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Multiband SINC-slotted Patch Antenna for 5G Applications

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Abstract

In this work, we presented the design, analysis and optimization of the multiband slotted antennas based on SINC function for 5G applications. The proposed antennas are designed and modelled by CST Studio Suite software. A parametric study is performed to determine sinc function parameters that control the performance of the proposed antenna. The parametric study is implemented by varying the amplitude of the sinc function, the frequency, the location of the slot along Y-axis, the slot width and the slot window (number of cycles). The simulated results showed that the designed slotted antennas in this paper exhibits multiband operation and they offer the feasibility of controlling and adjusting the resonant frequency by changing the sinc function parameters. The proposed antennas have various resonant frequencies at around 1.5 GHz, 2.65 GHz, 5 GHz and 5.8 GHz covering the 5G sub-6 GHz band. Extensive simulation process were carried out to determine the optimum antenna performance and three antennas were selected based on the reflection characteristics and number of operation frequency bands. Finally, the three selected antennas were manufactured and their performance were measured in the lab for validation. Experimental results showed that an excellent agreement between the measured and simulated results was achieved.

Keywords

patch antennas, SINC function, slot antennas, multiband, 5G

1 Introduction

The relentless search of faster and more reliable wireless communication has led to the advancement of cellular networks, with 5G technology evolving as an essential innovative in this journey. As 5G technology continues its global deployment, one of the critical challenges is to provide smooth and high-quality connectivity across various scenarios and frequency bands. To address this challenge, the research and development of novel antenna systems have gained supreme importance. Among these inventions, multiband slot antennas have arose as capable candidates to empower efficient 5G communication in an increasingly connected and data-demanding world [1].

The fifth generation of wireless communication has the potential to change the way we connect with our devices and the world around us. 5G technology, categorized by its exceptional data rates, low latency, and enormous device connectivity, opens up electrifying potentials in numerous areas, from improved mobile broadband to the Internet of Things (IoT) and other newly emerged technologies [2, 3]. However, comprehending the full potential of 5G requires the utilization of an extensive network infrastructure, capable of supporting a wide range of frequency bands and accommodating the different needs of an escalating user base.

Multiband slot antennas have gained considerable attention within the research community due to their adaptability in supporting multiple frequency bands and the prospective to simplify the difficult job of integrating several antennas for different applications [4–7]. These antennas, characterized by their unique slot structures and efficient radiation properties, have the potential to enable 5G communication across a wide range of frequency bands, including sub-6 GHz and mm Wave frequencies. By offering multiband abilities, these antennas can contribute considerably to reducing the complexity and cost associated with installing and maintaining 5G networks [8–13].

This research paper investigates multiband slot antennas designed for 5G applications. It aims to explore the design methodologies and performance characteristics of these antennas, focusing on their potential to enhance the evolution of 5G connectivity. The aim of this paper is to

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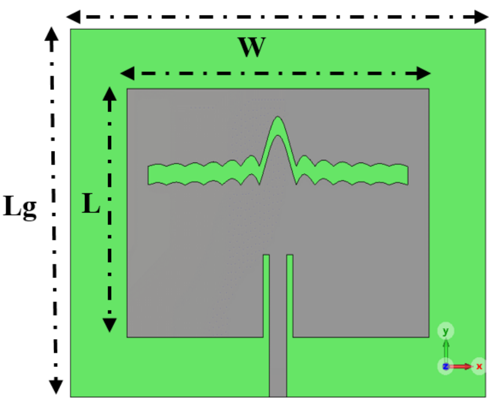
find a new way to control the reflection and radiation properties of slotted patch antennas by an organized modification of the slot geometry. This can be achieved by utilizing sinc function to control the resonant frequency. The idea of employing sinc function in patch antennas is previously proposed in [14], where the edges of the patch antenna were altered by a sinc function. However, in this research the sinc function is integrated as a slot in the heart of the patch antenna. The designed antennas were manufactured and their performance was tested in the lab.

2 Sinc-shaped slot of rectangular patch antenna

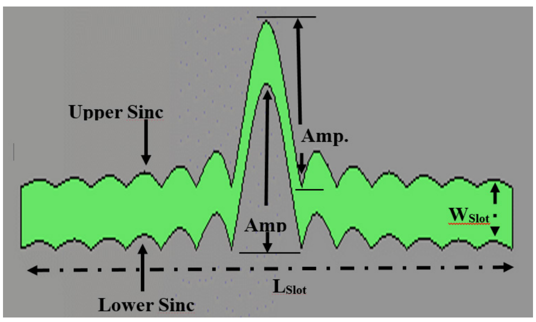
In this work, the width of sinc slot $W_{Slot}(x)$ is not constant and vary as a sinc function, while the length of sinc slot L_{Slot} is constant. The width of sinc slot is along x-axis while the length of slot is along y-axis as shown in Fig. 1.

The equation $f(x)$ of the upper and lower sinc for sinc slot at any value of x-axis with the rang of $-L_{Slot}/2 \leq x \leq L_{Slot}/2$ is given by:

$$f(x)=\begin{cases} Amp.\times\dfrac{\sin(mx)}{mx}, & x\neq 0 \\ Amp.\times\lim\limits_{x\to 0}\left(\dfrac{\sin x}{x}\right)=Amp., & x=0 \end{cases}, \quad (1)$$



(a)



(b)

Fig. 1 The proposed Sinc-slotted patch antenna. (a) Sinc-slotted patch antenna and (b) Sinc slot parameter

where:

- *Amp.*: is the amplitude value of sinc function;
- *m*: is the frequency argument of sinc function.

3 Parametric analysis and simulation results

To investigate the influence of the sinc-shaped slot on the patch antenna performance, several rectangular patch antennas with various shapes of slots are designed and simulated. The first antenna is a rectangular patch antenna with conventional rectangular slot (i.e., *Amp.* =0) and the others are rectangular patch antennas with sinc-shaped slots that have positive or negative sinc amplitude. Fig. 2 illustrates the geometrical details of the designed slotted antennas.

The designed slotted antennas were simulated by using CST Studio Suite where the antenna is placed on FR-4 substrate having a dielectric constant of 4.3 and a thickness 1.6 mm. Standard FR-4 substrate was selected due to its low cost and availability. The S-parameters of the slotted antennas are illustrated in Fig. 3. It is observed that the employing the sinc function as a slot in the geometry of the rectangular patch antenna has a noticeable effect on the performance. For the rectangular patch with conventional slot (rectangular slot), the antenna exhibits three resonant frequencies located in the sub-6 GHz at 1.1 GHz, 2.8 GHz and 5.65 GHz as shown in Fig. 3. However, when a sinc-shaped slot that has a positive amplitude is implemented in the middle of the patch antenna, the resonant frequency of all bands is slightly changed and a new resonant frequency appeared around 4.8 GHz. In contrast, the negative sinc function has caused a different change in the antenna performance with an obvious shift in the resonant frequencies. Finally, for the case of shorter sinc slot, the resonant frequency was significantly changed. It is seen that at lower frequencies (1 GHz band) the resonant frequency is increased while at the 2.8 GHz band the resonant frequency is decreased.

Based on the clearly evident influence of the sinc slots on the performance, it is found that the resonant frequency can be controlled by varying the sinc function parameter such as x, *Amp.* and m. A parametric study will hence be carried out with extensive simulations to select the antenna parameters that exhibit optimum performance for 5G applications.

The sinc function parameters were varied as follows: The sinc amplitude was varied as $(-8 \text{ mm} \leq Amp. \leq 8 \text{ mm})$ with step = 4 mm and $(0.5 \leq m \leq 2)$ with step = 0.5. In addition, the location of the slot on Y-axis was varied from 5.5 mm to 9.5 mm with a step of 2 mm to study the impact of the slot height inside the patch antenna. Moreover, the slot width was varied from 2 mm to 4 mm with a step of 1 mm. Finally, the slot length was controlled by changing

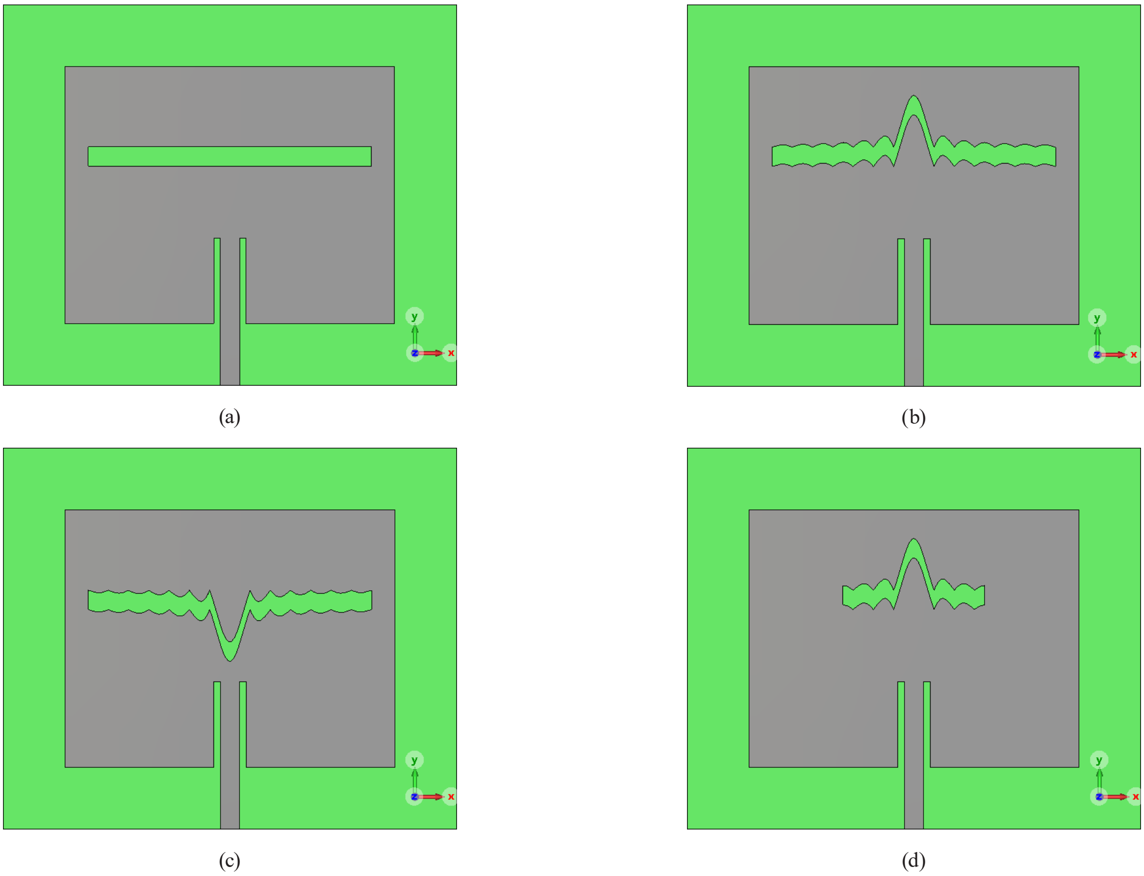


Fig. 2 Rectangular patch antennas with sinc slots; (a) rectangular slot; (b) with positive amplitude sinc; (c) with negative amplitude sinc; (d) with smaller window sinc slot (shorter slot)

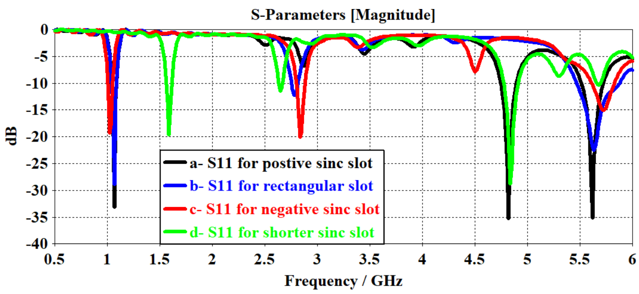


Fig. 3 Simulated (S11) for the designed antennas with different slots

the range of x along the patch antenna as $-7\pi \leq x \leq 7\pi$ with step $= \pi/2$. The total combination of simulations for studying the aforementioned sinc parameters simultaneously were 1890 cases. The S11 curves of selected cases are illustrated in Fig. 4 (a)–(d). It is noticed that when the amplitude is positive the resonant frequencies will be shifted to the lift whereas when the sinc amplitude is negative the resonant frequencies will be shifted to the right compared to the case of *Amp.* = 0. Additionally, it is found that moving the slot location inside the patch antenna with respect to Y-axis has a noticeable impact at higher frequencies with a slight shift to the left. Furthermore, increasing the slot width leads to an improved performance within the frequency range 2–3 GHz with increasing the distance between the first and second resonant frequencies, while decreasing the slot width improves the performance around 5 GHz band and decrease the distance between the first two resonant frequencies. Moreover, increasing the value of m will increase the resonant frequency, however, it is found that at higher frequencies 5–6 GHz increasing m led to shifting the resonant frequency to the left with poor reflection characteristics. Finally, it is found also that increasing the slot window (slot length (x)) have a noticeable influence on the antenna performance where it is observed that increasing x will shift the resonant frequencies to the left but each value of x targets different frequency band.

The dependence of the antenna performance on the sinc function parameters gives the designer a great control to target a specific frequency band with a fine tuning capability.

From the huge number of the simulated cases, three cases were selected that fits well within 5G applications in terms of the number of resonant frequencies and the reflection characteristics as shown in Fig. 5. The geometrical details of the selected antennas are depicted in Fig. 6 with *Amp.* = 8 mm and slot width = 3 mm for all antennas.

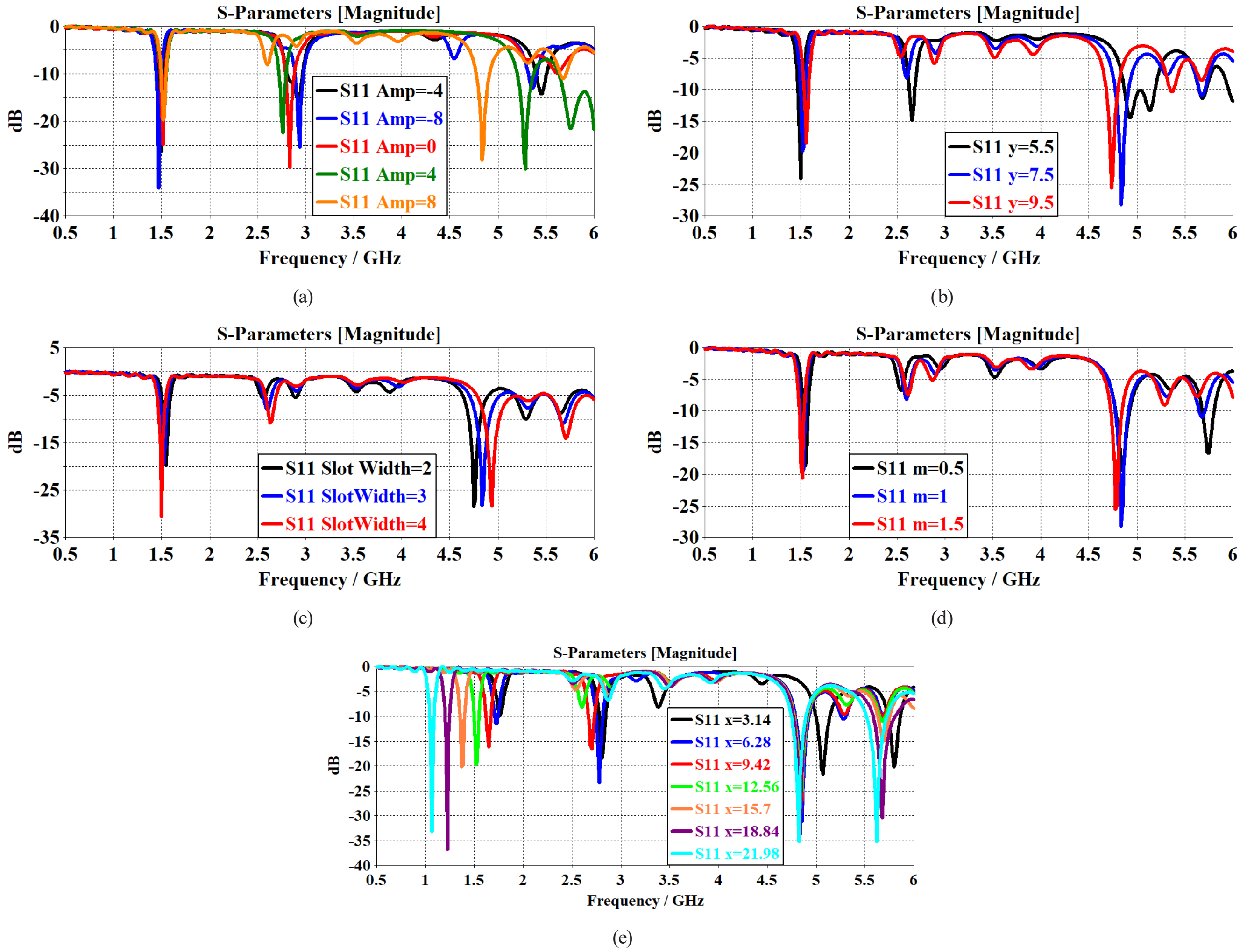


Fig. 4 Simulated (S11) for studied cases: (a) effect of *Amp.* ((Y = 7.5), (SlotWidth = 3), (m = 1) and (x = 12.56)); (b) effect of slot location according to Y-axis ((*Amp.* = 8), (SlotWidth = 3), (m = 1) and (x = 12.56)), (c) effect of slot width ((*Amp.* = 8), (Y = 7.5), (m = 1) and (x = 12.56)); (d) effect of m ((*Amp.* = 8), (Y = 7.5), (SlotWidth = 3) and (x = 12.56)); (e) effect of x ((*Amp.* = 8), (Y = 7.5), (SlotWidth = 3) and (m = 1))

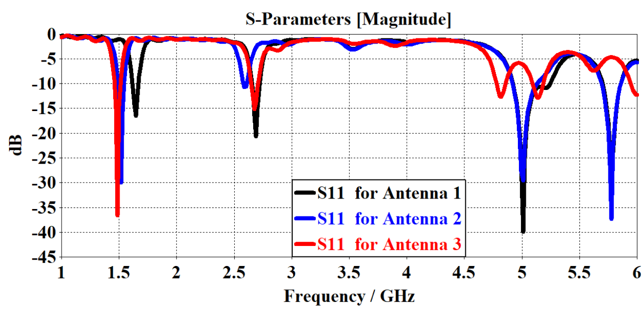


Fig. 5 Simulated (S11) of the three selected antennas

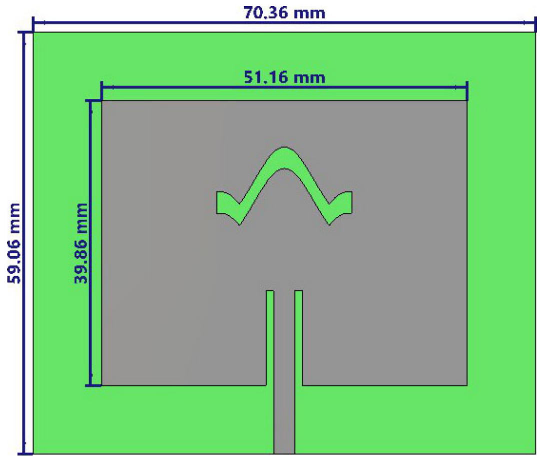
The third frequency band in all antennas is caused by the presence of the slot. For the case of the Antenna 3, the value of m was 1.5 which makes the slot have many bends and curves. This in turn will alter the current distribution around the slot and split the frequency band into two adjacent bands.

The simulated 2D and 3D radiation pattern of the selected antenna at different frequencies are illustrated in Figs. 7–9. The results showed that the designed antennas exhibit almost omnidirectional properties, which is preferable in this application.

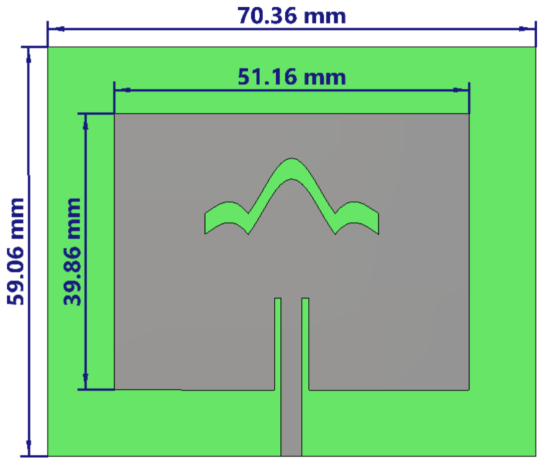
Table 1 summarizes the simulation results of selected antennas showing the resonant frequency at each operating band, the directivity and reflection characteristics.

4 Experimental results

The three selected slotted antennas (Antenna1, Antenna2 and Antenna3) are fabricated on FR-4 substrate and their reflection and radiation characteristics were measured in the lab within the frequency range 1-6 GHz. Fig. 10 depicts photographs of the three fabricated antennas. The testing arrangement was organized in the lab by



(a)



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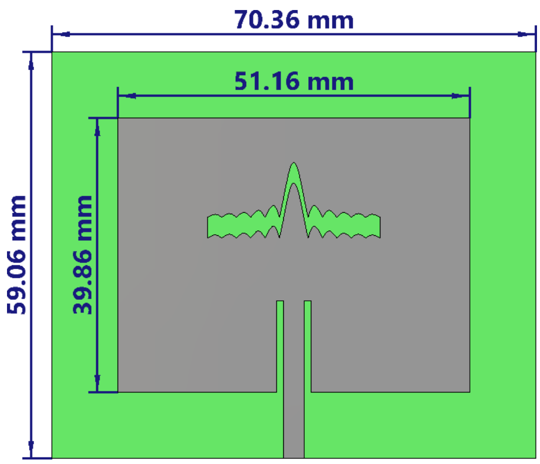
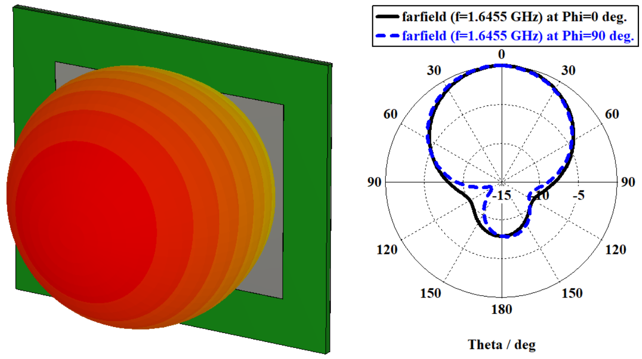


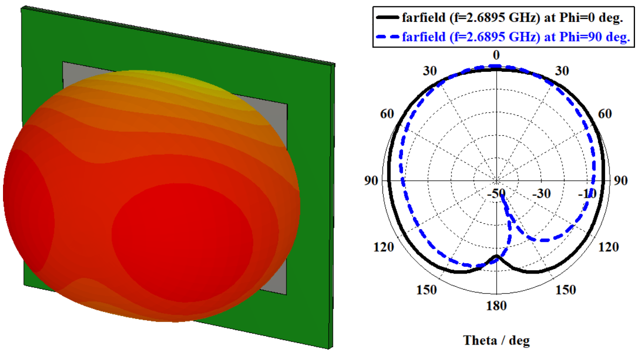
(c)

Fig. 6 Geometry and dimensions of the selected antennas; (a) Antenna1 (m = 0.5, and slot window = 3π); (b) Antenna2 (m = 0.5, and slot window = 4π); (c) Antenna3 (m = 1.5, and slot window = 4π)

employing absorbing material to mimic an anechoic environment to test the S11 and the radiation pattern experimentally as shown in Fig. 11 and 12 demonstrates a comparison between the measured and simulated S11 for the designed antennas within the frequency range 1–6 GHz. It is obvious that there is an excellent agreement between the simulated and measured return loss for all antennas, where they exhibited multiple resonance experimentally. The number of achieved frequency bands (with RL beyond −10 dB) are promising. Moreover, the measured radiation pattern of all fabricated antennas at different frequency bands compared with simulation results are shown in Fig. 13. The measured radiation pattern for all fabricated antennas were performed at 5 GHz for comparison purposes. It is clearly seen that the measured radiation pattern is approximately resembles the simulation results at some points.



(a)



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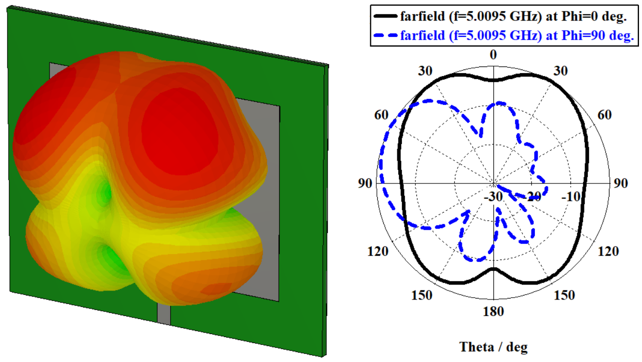


(c)

Fig. 7 Simulated radiation pattern of Antenna1 at different frequencies; (a) 1.65 GHz; (b) 2.68 GHz; (c) 5 GHz

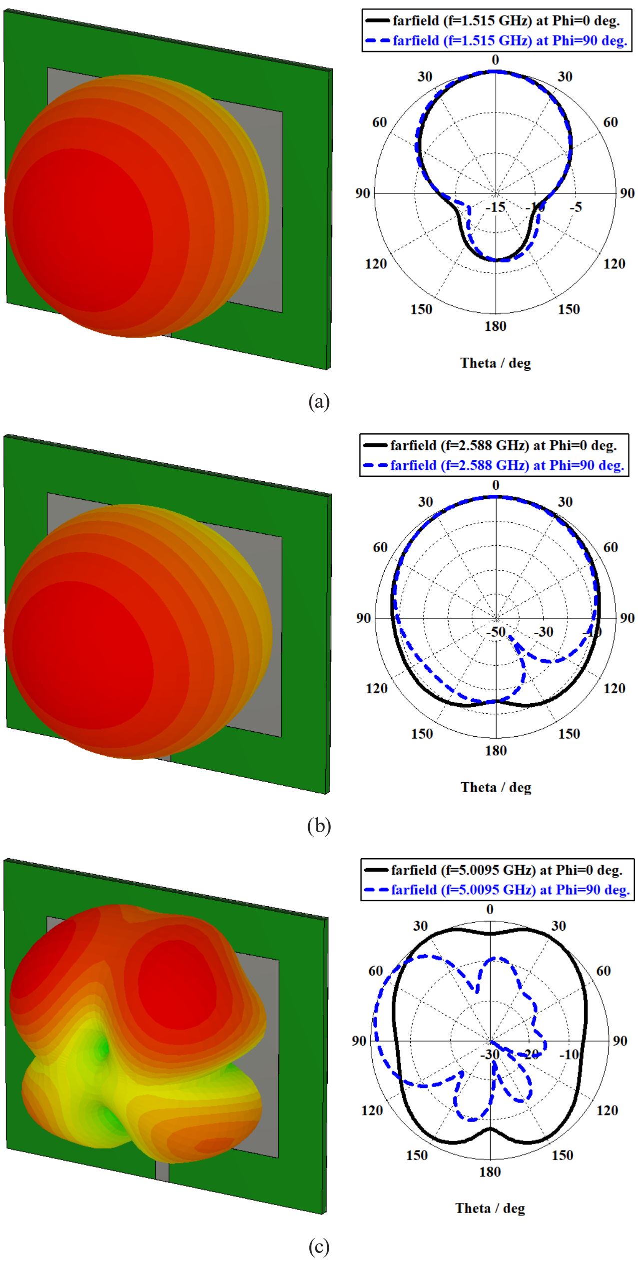


Fig. 8 Simulated radiation pattern of Antenna2 at different frequencies; (a) 1.51 GHz; (b) 2.58 GHz; (c) 5 GHz

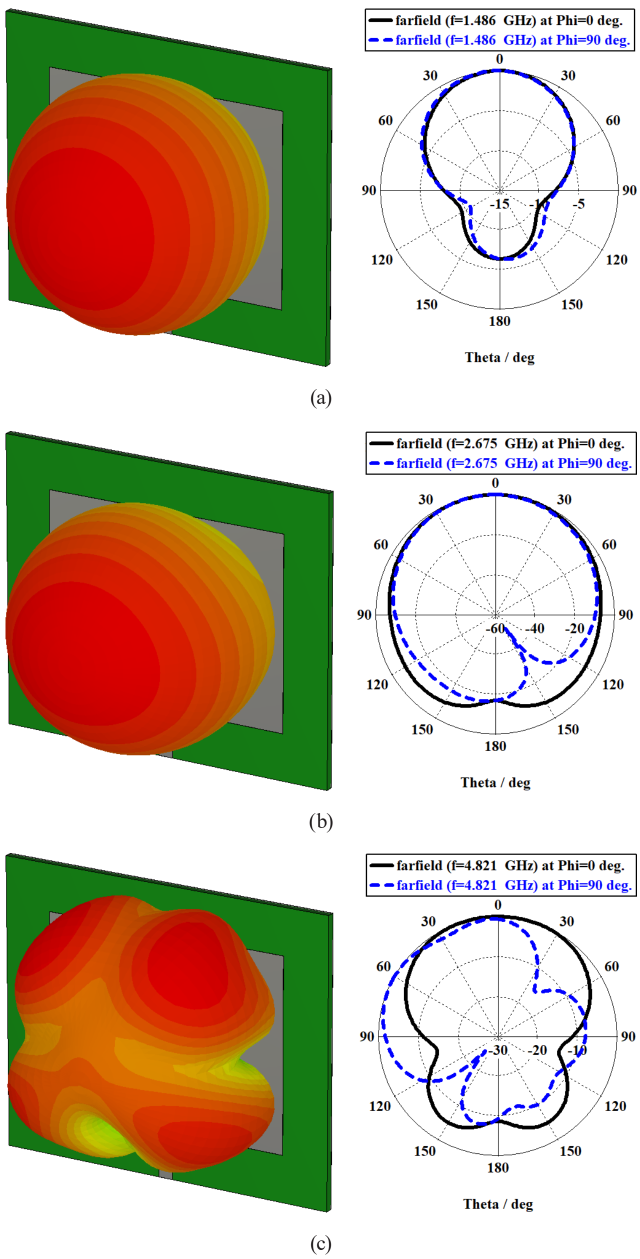


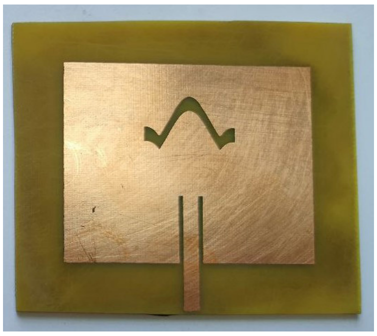
Fig. 9 Simulated radiation pattern of Antenna3 at different frequencies; (a) 1.48 GHz; (b) 2.67 GHz; (c) 4.82 GHz

RF source and spectrum analyzer were employed to measure the radiation pattern experimentally in the lab where an absorbing material is utilized to mimic anechoic environment by eliminating the reflections during the measurement process.

It can be clearly seen from Fig. 12 that the fabricated antennas show a multiband operation and resonate at various frequencies within the sub-6 GHz band around 1.5 GHz, 2.8 GHz, 5 GHz and 5.8 GHz. For achieving more precise measured results, two identical versions of each selected antenna of the three antenna were manufactured for the purpose of radiation pattern measurements. It is well known that the measurement losses increase at higher frequency. In addition, Antenna3 have more curves and bends than other fabricated antennas which make it more difficult to achieve high fabrication accuracy. Thus, we believe that the difference between the simulation and measurement results for Antenna3 at high frequencies is due to the fabrication inaccuracy caused by geometrical complexities for this antenna.

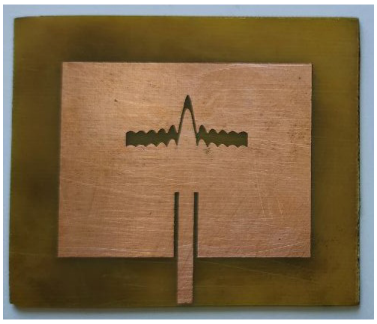
Table 1 Simulation results of selected antennas

Antenna	Frequency (GHz)	S11 (dB)	Directivity
Antenna1	1.6455	−16.49	5.62
	2.6895	−20.65	4.3
	5.0095	−39.89	6.75
	5.778	−33.56	8.66
Antenna2	1.515	−29.91	5.16
	2.588	−10.75	5.93
	5.0095	−29.57	6.68
	5.778	−37.29	8.66
Antenna3	1.486	−36.63	5.07
	2.675	−15.13	5.9
	4.821	−12.62	5.19
	5.14	−12.92	9.42



(a)

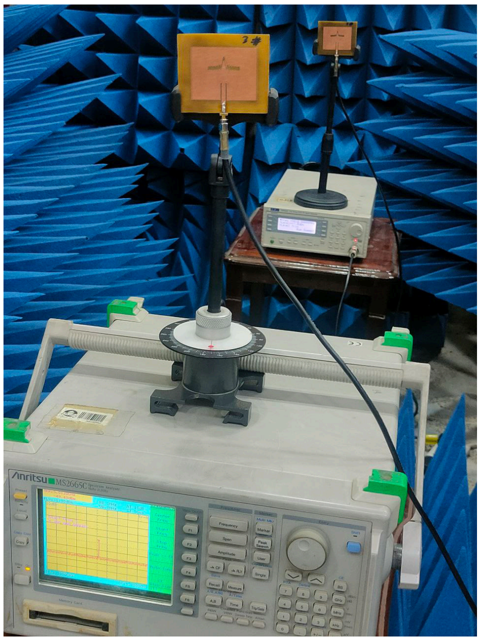
(b)



(c)

Fig. 10 Photograph of the fabricated antennas; (a) Antenna1, (b) Antenna2; (c) Antenna3

(a)



(b)

Fig. 11 Photograph of the experimental set up; (a) Antenna under test; (b) Testing environment

5 Conclusion

In this paper, sinc function was employed as a slot in the patch antennas to control the antenna performance. The designed rectangular patch antennas with inset feeding were incorporated a sinc-shaped slot at the middle of the rectangular patch. The effect of sinc function parameters such as *Amp.*, *m*, slot width, slot location and slot window *x* on the antenna performance was investigated.

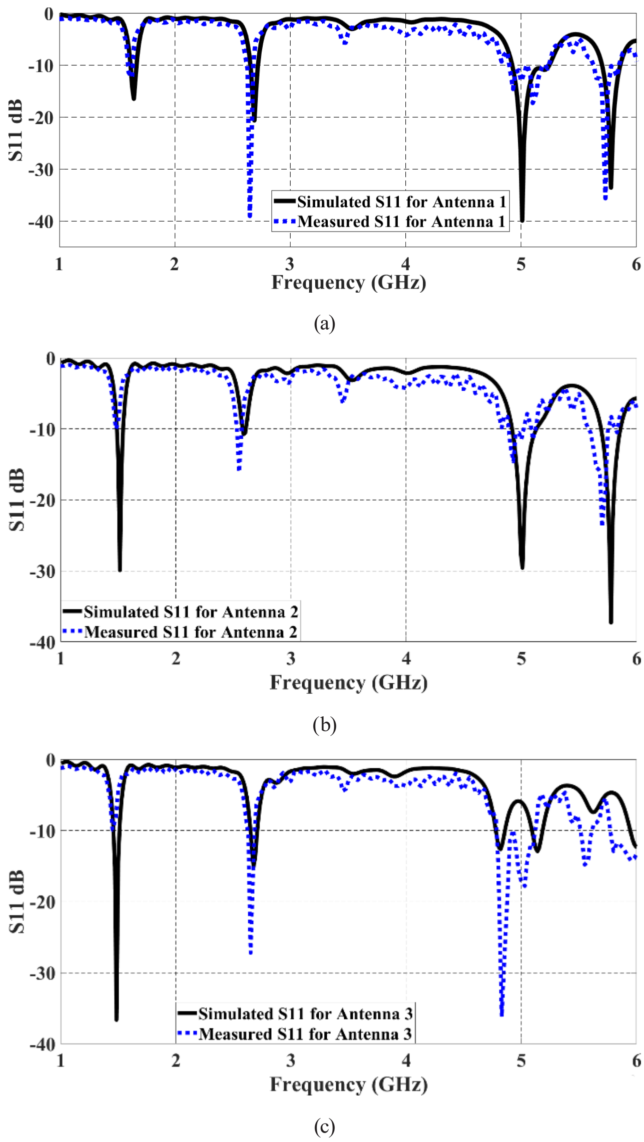


Fig. 12 Measured and simulated S11 for the designed sinc slotted antennas; (a) Antenna1; (b) Antenna2; (c) Antenna3

The designed patch antennas with sinc-shaped slots were simulated by using CST Studio Suite. The S_{11} parameters as well as the 2D and 3D radiation pattern were recorded. The results proved the direct and significant effect of the sinc slots parameters on the operating frequency of the designed antennas and number of bands. We concluded that the resonant frequency of the antenna can be smoothly controlled and adjusted by utilizing positive or negative sinc function. Extensive simulation process were performed (1890 cases) to find out the optimum antenna performance and three antennas were selected based on the number of operating frequency bands and reflection characteristics. The selected antenna were fabricated using PCB technology on FR-4 substrate. The performance of the manufactured antennas were tested in the lab in an anechoic environment. There was an excellent agreement between the measured and simulated results achieved. It is conclude in this paper that the suggested approach of employing sinc function as a slot in rectangular patch antennas provides the designer a great opportunity to control the antenna performance and tune its resonant frequency upon demand by varying the sinc function parameters.

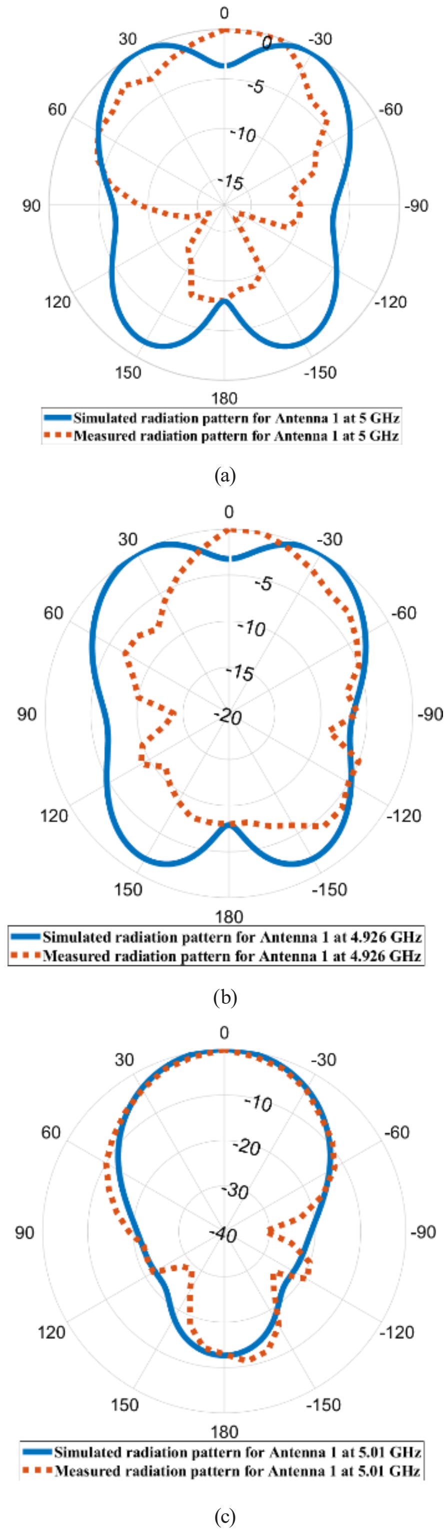


Fig. 13 Measured and simulated radiation pattern for the designed sinc slotted antennas; (a) Antenna1; (b) Antenna2; (c) Antenna3

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