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Circular Slotted Half Hexagonal Patch Multiband Antenna Design for 5G Applications

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ABSTRACT

In this article, a simple circular slotted half hexagonal patch antenna is designed for multiband applications. This antenna has nine resonant frequencies viz. 1.81GHz, 2.36 GHz, 3.45 GHz, 3.65 GHz, 5.14 GHz, 5.49 GHz, 5.99 GHz, 7.15 GHz and 7.71 GHz with acceptable peak realized gain of 3.42 dBi, 2.69 dBi, 3.51 dBi, 1.15 dBi, 3.05 dBi, 4.66dBi, 6.20 dBi, 5.78 dBi and 7.68 dBi respectively. Less than -10 dB reflection coefficients (S_{11}) are achieved in all the frequency bands. Therefore, this antenna can be used for 5G sub-6 GHz (lower band) applications. Along with this, this antenna can also be operated for aviation, satellite communications and wireless communications. It is observed that on introduction of a circular slot on the patch, the resonant frequencies may be controlled by varying the slot radius. A prototype of this antenna is fabricated on FR-4 substrate with good agreement between simulated and measured results.

Keywords: 5G, circular slot, hexagonal patch, multiband operation, wireless communication

INTRODUCTION

Rapid development of wireless communication systems in the last decade has increased the demand for microstrip antennas with compact size and multiple operating frequencies. Many multi-band microstrip antennas and wideband antennas utilizing hexagonal patch shapes have been reported in recent years (Kewei *et al.*, 2013; Rathod *et al.*, 2015; Ray *et al.*, 2009). In literature (Rathod *et al.*, 2015), authors have reported a dual band slotted Hexagonal Microstrip Antenna (HMSA) operating at two different frequencies of 1.3 GHz and 1.4 GHz with bandwidth greater than 15 MHz in each case. Ray *et al*. (2009) have designed a perturbed hexagonal patch antenna for circular polarization where a new configuration of circularly polarized HMSA with single feed have been investigated for GSM frequency of 915MHz.

In recent trends, scientists are focusing on designing devices for 5G applications. Therefore, antennas should be designed accordingly to support 5G facilities. Different 5G sub-6 GHz lower band antennas have been proposed in the literature (Serghiou *et al.*, 2020; Li *et al.*, 2020; Yuan *et al.*, 2021; Chen *et al.*, 2020). The above-mentioned designs are mainly designed for dual band and single band operation; whereas now-a-days it is desired that a single device can support many applications like the Wireless Area Network (WLAN) and Worldwide Interoperability for Microwave Access (WiMAX) etc. This necessitates the use of multiband antennas exhibiting more than two bands of operation with a fair amount of radiation (Das *et al.*, 2012; Ibrahim *et al.*, 2015). Moreover, multiple resonances help in increasing the number of users for the same or different services (Teotia *et al.*, 2015).

Considering the necessity of obtaining as many operating frequencies as possible within a frequency range, a half hexagonal circular slot loaded patch antenna is designed in this manuscript which is resonating at nine different frequencies within the frequency range of 1 GHz to 8 GHz. The resonant frequencies are obtained as 1.81GHz, 2.36 GHz, 3.45 GHz, 3.65 GHz, 5.14 GHz, 5.49 GHz, 5.99 GHz, 7.15 GHz, 7.71 GHz with peak realized gain of 3.42

dBi, 2.69 dBi, 3.51 dBi, 1.15 dBi, 3.05 dBi, 4.66 dBi, 6.20 dBi, 5.78 dBi, 9.68 dBi respectively. Circular slot is incorporated therein for frequency control and the probe position is optimized to achieve good impedance matching and acceptable radiation patterns, mostly broadside. The proposed designs are simulated using FEM based software using material FR-4 with dielectric constant 4.4 and loss tangent of 0.03 with the thickness of 1.6 mm (60 mils).

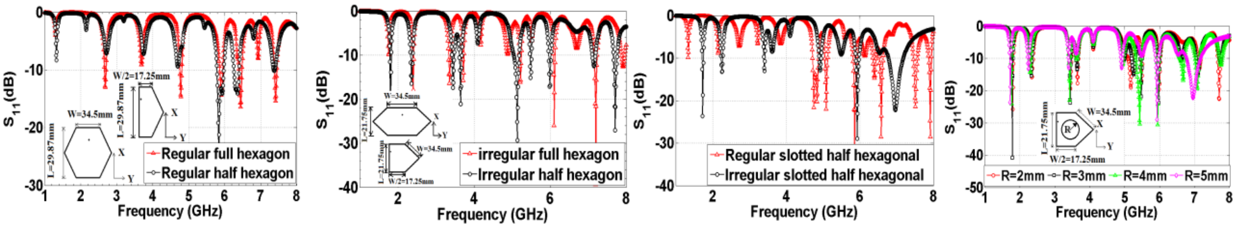


Figure 1. S11 vs frequency plots for (a) regular full and half, (b) irregular full and half, (c) circular slotted regular and irregular half hexagonal patch antenna (d) for variation of radius of the circular slot

DESIGN AND ANALYSIS OF CIRCULAR SLOT LOADED HEXAGONAL PATCH ANTENNA

In this section, circular slot loaded irregular shaped half hexagonal patch antenna is designed. At first, simple regular hexagonal patch has been designed and subsequently halved. The same procedure has been followed for irregular shaped hexagonal patch also. Finally, a circular slot is loaded on the half hexagonal patch. The radius of the slot is varied to observe its effect on antenna performances.

Simple Regular Hexagonal Patch

A regular hexagon of side arm W = 35.4 mm and length L = 29.87mm is considered as the basic patch shape. The patch is fed at point of (-8.0, 0.0) with coaxial probe having inner radius of 0.63 mm and outer radius of 2.11 mm. The feed position is optimized through parametric studies. The reflection coefficient (S_{11}) of this structure is less than -10 dB for the frequency values of 2.69GHz, 4.7GHz, 5.91GHz, 6.45GHz, and 7.42GHz. Simulated S_{11} for this configuration is shown in Figure 1(a), which indicates that there are multiple resonant modes for the antenna but good impedance matching is not obtained for many of them. An empirical formula for resonant frequency of hexagonal patch antenna given by Ray *et al*. (2007) is used in this work as the initial step for the design procedure. The resonant frequency for this configuration is given as

$$f = \frac{c}{2(S_{eff} + 2\Delta l)\sqrt{\varepsilon_{eff}}} \tag{1}$$

where the effective resonant length S_{eff}, the effective dielectric constant ε_{eff} and the line extension factor Δl can be calculated using the expressions

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

$$S_{eff} = 1.60352 * W + 0.00175 \tag{3}$$

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

with the symbols having their usual meanings.

Regular Half Hexagonal Patch Antenna

Distinct symmetry planes of a regular hexagonal shape are utilized for antenna miniaturization. A regular half hexagon is obtained from the regular full hexagon shape by equally dividing it into two halves as shown in Figure 1. Probe position is kept same as in the case of the regular full hexagonal antenna discussed earlier. A comparison of simulated S_{11} between the full and half hexagonal patches is shown in Figure 1(a). It can be observed that the resonant frequencies are not substantially altered in the process while the patch area is effectively reduced by 50%.

Irregular Full Hexagonal Patch Antenna

An irregular hexagon is designed here with length (L) of 21.75 mm keeping arm length (W) same as that of the regular one i.e. W = 35.4mm. Feed position is kept also same as regular hexagon to build comparison between regular and irregular hexagonal patch performances efficiently. This information revealed by simulated S_{11} vs frequency plot (Figure 1(b)) is indicating better impedance matching at resonant frequencies compared to the regular patch. Along with that, this antenna can also be operated in 5G applications as it is resonated at 3.65 GHz with is laid within lower band sub-6 GHz for 5G applications. Therefore, irregular shaped hexagonal patch is chosen for this work.

Irregular Half Hexagonal Patch Antenna

An irregular half hexagon is obtained from the irregular full hexagon by equally dividing it into two halves exploiting its symmetry as shown in Figure 1 (b). A comparison of S_{11} between the irregular full and half hexagons indicates (refer to Figure 1(b)) that the later yields better impedance matching as well as increased bandwidth although the resonant frequencies remain unchanged. The irregular half hexagonal antenna thus exhibits the best impedance characteristics among all antennas investigated.

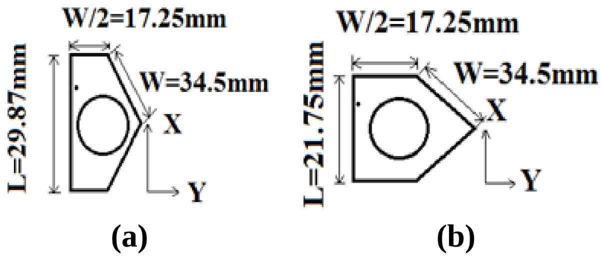


Figure 2. Circular slot loaded on (a) regular and (b) irregular half hexagonal patch

Effect of Circular Slot on Half Hexagonal Patch

In this sub-section, the regular and irregular half hexagonal patch antennas perturbed with a circular slot and corresponding changes in resonant frequencies are reported to ensure additional control over the operating frequencies.

Slot on regular half hexagonal patch

A slotted regular half hexagonal antenna is conceived by introducing a circular slot in the middle of the patch (Figure 2(a)) to tune the resonant frequencies. Probe position is kept same as before. Resonant modes of the unperturbed antenna are shifted towards lower frequencies as the slot radius is increased. It is however observed that S_{11} below -10 dB is obtained for only three resonant modes for the slotted regular half hexagonal patch as shown in Figure 4. Dimensions of the hexagon are kept same as in the case of the regular half hexagon discussed earlier.

Slot on irregular half hexagonal patch

A circular slot is incorporated on the surface of the designed irregular half hexagonal patch as shown in Figure 2(b) to tune its resonant frequencies. Probe position and patch dimensions are kept same as in the case of the irregular half hexagonal patch discussed earlier. It is observed that S_{11} below -10 dB is obtained for six resonant modes for the slotted irregular half hexagonal patch as shown in Figure 1(c).

Table 1. Comparison of resonant frequency and fractional bandwidth for regular and irregular hexagonal patch antenna

Patch shape	Results of antenna structures	
	Resonant Frequency (GHz)	Fractional Bandwidth (%)
Regular full	2.69	1.85
	4.79	1.02
	5.91	1.35
	6.45	1.38
	7.42	1.07
Irregular full	2.4	1.66
	3.36	1.48
	3.72	0.8
	5.23	0.95
	6.11	0.81
Regular half	5.84	3.25
	6.36	2.20
Irregular half	1.81	2.20
	2.36	2.54
	3.45	1.73
	3.65	1.64
	5.14	2.52
	5.49	0.72
	5.99	1.16
	7.15	1.11
	7.71	1.42

Slot on irregular half hexagonal patch

Simulated S_{11} for different slot radius values are shown in Figure 1(d). Observations presented in the previous subsections are summarized in Tables 1 and 2. Table 1 shows the comparison of resonant frequencies and fractional bandwidths for full and half hexagonal patches with regular and irregular shapes. Clearly, the irregular half hexagon yields best performance in terms of impedance matching and bandwidth. Table 2 on the other hand indicates the comparison of regular and irregular hexagonal patches for different slot radii. It is observed that the slotted irregular hexagon retains optimal performance in terms of matching and bandwidth, whereas the slot radius may be varied to control the resonant frequencies as per requirement. Therefore, the circular slot loaded irregular hexagonal patch structure is finalized for this work. Finally, Table 2 summarizes the realized antenna gains for each resonant frequency of the final antenna. Increasing the slot radius shifts the resonant modes to lower frequencies probably due to accumulation of more surface charge. The slot radius for the final structure is chosen as 2 mm to obtain better optimal.

FABRICATION AND MEASUREMENT

The optimally designed circular slot incorporated irregular half hexagonal patch, whose simulated behavior has been presented earlier, is fabricated on FR-4 substrate with relative permittivity of 4.4 and loss tangent of 0.003 with the thickness of 1.6 mm. The photograph of the fabricated half hexagonal patch is shown in Figure 3(a). The simulated and measured return loss characteristics of the antenna up to frequency 8 GHz is shown in Figure 3(b).

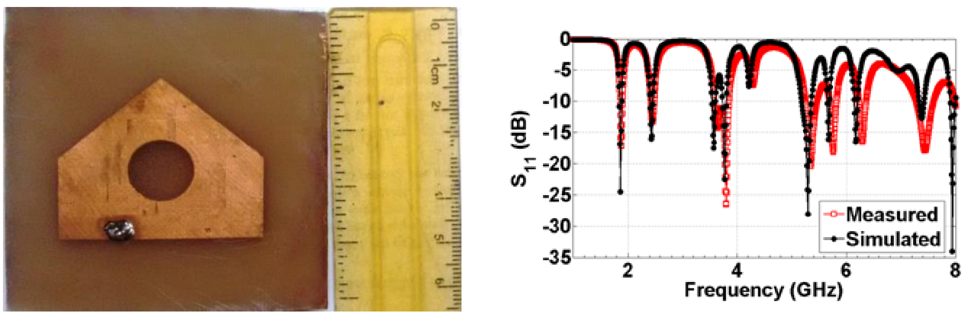
Table 2. Resonant frequency and fractional bandwidth of circular slotted regular and irregular hexagonal patch antenna for different radii of slot

Patch shape	Radius (mm)	Results of antenna	
		Resonant Frequency (GHz)	Fractional Bandwidth (%)
Regular	2 mm	5.9	1.35
		6.14	1.14
		6.39	1.4
		6.57	1.36
		7.55	2.11
	3 mm	5.9	1.35
		6.15	1.3
		6.38	1.56
		7.54	1.85
	4 mm	4.7	2.55
		5.03	0.79
		5.87	1.53
		6.36	1.41
		7.49	1.46
	5 mm	4.75	3.36
		5.09	1.57
		5.86	1.53
		6.58	1.36
Irregular	2 mm	1.8	2.22
		2.36	2.11
		3.45	2.02
		3.65	1.64
		5.18	2.31
		5.49	1.82
		5.99	1.16
		7.13	1.26
		7.71	1.29
	3 mm	1.79	2.23
		2.34	2.13
		3.45	2.02
		3.64	1.64

		5.25	1.90
		5.48	1.09
		5.98	8.69
		7.10	1.54
	4 mm	1.77	2.25
		2.30	2.17
		3.43	1.45
		5.44	2.94
		5.95	1.34
		7.08	1.84
	5 mm	1.73	2.31
		2.25	2.22
		3.41	0.87
		4.92	2.23
		5.93	1.52
		6.97	5.59

Table 3. Results of the final antenna structure

Resonant Frequency (GHz)	Fractional Bandwidth (%)	Realized Gain (dBi)
1.81	2.22	3.42
2.36	2.11	2.69
3.45	2.02	3.51
3.65	1.64	1.15
5.18	2.31	3.05
5.49	1.82	4.66
5.99	1.16	6.20
7.13	1.26	5.78
7.71	1.29	7.68



(a) **(b)**

Figure 3. (a) Photograph and (b) simulated and measured S_{11} vs frequency plot of the fabricated antenna

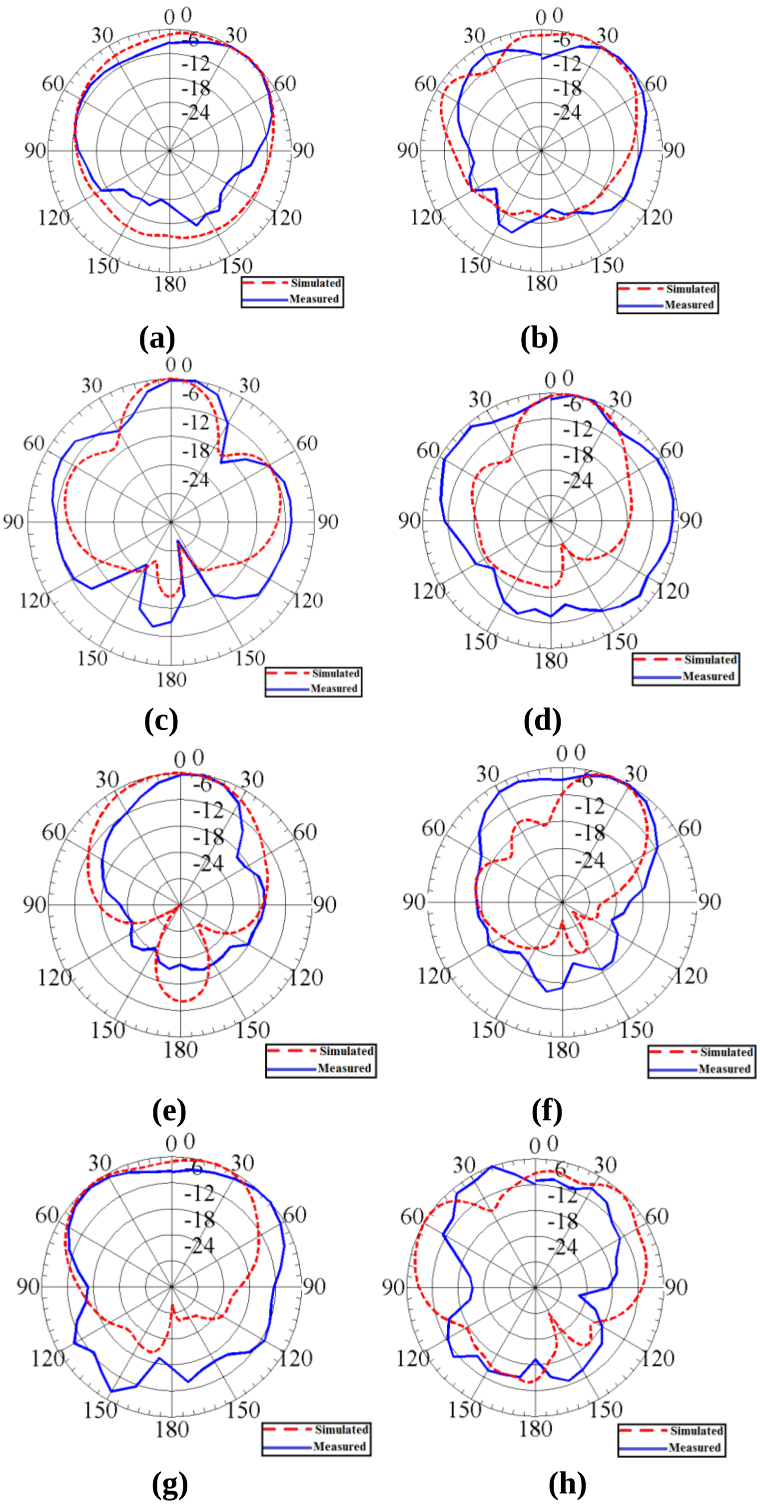


Figure 4 (a). Simulated and measured far field patterns for H plane at the resonant frequencies: (a) 2.36 GHz, (b) 3.45 GHz, (c) 3.65 GHz, (d) 5.18 GHz, (e) 5.49 GHz, (f) 5.99 GHz, (g) 7.13 GHz and (h) 7.71 GHz

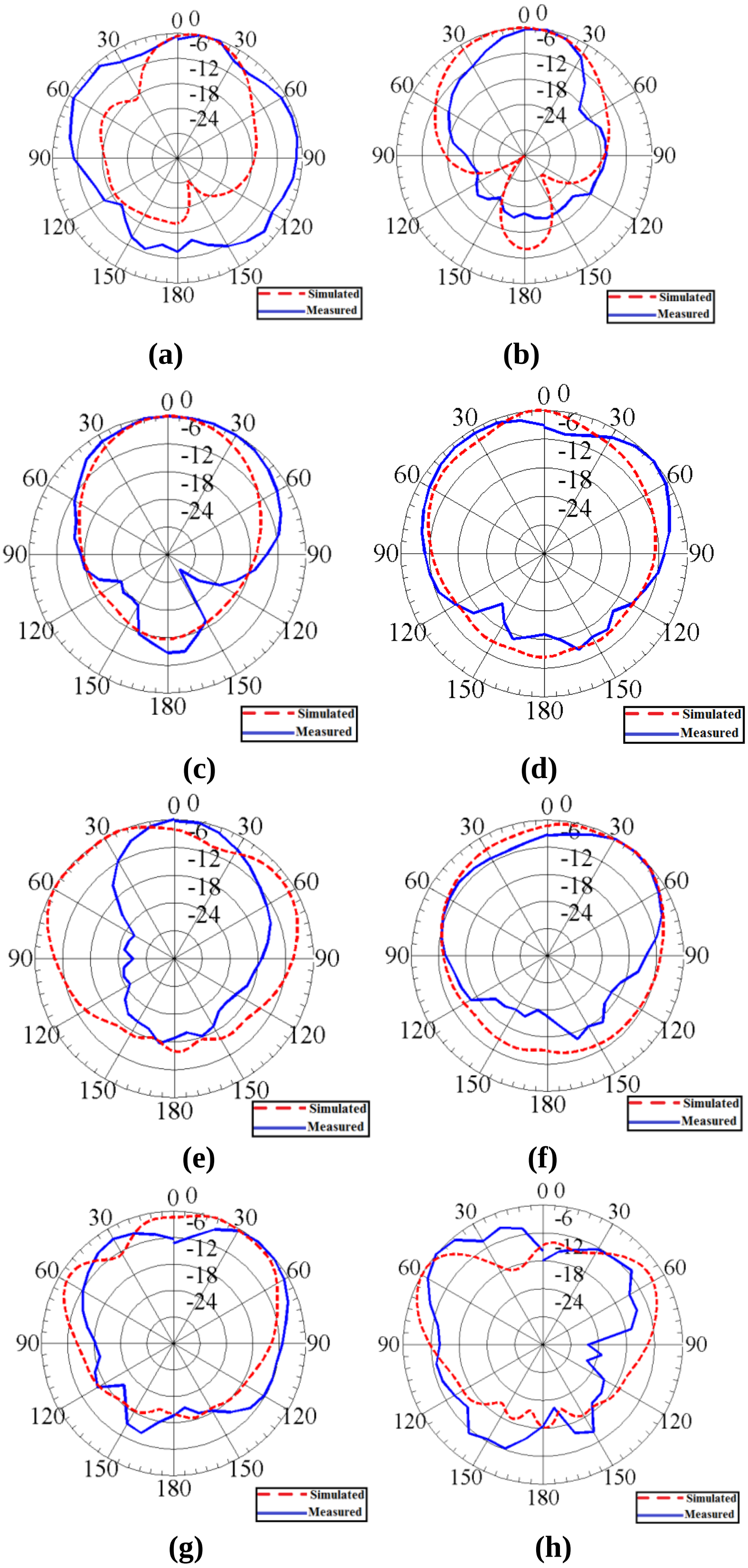


Figure 4 (b). Simulated and measured far field patterns for E plane at the resonant frequencies: (a) 2.36 GHz, (b) 3.45 GHz, (c) 3.65 GHz, (d) 5.18 GHz, (e) 5.49 GHz, (f) 5.99 GHz, (g) 7.13 GHz and (h) 7.71 GHz

The results of the final antenna in terms of resonant frequency, realized gain and fraction gain are mentioned in Table 3. Normalized radiated far field patterns for H plane ($\varphi=0^0$) and E plane ($\varphi=90^0$) are plotted in Figure 4 (a) and 4 (b) respectively based on simulation and measurement for different resonant frequencies. From Table 4, it is observed that the proposed antenna provides better realized gain than other reported hexagonal based 5G antennas and it provides as many as 9 operating bands to be utilized for applications such as aviation, satellite communications and wireless communications. Therefore, it can be concluded that this antenna has novelty in terms of its performance compared to other reported similar antennas.

Table 4. Comparison with previously reported hexagonal shaped 5G antennas

References	Operating Frequency (GHz)	Realized Gain (dBi)
Aathmanesan (2021)	3.5	4.42
Ullah (2020	2 2.45 3.1 3.4	1.3 1.76 1.98 1.74
This Work	1.81 2.36 3.45 3.65 5.14 5.49 5.99 7.15 7.71	3.42 2.69 3.51 1.15 3.05 4.66 6.20 5.78 7.68

CONCLUSION

A circular slotted irregular half hexagonal patch antenna is designed for multiband operation purposes. This antenna has nine resonant frequencies viz. 1.81GHz, 2.36 GHz, 3.45 GHz, 3.65 GHz, 5.14 GHz, 5.49 GHz, 5.99 GHz, 7.15 GHz and 7.71 GHz with acceptable peak realized gain of 3.42 dBi, 2.69 dBi, 3.51 dBi, 1.15 dBi, 3.05 dBi, 4.66dBi, 6.20 dBi, 5.78 dBi and 7.68 dBi respectively. The antenna is covering Bluetooth, WLAN and point to point high speed wireless communication bands. This antenna also covers 5G sub-6 GHz lower band to support recent trends of communication facilities. On slot loading, it is found that the resonant frequencies of the unperturbed antenna are shifted downwards as the slot radius is increased. This antenna is fabricated on FR-4 substrate with thickness of 1.6 mm. The measured results show good agreement with simulation results.

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