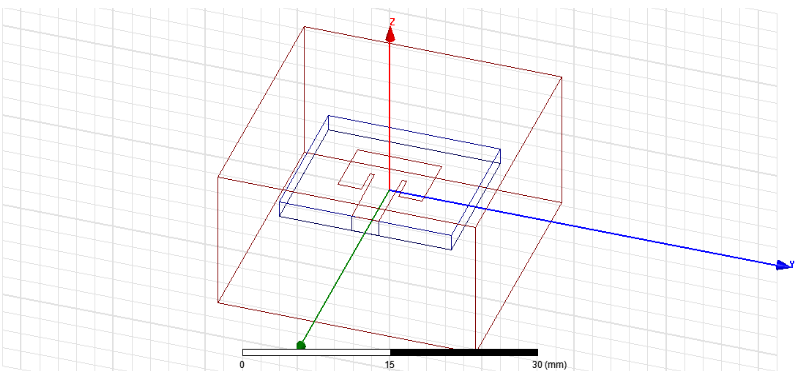

Fig. 1. Rectangular slot design patch antenna. The antenna patch is of dimension 6.42 × 9.12 mm with a substrate thickness of 1.6 mm. The ground and substrate dimensions are 16.02 × 18.72 mm.

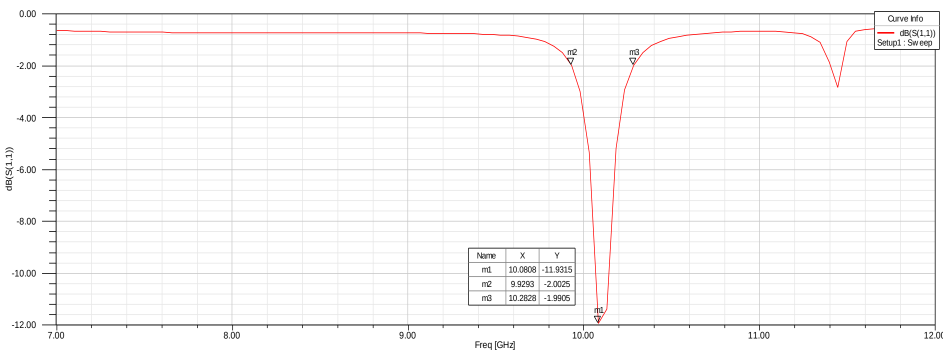

Fig. 2. S11 parameter variation with operational frequency. Resonance is obtained at frequency 10.08 GHz.

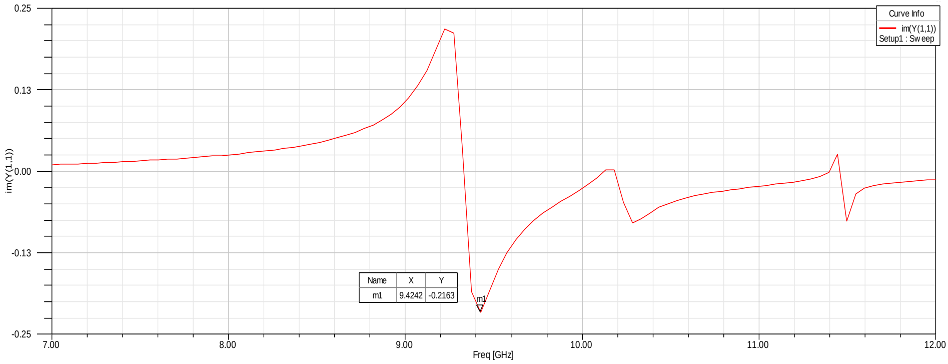

Fig. 3. Imaginary part of Y-parameter against the operational frequency for the rectangular slot.

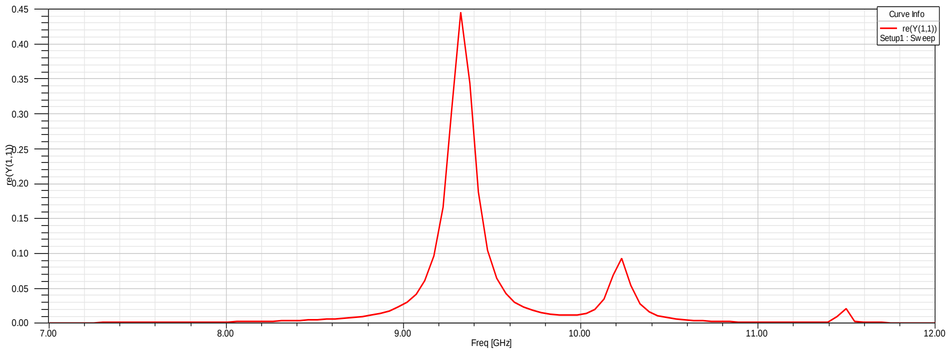

Fig. 4. Real part of Y-parameter against the operational frequency for the rectangular slot.

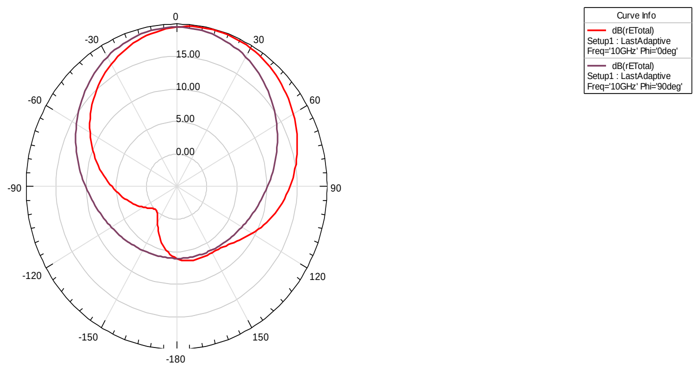

Fig. 5. The radiation pattern of the rectangular slot at the resonant frequency.

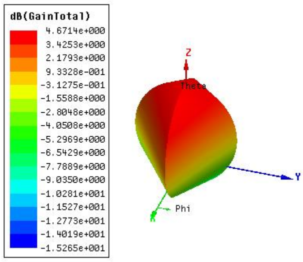

Fig. 6. Gain plot for the rectangular slot. A gain of 4.67 dB is obtained.

Figs. 2-6 depict the variation of S11 Parameter with operational frequency, imaginary and real parts of Y-parameter, radiation pattern, and gain for the rectangular slot patch. The reflection coefficient (S11 parameter) for mobile communication in the proposed frequency range is -10 dB. We have obtained a value of -12 dB with an operational bandwidth of 0.5GHz, which is an improvement. Driving point admittance, i.e., Y11 Parameter, is also in the desired range of efficient operation of the antenna. A gain of 4.67 dB is obtained for the rectangular slot, which is a remarkable result. Further, the radiation pattern is also fine in the forward direction.

3.2. *Circular slot*

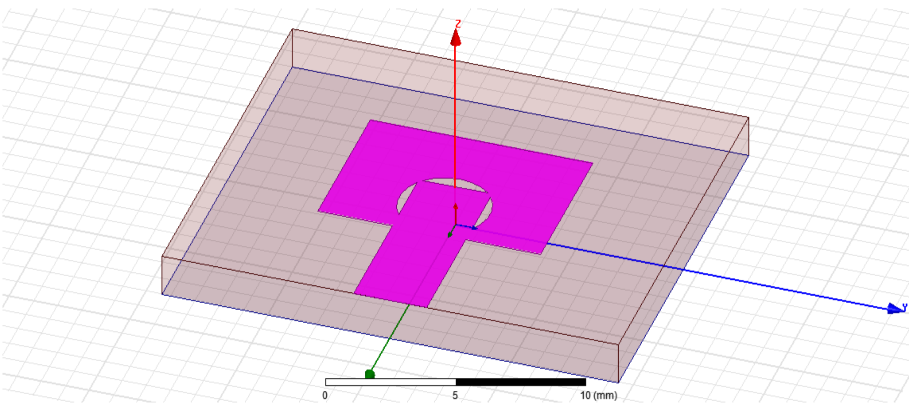

Fig. 7. HFSS circular slot design of radius 1.88 mm and area fixed at the value of 11.2 mm^2.

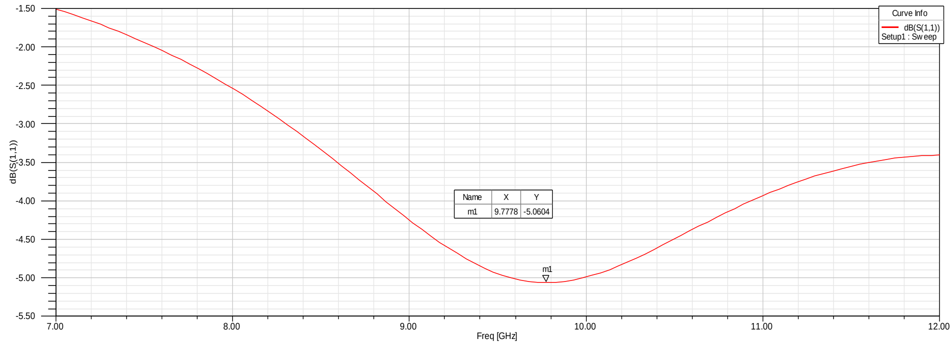

Fig. 8. S11 parameter variation within the range of operational frequency. The circular slot antenna resonates at 9.77 GHz with an S11 value of -5.06 dB.

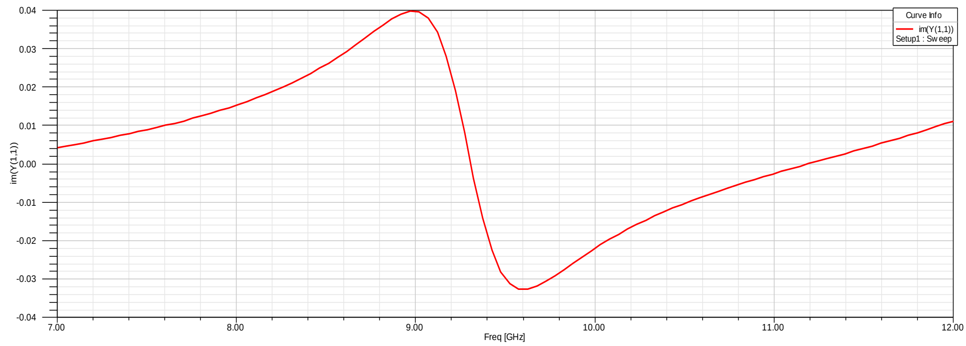

Fig. 9. Imaginary part of Y-parameter for the circular slot. The maximum and minimum values of the Y parameter are obtained at 9.02 and 9.62 GHz, respectively.

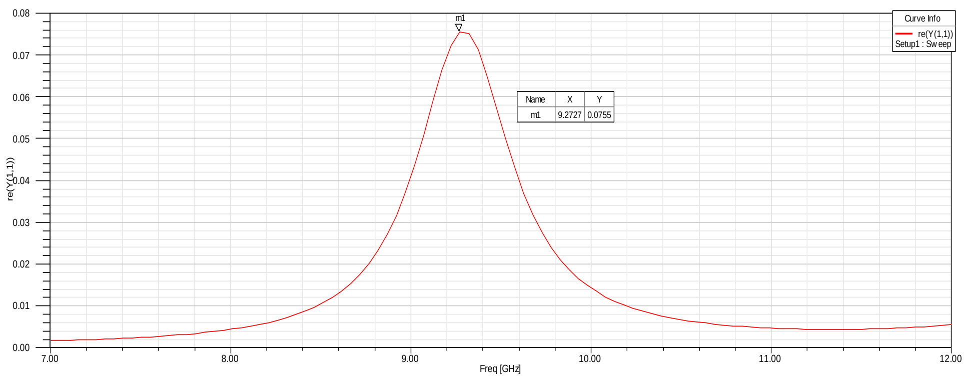

Fig. 10. Real part of Y-parameter for the circular slot, maximum is obtained at 9.27 GHz.

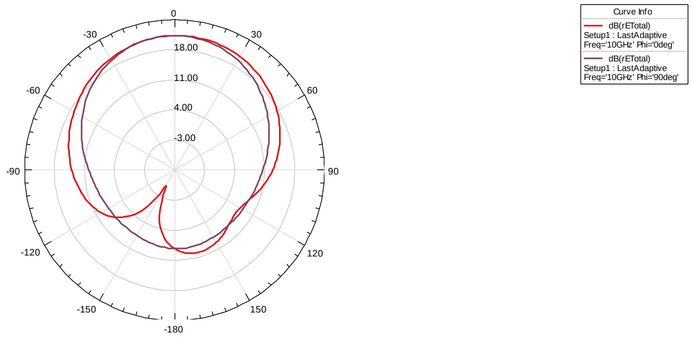

Fig. 11. Radiation pattern for circular slot patch antenna.

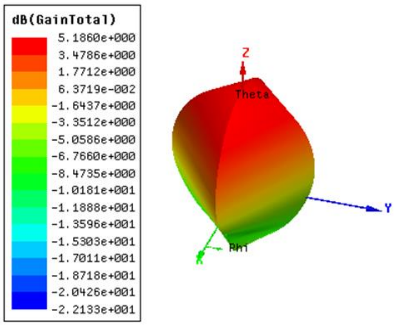

Fig. 12. The gain plot for the circular slot. The gain observed for the circular slot is 5.18 dBi.

Figs. 8-12 depict the variation of S11 Parameter with operational frequency, imaginary and real parts of Y-parameter, radiation pattern, and gain for the circular slot patch. The circular slot antenna resonates at 9.77 GHz with an S11 value of -5.06 dB. The maximum and minimum values of the Y parameter are obtained at 9.02 and 9.62 GHz, respectively. The real part of the Y-parameter for the circular slot has a maximum of 9.27 GHz. The gain obtained for the circular slot is 5.18 dBi.

3.3. *Elliptical slot*

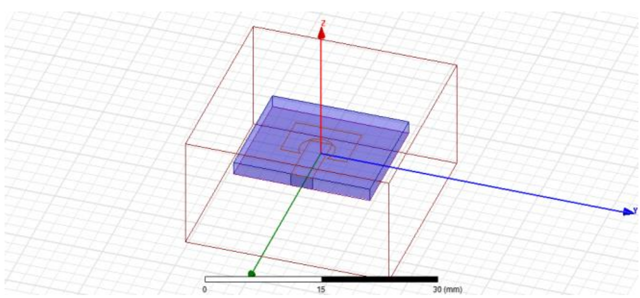

Fig. 13. HFSS design of elliptical slot of with major radius 2.37 mm and area 11.2 mm^2.

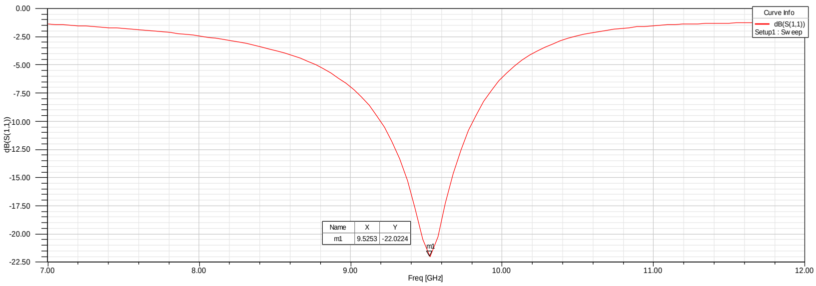

Fig. 14. S11 parameter variation with frequency for the elliptical slot patch. The S11 parameter value is obtained to be -22.02 dB at the resonance frequency of 9.52 GHz.

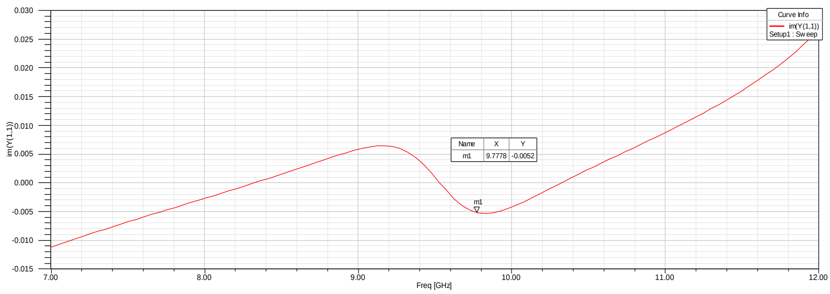

Fig. 15. Imaginary part of Y-parameter for the elliptical slot.

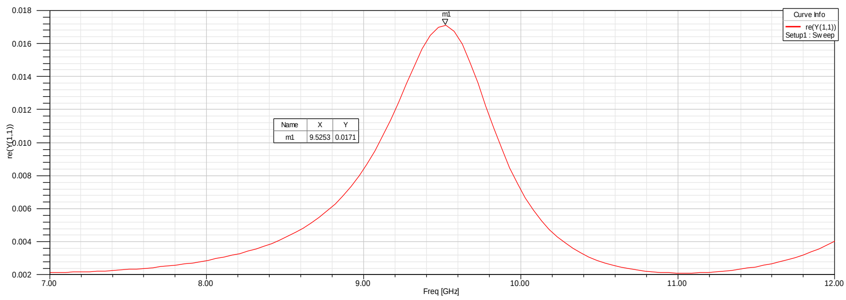

Fig. 16. Real part of Y-parameter for the elliptical slot. A maximum is obtained around 9.50 GHz.

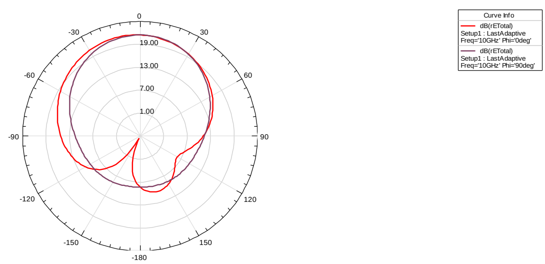

Fig. 17. The radiation pattern for elliptical slot patch.

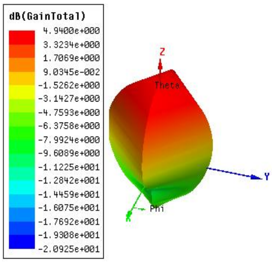

Fig. 18. Gain plot for elliptical slot design. A gain value of 4.94 dBi is obtained at the resonant frequency.

Figs. 14-18 depict the variation of S11 Parameter with operational frequency, imaginary and real parts of Y-parameter, radiation pattern, and gain for the elliptical slot patch. A very good value of the S11 Parameter is obtained, which is -22.02 dB, at the resonance frequency 9.52 GHz. Bandwidth at the resonant frequency is 0.6 GHz. A maximum admittance is obtained at the resonance frequency of 9.50 GHz. An antenna gain obtained is at 4.94 dBi.

3.4. *Spherical slot*

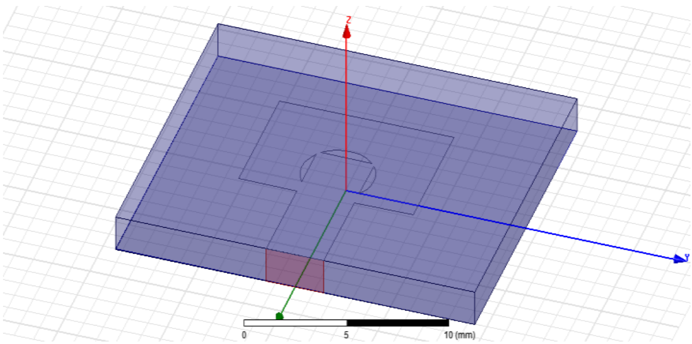

Fig.19. HFSS spherical slot design. The spherical slot has a radius of 1.88 mm.

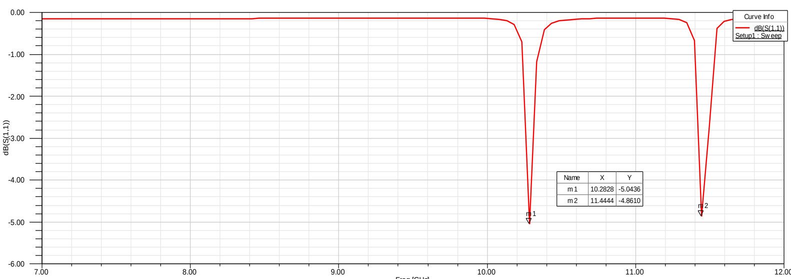

Fig. 20. S11 parameter variation with operational frequency for the spherical slot. Unlike rectangular, elliptical and circular slot patches, a spherical slot antenna resonates at dual frequencies 10.28 GHz and 11.44 GHz.

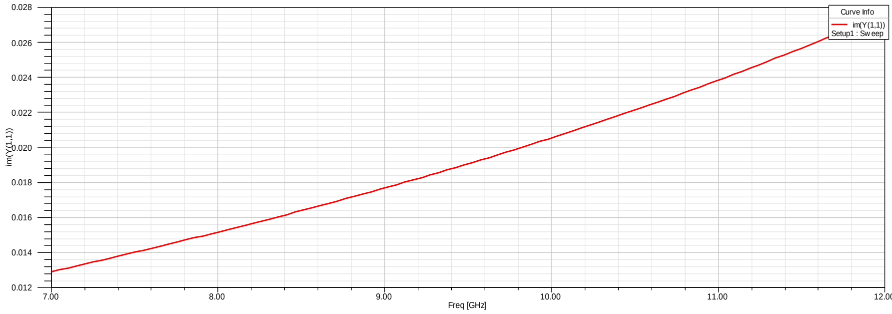

Fig. 21. Imaginary part of Y-parameter for the spherical slot.

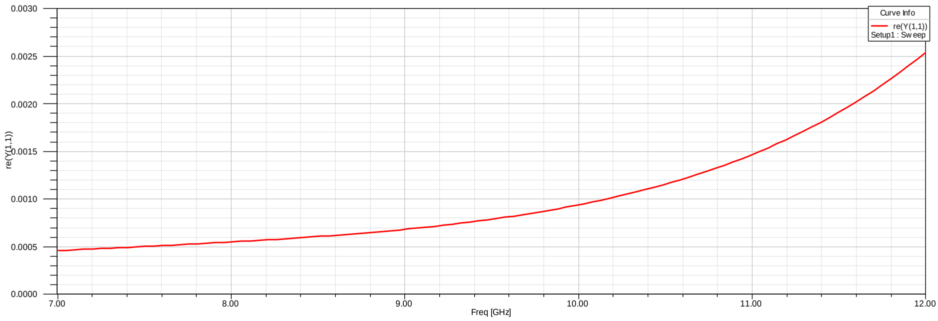

Fig. 22. Real part of Y-parameter for the spherical slot.

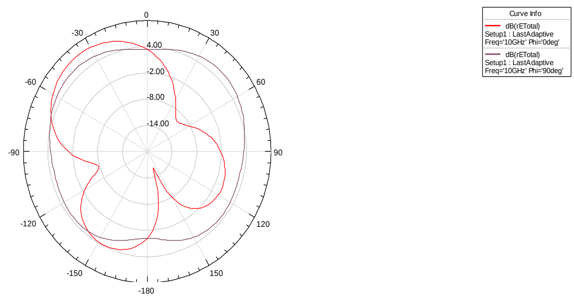

Fig. 23. The radiation pattern for the spherical slot antenna.

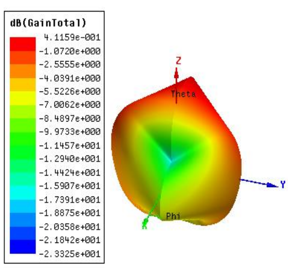

Fig. 24. Gain plot for spherical slot patch antenna. A gain of 4.11 dBi is observed at the resonant frequency.

Figs. 20-24 depict the variation of S11 Parameter with operational frequency, imaginary and real parts of Y-parameter, radiation pattern, and gain for the spherical slot patch.

Unlike rectangular, elliptical, and circular slot patches, the spherical slot antenna resonates at dual frequencies 10.28 and 11.44 GHz with matching S11 parameter values of -5 and -4.9 dB, respectively. Admittance is well appreciable about the resonant frequency. The radiation pattern is also good in the forward direction.

Comparison among result parameters obtained from four different shaped slots [19-22] is expressed in Table 2.

Table 2. Comparative value of the resonant frequency, VSWR, S11, and gain for different slot patch designs.

Slot shape	Resonance Frequency (GHz)	S11(dB) (Return loss or reflection coefficient)	VSWR	Gain (dB)
Rectangular	10.08	-11.93	4.49	4.67
Circular	9.77	-5.06	10.95	5.18
Elliptical	9.52	-22.02	9.52	9.94
Spherical	10.28,11.44	-5.04, -4.86	10.98, 11.2	4.11

4. Conclusion

With different slots, antenna designed for the target frequency of 10 GHz yields a mix of results. Gain is high for the elliptical-shaped slot. The rectangular slot provides the approximate target resonance frequency of 10 GHz and is the best fit for the imaginary and real parts of the Y-parameter. Circular, spherical, and elliptical-shaped slots have a high VSWR value, which indicates a larger degree of mismatch. But for rectangular shapes, VSWR is low, and we say that there is a ‘Good Match.’ Surprisingly different results are obtained for the spherical-shaped slot. In this case, the antenna will work at the target resonance frequency and exhibits dual resonance frequency. The real and imaginary part of the Y-parameter could not achieve the maximum within the operational frequency range.

On the other hand, if the result parameters are collected without a slot on the same design, then it is observed that S11, Y-parameter, and VSWR do not show similarity with their real graph. Also, gain, in that case, turns out to be -1.25 dB. The simulation results lead us to conclude that the shape-changing of slots in symmetrical patterns plays a decisive role in determining the best results for the antenna. The resonant frequency shifts with increasing length along X-axis, keeping other parameters fixed. For a rectangular slot length of 2.2 mm along the X-axis, the resonance frequency becomes 10.48 GHz. Similarly, for the length of 2.6 mm along the X axis, the frequency reaches 10.13 GHz for the rectangular slot. These observations aptly and strongly indicate that slot shapes and slot areas have a major stake in the resonance frequency of the antenna.

While designing an antenna, the slot takes the major decisive role to achieve effective resonance frequency. Slot shape and slot area both have a crucial role in achieving sustainable result parameters from simulation. If the target resonance frequency is 10 GHz for a patch antenna, then rectangular slot is the best choice. This study will help a designer to design compact and reconfigurable antennas. The impact of substrate thickness on the fringing effect could be explored in the next assignment.

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