# Compact wideband-printed antenna for sub-6 GHz fifth-generation applications

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## Abstract

The design of a compact wideband partial slotted ground rectangular-printed antenna is presented. The design approach utilizing the slotted partial ground plane is much more flexible for improving the antenna performance. A detailed design guideline to estimate the antenna dimensions is given, which is based on mathematical and parametric analysis. The effects of variation of length of the ground and slot position in the ground plane are investigated. The simulation has been performed by using HFSS V20 simulator. The designed antenna is meant for being operated in the C band of super-high-frequency (SHF) spectrum and in the n77 band (3.3-4.2 GHz) and n78 band (3.3-3.8 GHz) of frequency range 1 (FR1) in sub-6 GHz 5G-frequency bands. The designed antenna is showing a wide bandwidth (700 MHz) with a low-reflection coefficient of –31.15 dB. The wide bandwidth and compact size of the antenna makes it suitable for use in sub-6 GHz 5G compact wireless communication systems. The measured results of the antenna prototype are firmly authenticated with simulation estimations.

### Keywords

Rectangular patch antenna (RPA), Sub-6 GHz 5G bands, Bandwidth (BW), Reflection coefficient, Partial ground (PG), Partial slotted ground (PSG), Flame retardant 4 (FR4).

In this decade, a huge leap has been seen from 2nd-generation wireless mobile systems to 5th-generation wireless mobile systems, so there has been a need for compact miniaturized antennas, which can occupy lesser space with adequate performance. The antennas for this purpose must be light in weight and small in size, with ease of fabrication. Progressions in the communication industry have constrained engineers to configure scaled-down electronic frameworks, which has empowered us to deal with both embedded systems and patch-antenna innovation. Most recent research works have indicated that because of a few alluring highlights, microstrip-patch antennas have become an integral part of scaled-down wireless systems. In its simplest form, the microstrip antenna comprises a metallic transmitting patch that is created over a dielectric substrate backed by a metallic ground plane, and it finds applications as reception devices in almost all generations of wireless mobile systems. All the characteristics and features of the microstrip antennas are derived from its design constraints (Garg et al., 2001; Balanis, 2005; Mishra, 2016; Croq and Papiernik, 1990; Targonski and Pozar, 1993; Roy, 1998).

Microstrip-patch antenna has accolade a significant consideration in the latest generations of wireless communications, including Industry 4.0 and Internet of Things devices. Regardless of different points of interest, the design of the patch antennas has a significant disadvantage in the form of narrow bandwidth with low gain. To conquer this issue, various procedures for the improvement of the narrow bandwidth of microstrip-patch antennas have been developed (Duffy, 2000; Mishra et al., 2016; Yang et al., 2001; Islam et al., 2018). A large portion of these wideband microstrip-patch antennas are multilayered stacked microstrip apertures, proximity-coupled microstrip apertures, or gap-coupled microstrip patches. It is exceptionally hard to design a compact wideband microstrip-patch antenna, due to the inborn narrow-band behavior.

Fifth-generation (5G) forums constituted by the group of Asian countries have finalized frequency bands for 5G applications at 4.5 to 5.5 GHz. Fixed-satellite service (FSS) has also recognized its frequency bands of operation at 3.3 to 3.8 GHz, specifically designated for 5G cellular communications. Both the mentioned frequency ranges are in super-high-frequency (SHF) band. These developments have motivated us for developing antennas for the specified bands (XXXX, 2019). As part of the latest advancements in the communication field and with the invention of 5G devices, FR1 band will be of much use as it will bridge the technology between exiting 4G to 5G. The design concentrated in this paper is targeted to achieve frequency operating in n77 and n78 bands of FR1 spectrum of 5G New radio (NR). The applications of our design will be mainly in the area of broadband mobile that will feature highly reliable and low-latency service involving massive machine-based technology (XXXX, 2019). Applications of partial ground plane have been previously engaged to increase the bandwidth for printed antennas (Kumar and Guha, 2014; Nouri and Dadashzadeh, 2011; Mabaso and Kumar, 2018; Khandelwal et al., 2014; Kumar and Masa-Campos, 2014; Radiom et al., 2009; Ngobese and Kumar, 2018; Njokweni and Kumar, 2020).

In this paper, we have reported a technique to boost up bandwidth and to reduce the size of the microstrip antenna. The technique reported in this paper is the reduction of the ground plane and making a slot in the ground plane. After detailed investigation in our study, it has been found that for a microstrip antenna, if we load the antenna with slots in the ground plane, then we are able to get a wider bandwidth as it reduces the return loss of the antenna. An added advantage of making slotted ground is that we can get reduced size, a simple design that can be easily adapted and integrated with chip technology. The partial slotted ground rectangular-patch antenna with a microstrip feed line is fabricated on the FR4 substrate. Bandwidth is enhanced by modifying the original ground plane to half in dimension along the major axis and subtracting an 18-segment polygon-shaped structure from it. The measured results of our designed partial slotted ground rectangular patch antenna are in resemblance with the simulated results.

The structure of the paper is oriented as follows. The second section is concerned with antenna design and geometry. The third section presents antenna results and discussions. The fourth section describes the measurement setup and analysis of the results, and finally the last section concludes our work.

## Antenna design and geometry

In the first step, we have designed a rectangular-patch antenna by using the transmission-line model. The following equations are utilized for designing the rectangular-patch antenna:

The width ($W$) of the patch antenna is given by

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\epsilon_r + 1}} \tag{1}$$

where $W$ is the width of the patch $c$ the speed of light, $3\times10^8$ m/sec $\epsilon_r$ the dielectric constant of substrate $f_r$ the resonant frequency

The effective dielectric constant is a valuable parameter, while designing a rectangular-patch antenna. The electromagnetic waves traveling from the radiating rectangular patch in the direction of the ground plane pass through air and some escape through the substrate (called as the fringing effect). As the wave travels through different medium having different dielectric values, there is a need to find the value of the effective dielectric constant. The value of the effective dielectric constant ($\epsilon_{reff}$) is calculated by using the following equation:

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2}, \quad \frac{W}{h} > 1 \tag{2}$$

With the virtue of the fringing effect, an increase in electrical dimension of the antenna is seen by amount ($\Delta L$). Hence, this extended length of the rectangular-patch antenna is calculated by using the following equation:

$$\frac{\Delta L}{h} = 0.412\frac{(\epsilon_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\epsilon_{reff} - 0.258)(\frac{W}{h} + 0.8)} \tag{3}$$

where $h$ is the height of the substrate.

The length $L$ of the rectangular-patch antenna is calculated as follows:

$$L = \frac{c}{2f_r\sqrt{\epsilon_{reff}}} - 2\Delta L \tag{4}$$

The length and width of the substrate are taken to be equal to that of the ground plane. The width of the ground plane ($W_g$) and the length of the ground plane ($L_g$) are calculated using the following equations:

$$L_g = 6h + L \tag{5}$$

$$W_g = 6h + W \tag{6}$$

Using the above-mentioned formulas, we have calculated the dimensions of the basic rectangular-patch antenna and the design is simulated using HFSS software, and some values are optimized using parametric sweep to ensure that the output of the return loss lies in the desired frequency band, i.e., from 3.3 to 4.2 GHz. In the literature, researchers have already identified that the conventional rectangular-patch antenna (RPA) has a low bandwidth, which is targeted to get enhancement in our design. To remove the said limitation along with attaining compactness, we have modified the basic structure of the rectangular-patch antenna and followed some basic design patterns to achieve our finalized designs as shown in Figure 1. The rectangular-patch antenna shape has been selected because it offers many advantages, such as compactness, lesser cost, and it is light in weight. A very low transmission in the form of narrow bandwidth is a major disadvantage for our basic design structure. We targeted this limitation and made an objective, which was to alter the basic design and utilize the techniques for improving the bandwidth. The design steps followed for getting finalized antenna geometries and the optimized value of the parameters have been presented in Figure 1 and Table 1, respectively.

Here, we have discussed the brief analysis of the steps followed for finalizing the wideband design by using parametric analysis for estimating dimensions targeting adequate values of the reflection coefficient with bandwidth. The final design with a bandwidth of 700 MHz is holding a great candidate for sub-6 GHz 5G New Radio (NR) spectrum because of its lesser complexity, having single-layer design, and moreover compactness, which is the demand of 5G wireless

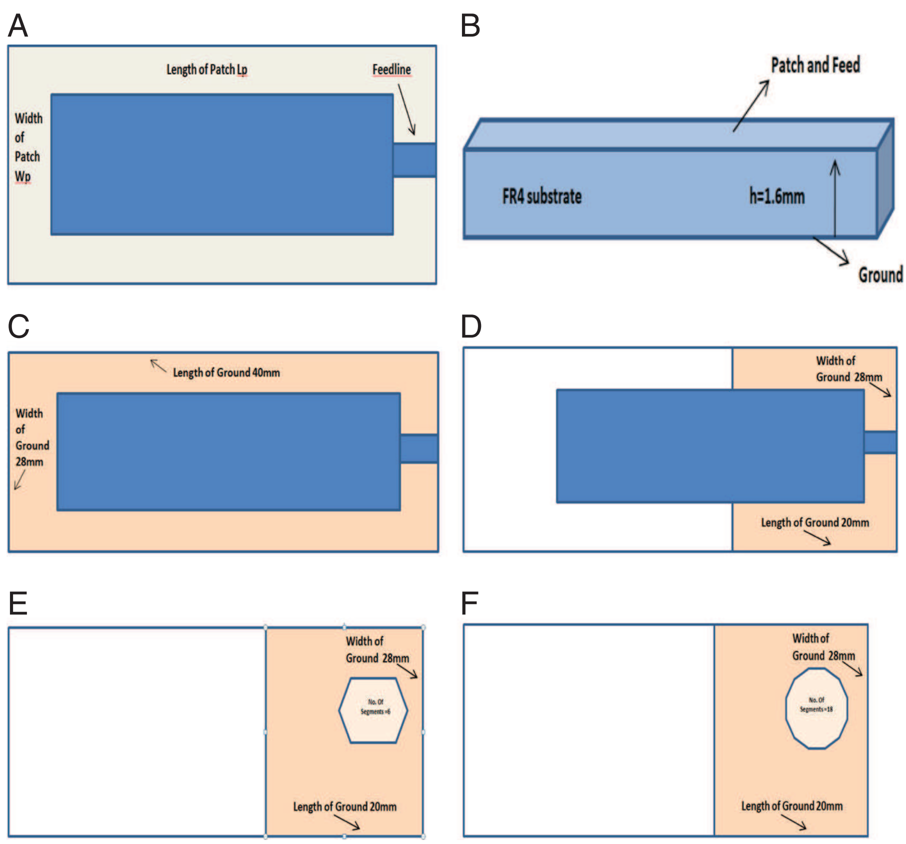


Figure 1: Geometry of the antenna. (A) Top view of the rectangular-patch antenna (RPA), (B) side view of RPA, (C) RPA with full ground plane, (D) PG-RPA, (E) PSG-RPA1 with a polygon cut with six segments, and (F) PSG-RPA2 with a polygon cut with 18 segments.

**Table 1. Dimensions of PSG-RPA2 (FR4 substrate with h = 1.6 mm).**

| Parameters | Lp | Wp | Wf | Lf | Lg | Wg | No. of polygon segments in PSG-RPA2 |
|---|---|---|---|---|---|---|---|
| Dimension | 36 mm | 16 mm | 0.5 mm | 2 mm | 20 mm | 28 mm | 18 |

systems. Therefore, to achieve a proper radiating mode at 3.80 GHz (which is the center frequency), we have reduced the size of the ground plane to half of the original value making it as partial ground rectangular-patch antenna (PG-RPA). Further, the bandwidth has been increased by modifying the PG-RPA structure by cutting a six-segment polygon to get partial slotted ground rectangular-patch antenna (PSG-RPA). This design yields a bandwidth of 500 MHz, which constituted the first design of the partial slotted ground rectangular-patch antenna (PSG-RPA1). The structure was further modified with increasing the number of segments to a value of eighteen for creating the second partial slotted ground rectangular patch antenna (PSG-RPA2), by which a bandwidth of 700 MHz is made an achievable target. The optimized value of the parameters has been presented in Table 1.

## Antenna parameters and discussion

The parametric investigation was done for getting the proposed finalized antenna with improved bandwidth. By varying the dimensions of strip-feed width (Wf) and using different DGS shapes, we have done an assessment that variation in the parametric values can increase the performance of the proposed antenna design. All the results obtained through parametric analysis are presented in Table 2. Antenna parameters are optimized by using HFSS for the desired frequency bands, i.e., in n77 and n78 bands.

**Table 2. Parametric performance analysis of different design iterations (FR4 substrate is used).**

| Parameter variation | Resonant frequency (GHz) | Impedance bandwidth (MHz) | Reflection coefficient (dB) |
|---|---|---|---|
| Conventional RPA | 4.02 | 30 | –10.64 |
| RPA with partial ground plane | 3.88 | 250 | –53 |
| RPA with hexagonal partial ground plane | 3.64 | 5.3 | –14.56 |
| RPA with polygon partial ground plane (proposed) | 3.41 and 3.83 | 700 | –26.17 and –31.15 |
| Variation of width of strip feed (Wf) in mm in RPA with polygon partial ground plane | | | |
| 0.5 | 3.41 and 3.83 | 700 | –26.17 and –31.15 |
| 1 | 3.69 | 650 | –38.27 |
| 1.5 | 3.69 | 600 | –38 |
| 2 | 3.66 | 550 | –27.61 |
| 2.5 | 3.66 | 500 | –22.51 |
| 3 | 3.66 | 479 | –21.30 |

## Reflection coefficient and voltage-standing wave ratio (VSWR)

Parametric analysis is done for different iterations of patch antenna as shown in Figure 2. Based on equations (1) to (6), a design of a basic conventional rectangular-patch antenna is presented, which is resonating at 4.03 GHz but does not radiate as it is having a reflection-coefficient value of less than –9.50 dB. RPA with a partial ground plane is produced by reducing the ground plane to exactly half in dimensions, by which we are getting resonating frequency at 3.89 GHz, with attaining bandwidth of nearly 250 MHz. In the next step, the PG-RPA is further modified by cutting a six-segment slot (i.e., hexagonal shape), making it as the first design of partial slot ground rectangular-patch antenna (PSG-RPA1). Here, we are getting a value of the reflection coefficient to be –13.35 dB at a frequency of 3.6 GHz, attaining bandwidth of about 500 MHz. In the next step for further increasing of the bandwidth, we have increased the number of segments gradually and take its value to eighteen. This design showed that our antenna is resonating at 3.36 dB with a bandwidth of 700 MHz and reflection-coefficient value of –31.15 dB. The schematic configuration is illustrated in Figure 2.

Comparative analysis of the reflection coefficient for design iterations is plotted in Figure 3. A significant increase in the operating bandwidth with a low reflection coefficient is observed, when we shift from one design to the next. After performing all iterations, we have reached a final design of PSG-RPA1 attaining a bandwidth of 500 MHz and the reflection coefficient of –13.35 dB at a frequency of 3.63 GHz. We have given our finalized design in the form of PSG-RPA2, which gives a wideband of 700 MHz (i.e., from 3.28 GHz to 4.00 GHz), attaining the maximum value of the reflection coefficient at –26.17 dB and –31.15 dB at a frequency of 3.41 GHz and 3.83 GHz, i.e., in n77 and n78 bands. In Figure 3, a comparison of the reflection coefficient (dB) of various stages of an antenna is visualized, which clearly indicates that there is gradual increase in the bandwidth of the antenna. The position of the slot is an important concern while designing our antenna, and once we identify it, then by increasing the number of segments of the slot can help to get the wideband characteristics. The results obtained by the parametric analysis are presented in Table 2. So, using a single-layer structure and simplified design, we are able to attain the desired value of the reflection coefficient along with the bandwidth.

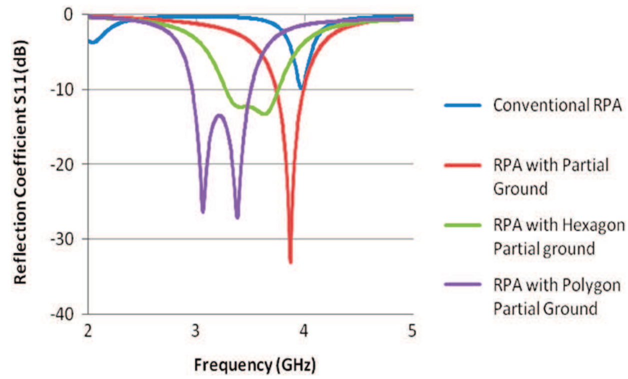


Figure 3: Comparative analysis of the reflection coefficient for various design steps.

Voltage-standing wave ratio (VSWR) is a salient parameter that dictates the amount of power captured in the opposite direction to the direction of the transmission from an antenna. VSWR always holds a positive-integer value. The lesser is the value, the better is an antenna matching to the feed line and greater is the power delivered to an antenna. As shown in Figure 4, PSG-RPA1 and PSG-RPA2 are giving adequate results in terms of VSWR. As per Figure 4, almost within all the ranges of the n77 band, i.e., from 3.3 GHz to 4.2 GHz, and in the n78 band,

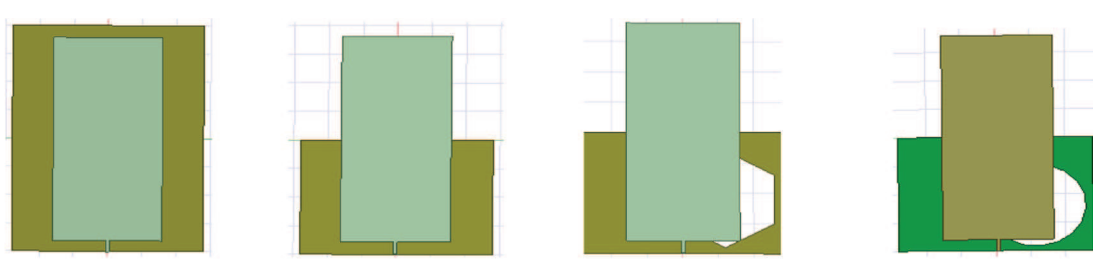


Figure 2: Schematic configuration steps followed to reach our design geometry.

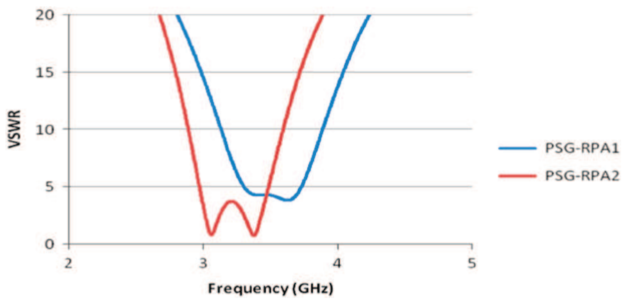


Figure 4: Voltage-standing wave ratio (VSWR) of the antennas PSG-RPA1 (bandwidth of 500 MHz) and PSG-RPA2 (bandwidth of 700 MHz).

i.e., from 3.3 GHz to 3.8 GHz, the value of VSWR is below 2 that is a great sign for getting far-field radiation characteristics of the designed antennas. The comparison of simulated results of designed antennas, i.e., PSG-RPA1 and PSG-RPA2, is shown in Table 3. From this table, it is observed that PSG-RPA2 gives a wide bandwidth, better gain, and low-reflection coefficient.

## Radiation patterns

Radiation intensity is an important parameter that describes the amount of power being radiated from an antenna. The radiation patterns in E and H planes for resonating frequencies of 3.41 GHz and 3.83 GHz are visualized in Figure 5.

### Table 3. Comparison of simulated results of designed antennas, i.e., PSG-RPA1 and PSG-RPA2.

| Parameters | PSG-RPA1 | PSG-RPA2 |
|---|---|---|
| Lower cut-off frequency ($f_L$) | 3.25 GHz | 3.28 GHz |
| Higher cut-off frequency ($f_H$) | 3.75 GHz | 4.00 GHz |
| Bandwidth | 500 MHz | 720 MHz |
| VSWR (at 3.41 GHz) | 1.95 | 1.55 |
| VSWR (at 3.83 GHz) | 1.66 | 1.70 |
| Gain | 2.3 dB | 2.5 dB |
| Reflection coefficient | –13.35 dB | –31.15 dB |

The red curve shows E-plane radiation pattern and the green curve shows H-plane radiation pattern. The radiation pattern is extracted after simulations from HFSS software in which the maximum gain is observed to be 0.6 dBi at 3.41 GHz and 2.5 dBi at 3.83 GHz for PSG-RPA2. A small degradation is observed in the radiation pattern at higher frequencies. E-plane radiation pattern shows the “figure of eight,” and on the H plane, we get the omnidirectional radiation characteristics. The three-dimensional patterns of the antennas are shown in Figure 6. It is clearly visible that the antenna gain is also increased when we move from PSG-RPA1 to PSG-RPA2 design along with the bandwidth of the antenna, making it suitable in wideband applications.

## Measurement setup and validation of the results

Figure 7 displays the antenna prototype of PSG-RPA2 with a maximum bandwidth of 700 MHz developed to experimentally test our simulated design. The design prototype was created using commercially accessible FR4 substrate.

Figure 8 depicts the reflection coefficient of the measured and the simulated structures, which clearly indicate that both the simulated and measured results are in good agreement. The patterns of both are in line, which validates our design and makes it a good candidate for utilization in sub-6 GHz bands.

The comparison of the simulated and measured parameters of the designed antenna is given in Table 4. As per the analysis done in Table 4, the measured results are almost in accordance with the simulated results. The antenna so designed can be used in wideband applications in sub-6 GHz 5G spectrum. So, due to the single-layer structure, simple design, and smaller size, our designed antenna is suitable for sub-6 GHz 5G NR spectrum applications.

Table 5 shows the comparison of the proposed antenna with the other antennas published in previous researches. The dimensions of the patch and thickness of the substrate are given in terms of free-space center wavelength ($\lambda_0$). It can be observed that the proposed antenna provides the compact size and wideband operation.

## Conclusions

The compact printed antenna with significant improvement in the bandwidth by using a partial slotted ground plane, i.e., PSG-RPA2, has been proposed. This methodology can be applied to broaden the

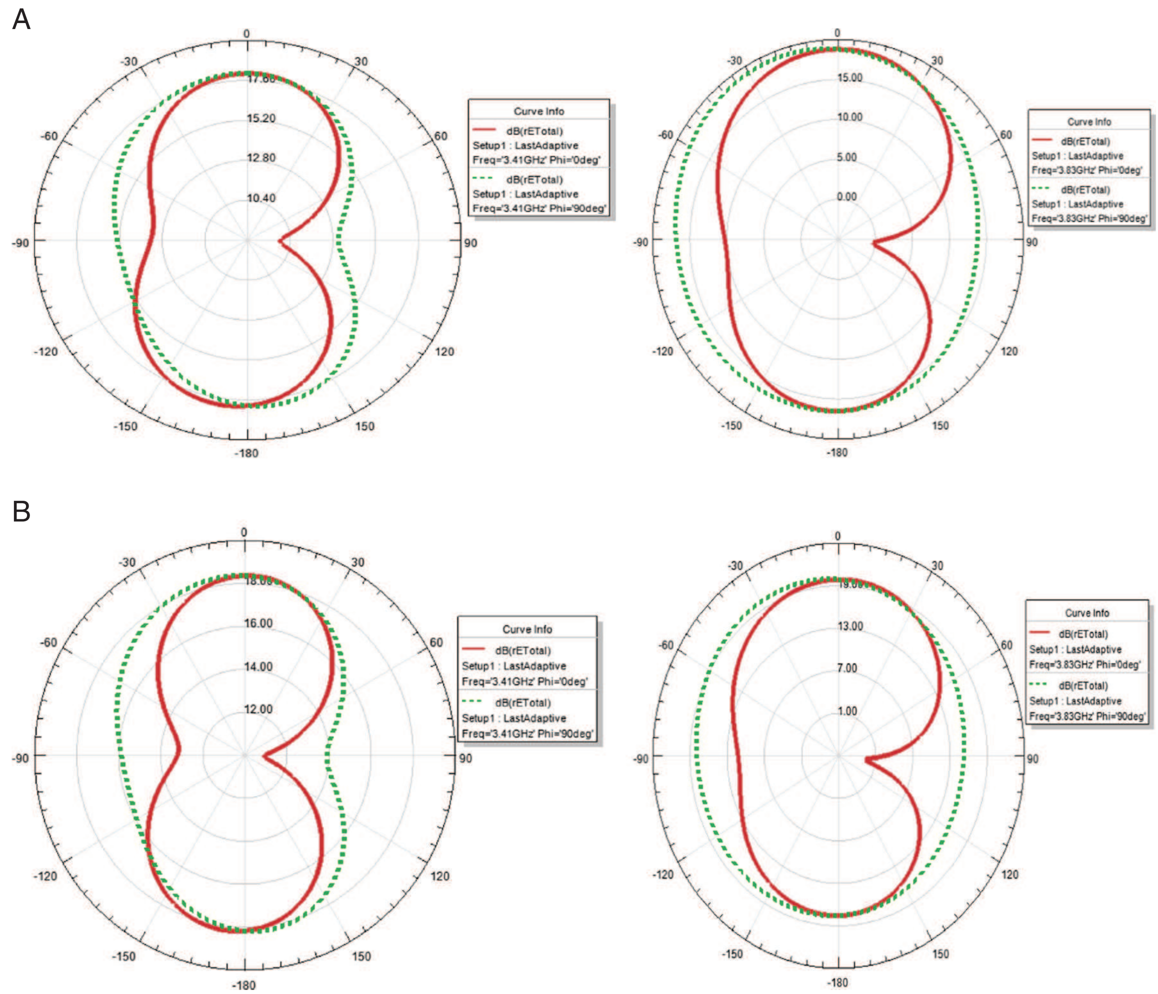


Figure 5: Radiation intensity for the proposed antenna with (A) E- and H-plane pattern of PSG-RPA1 at 3.41 GHz and 3.83 GHz (BW 500 MHz) and (B) E- and H-plane pattern of PSG-RPA2 at 3.41 GHz and 3.83 GHz (BW 700 MHz).

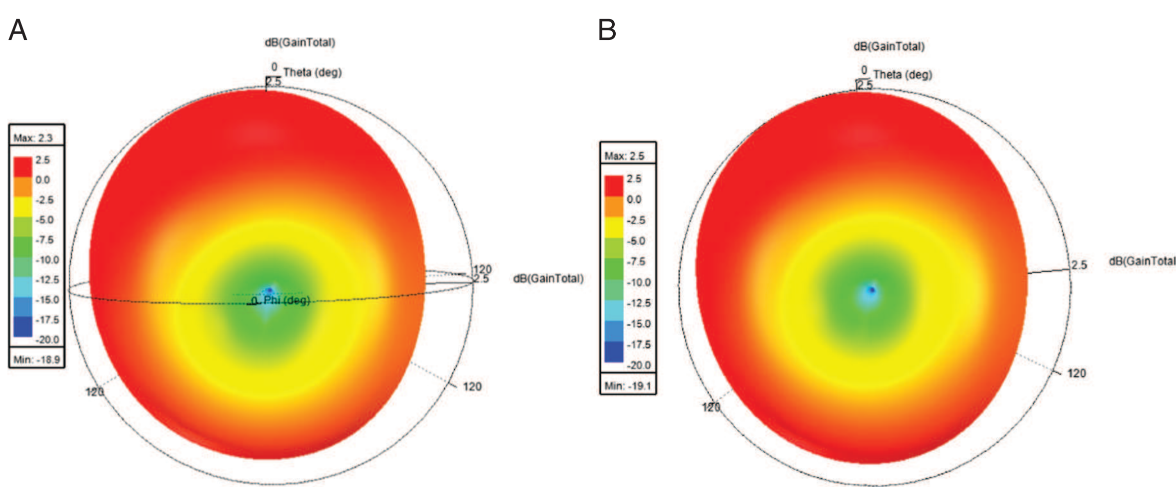


Figure 6: Gain plot for the proposed antenna with (A) PSG-RPA1 (BW 500 MHz) and (B) PSG-RPA2 (BW 700 MHz).

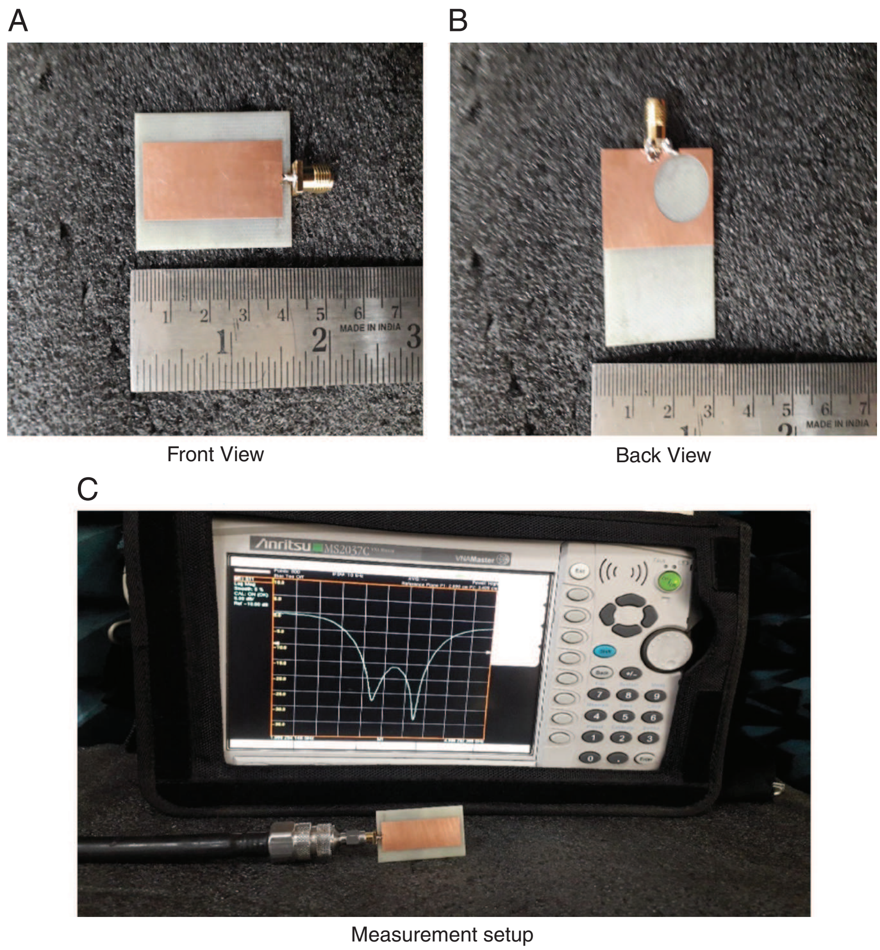


Figure 7: Antenna prototype of PSG-RPA2 (A) front view, (B) back view, and (c) measurement setup.

operating frequency band of any basic rectangular-printed antenna structure in working condition without alteration in the patch shape. The parametric analysis is performed by using the HFSS software.

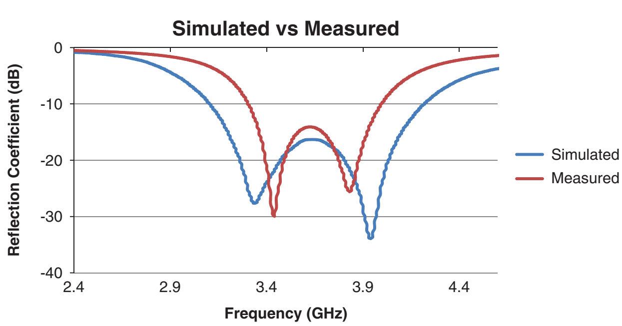


Figure 8: Comparison of reflection-coefficient curves of simulated and measured designs for PSG-RPA2 possessing a bandwidth of 700 MHz.

### Table 4. Comparison of simulated and measured results of the PSG-RPA2 (FR4 substrate with h = 1.6 mm).

| Parameters | Simulated results | Measured results |
|---|---|---|
| Lower cut-off frequency ($f_L$) (GHz) | 3.28 | 3.3 |
| Higher cut-off frequency ($f_H$) (GHz) | 4.00 | 4.02 |
| Bandwidth (MHz) | 720 | 720 |
| VSWR (at 3.41 GHz) | 1.55 | 1.14 |
| VSWR (at 3.83 GHz) | 1.70 | 1.17 |
| Minimum reflection coefficient (dB) | –31.15 | –34.98 |

Table 5. Comparison of our design with previous researches.

| References | Parameters | | | | |
|---|---|---|---|---|---|
| | Bandwidth (GHz) | Center frequency (GHz) | Patch size | Substrate parameters | Maximum gain (dBi) |
| Guo et al. (2011) | 2.6-6 | 4.3 | $0.78\lambda_0 \times 0.31\lambda_0$ | $\in_r = 2.2$, $h = 0.01\lambda_0$ | ~9 |
| Sekeljic et al. (2019) | 2.5-4.9 | 3.7 | $0.61\lambda_0 \times 0.24\lambda_0$ | $\in_r = 4.4$, $h = 0.01\lambda_0$ | ~4 |
| Tang et al. (2019) | 2.3-5.2 | 3.7 | $0.58\lambda_0 \times 0.23\lambda_0$ | $\in_r = 2.5$, $h = 0.006\lambda_0$ | ~3 |
| Shukla et al. (2016) | 4.0-9.7 | 6.8 | $0.68\lambda_0 \times 0.68\lambda_0$ | $\in_r = 4.4$, $h = 0.03\lambda_0$ | ~4 |
| Pathak and Singhal (2018) | 5.1-7.5 | 6.3 | $0.42\lambda_0 \times 0.31\lambda_0$ | $\in_r = 4.4$, $h = 0.03\lambda_0$ | ~2.8 |
| Proposed antenna PSG-RPA2 | 3.3-4.0 | 3.65 | $0.43\lambda_0 \times 0.19\lambda_0$ | $\in_r = 4.4$, $h = 0.01\lambda_0$ | ~2.5 |

The antenna prototype is fabricated using the low-cost FR-4 glass epoxy substrate. The proposed antenna is compact with a wide bandwidth of 700 MHz. The antenna can cover 5G NR sub-6 GHz wireless application bands, such as n77 band, i.e., from 3.3 GHz to 4.2 GHz, and n78 band, i.e., from 3.3 GHz to 3.8 GHz. The closeness of the measured and simulated results, along with the compactness, shows that the designed antenna can be a good candidate for compact wideband sub-6 GHz 5G wireless applications.

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