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A Series-Fed Conformal Antenna at 60 GHz for 6G and Beyond Applications

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***Abstract*—This work deals with the design and development of a conformal series-fed antenna structure operating at the 60 GHz frequency. The proposed antenna operates from 57 GHz to 62 GHz with good return loss and radiation characteristics for 6G and beyond applications. The antenna is shown to give a good gain of more than 14.7 dBi with directional radiation beam in the hemispherical boresight direction. The fabricated prototype is verified with the simulated result, and it is found to be a good matching. The step-by-step antenna design process, parametric variation, and a detailed study are also reported. For a case study, this series-fed antenna conformal configuration is also embedded on a cylindrical structure. From this study, similar resonant and radiation performance characteristics are observed. Since the structure is compact, conformal, and gives better performance, it can be suitable for applications such as 6G, radar, guided missiles, body-centric medical imaging, etc.**

***Index Terms*—6G; Boresight direction; Conformal antenna; Cylindrical body; Hemispherical; Series-fed antenna.**

I. INTRODUCTION

The demanding requirements of the present advanced communications in terms of speed, reliability, latency, data traffic, and spectral efficiencies have led to the rapid exponential growth of wireless devices. As the current available radio spectrum bands are not sufficient to meet these projected requirements, the Federal Communications Commission (FCC) defines new spectrum bands. Especially, mm wave spectrum has attracted the attention of wireless engineers to explore the new horizons of wireless communications. However, the high-frequency bands suffer from atmospheric attenuation like rain drop attenuation, etc. There are some bands like 40 GHz to 50 GHz and 70 GHz to 80 GHz that undergo minimum atmospheric attenuation and hence are attractive for mm wave applications [1]. The identified frequency bands for high-speed indoor and outdoor communications are 28 GHz, 38 GHz, 60 GHz, and 73 GHz [2]–[4]. In these bands, the 60 GHz band is commonly used for high-speed wireless communication, including WiFi (802.11ad) and some 6G implementations. In addition, this band is highly preferred compared to the ultra high frequency (UHF) band as it involves smaller antennas, with high beam direction capabilities, high transmission rates with minimum interference [5].

In the literature, various antennas operating at 60 GHz band are presented that meet the requirements of current wireless communications. In [6], the design of a wideband reflective surface antenna with a high gain of 16.4 dBi is presented. In [7], the design of a 60 GHz antenna based on open end fringing fields is designed and developed. The developed antenna gives a peak boresight gain of 11.5 dBi with a 2.5 GHz bandwidth. Today, 3D printing technology plays a pivotal role in the design and development of novel antenna models, and one such antenna at 60 GHz frequency is presented in [8]. Another significant application of 60 GHz antennas is in textile antenna models for body-centric communications [9]. These antennas can be conveniently placed on printed circuit boards (PCBs) that are low cost and easy to implement, as described in [10]. Another high-gain broadband mm wave antenna resonating from 53.9 GHz to 63.5 GHz is presented by Khaled, Fathallah, Ashraf, Vettikalladi, and Alshebeili in [11]. A novel 60 GHz switched beam broadband antenna fed by a horn antenna is presented by Jang, Kim, and Park in [12]. A comprehensive review on mm wave antennas operating at different bands with different specifications is given in [13]–[15].

Conformal antennas have recently attracted the attention of antenna researchers. Various antennas are conformed to the surface of the desired structure [16]. In mobile, automotive, medical, and radar applications, these conformal antennas play a significant role in meeting the requirements [17]. The design of a phase-compensated microwave conformal antenna for spherical mounts is presented in [18]. The developed 4×4 array operates at 2.4 GHz, giving good resonant and radiation characteristics. A 2D monopulse antenna with dual band characteristics for conical conformal applications is presented in [19]. The antenna operates from

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8.96 GHz to 11.2 GHz with gain in the range of 9 dBi to 11 dBi. Another dual band conformal antenna operating at 1.189 GHz and 1.575 GHz was developed by Yinusa in [20]. This antenna works effectively for small cylindrical applications. Semkin *et al.* [21] have developed an mm wave beam switching microwave antenna array consisting of 16 elements. This antenna is mounted on a cylindrical surface, giving effective radiation characteristics. Similarly, the design principles of microstrip arrays for sub-6 GHz applications, specially aimed at WiFi-5/6 routers, are presented in [22]. Dielectric resonator antennas (DRA) are one of the best choices for mm wave antenna design as they give better efficiency, and one of such antennas with an operating band from 54.152 GHz to 63.252 GHz is presented in [23]. Similarly, a semicircular ground plane 5G antenna is presented in [24].

The novelty of the proposed work is summarised as follows.

– Design of a simple series-fed microstrip antenna using well-known design equations resonating at 60 GHz frequency with a wideband from 57 GHz to 62 GHz enabling the antenna suitable for 6G and beyond applications.

– Embedding the proposed antenna on a conformal and cylindrical structure and studying the resonant and radiation characteristics in the desired operating band of frequencies and verifying the results practically.

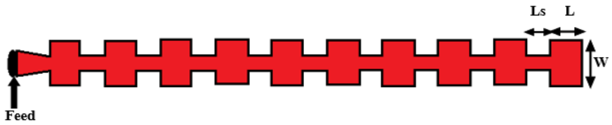
– The proposed antenna is compact in nature compared to many existing antennas as mentioned in the comparison table presented in Section III. Therefore, it can be used for 6G, radar, guided missiles, body-centric medical imaging, etc. The design and study of the proposed antenna are performed in the electromagnetic (EM) simulation tool high frequency structure simulation (HFSS).

The organisation of this paper is as follows. Section II reports on the design study of a proposed planar series-fed antenna structure. Section III focusses on the conformality of the proposed antenna and its placement on a cylindrical body. Section IV concludes the work.

II. ANTENNA DESIGN

A. Proposed Structure

As per the IEEE 802.15.3c standards, for standard line of sight communications using the 60 GHz band, it is divided into four channels and the minimum requirement of bandwidth for any channel is 2.16 GHz. Hence, in the present work, the aim is to design antenna that resonates at 60 GHz with good bandwidth characteristics. Also, the antenna is required to give a stable radiation pattern with good directional properties in boresight direction. Based on these requirements, the antenna resonating at 60 GHz is designed and developed as shown in Fig. 1(a). The values of W, L, and Ls are noted to be 2 mm, 1.75 mm, and 1.5 mm, respectively. This antenna is printed on a Rogers RT substrate with a dielectric constant value of 2.2 having a thickness of 0.8 mm. The overall dimensions of the antenna structure are 7 mm × 35 mm. The prototype fabricated of the final designed antenna is shown in Fig. 1(b).



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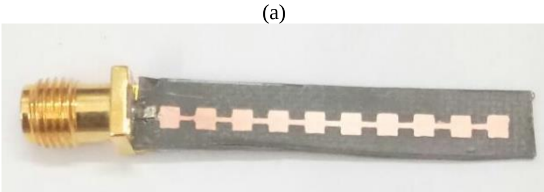


(b)

Fig. 1. Proposed 60 GHz antenna: (a) Schematic View; (b) Fabricated prototype.

B. Design Evolution

In the antenna design process, initially a simple patch with dimensions W×L mm^2(2×1.75 mm^2) is considered as shown in Fig. 2(a), where the dimensions are obtained using the basic rectangular microstrip patch equations given in (1) and (2), respectively:

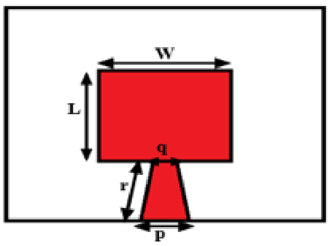
$$W = \frac{c_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}}, \tag{1}$$

$$L = \frac{c_0}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L, \tag{2}$$

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2}, \tag{3}$$

where ε_{reff} is the effective relative dielectric constant, h is the height of the substrate, ΔL is the increase in patch length due to fringing fields, and L is the actual length of the patch. A tapered feed structure is used to feed the antenna to obtain the desired resonant characteristics and impedance matching over a broad range. The feed line has a length of r = 1.65 mm and width is varying from q = 0.25 mm to p = 0.375 mm as shown in Fig. 2(a). In this case, the resonant frequency is obtained at 58.75 GHz with bandwidth from 55.6 GHz to 61.6 GHz as shown in Fig. 3. Parametric analysis is carried with respect to the antenna's dimensions viz; patch length (L) and patch width (W) as portrayed in Fig. 4. From the values obtained in this curve, it is clear that better resonant values with good reflection coefficient values are obtained for L = 1.75 mm and W = 2 mm.

To get the desired target frequency, the rectangular shaped patch is series-fed with two more rectangular shaped patches as shown in Fig. 2(b). This structure gives resonant frequency near to 59.75 GHz with bandwidth from 57.6 GHz to 61.6 GHz as shown in Fig. 3.



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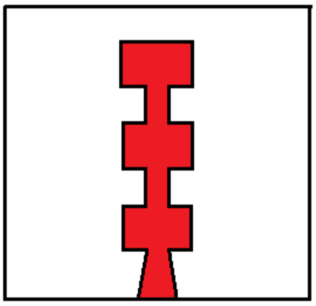

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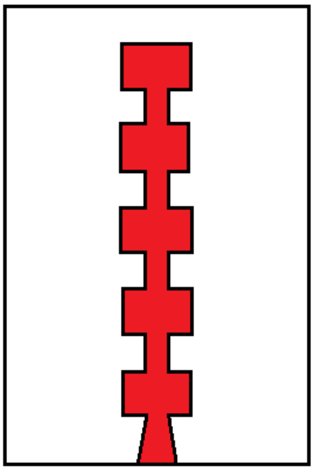


(c)

Fig. 2. Evolution of the antenna: (a) Design 1; (b) Design 2; (c) Design 3.

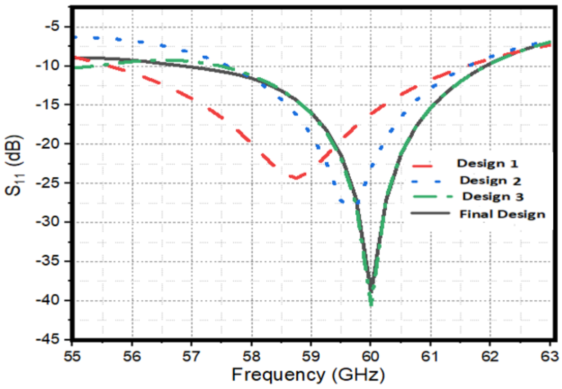
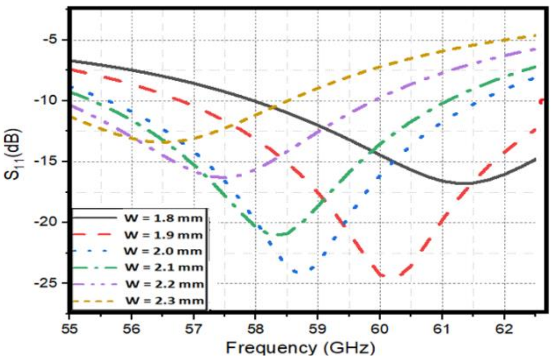
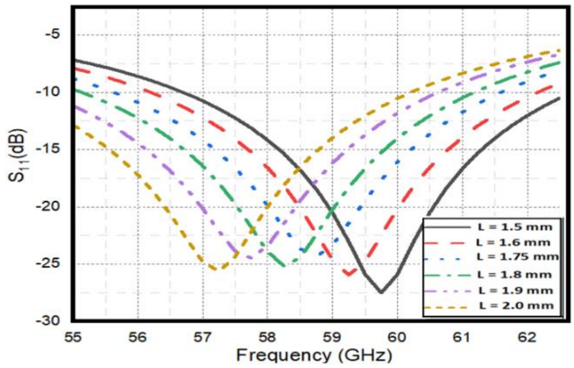


Fig. 3. Comparison of the S-parameters with various initial designs.

As the obtained resonant characteristics are still not satisfactory, the design is further modified as shown in Fig. 2(c). For this case, the desired resonance at 60 GHz is obtained with a bandwidth of 57.5 GHz to 61.9 GHz. This structure is further modified to the final proposed antenna as shown in Fig. 1(a) so that 60 GHz resonance is obtained with increased bandwidth from 57 GHz to 62 GHz.



(a)



(b)

Fig. 4. Parametric analysis with respect to patch length (L) and width (W) for Design 1.

The simulated and measured S_{11}-parameters of the proposed antenna are given in Fig. 5, from which it is observed that the proposed antenna resonates at 60 GHz, meeting the current wireless applications at the mm wave band.

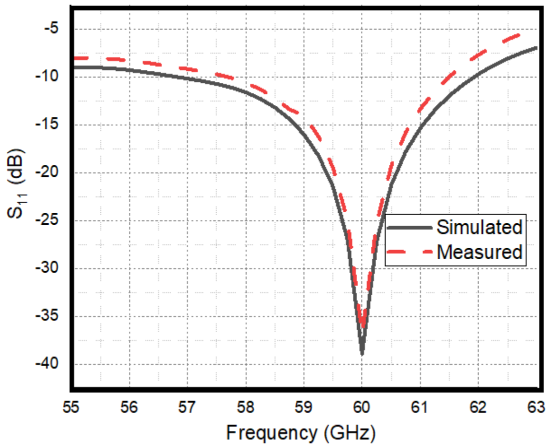
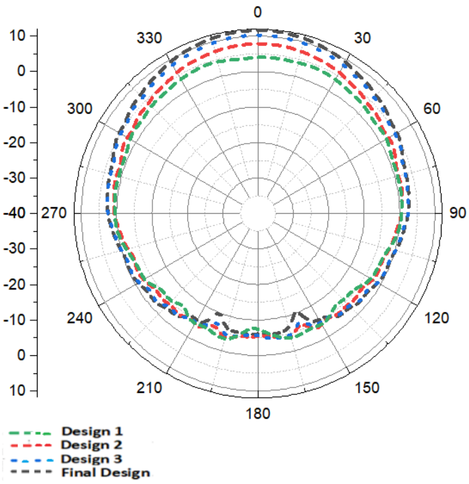


Fig. 5. S_{11}-parameters of the proposed antenna.

As discussed earlier, the important requirement of 60 GHz antennas is to get stable and directional properties in the boresight direction. Therefore, the radiation patterns of each antenna designed at different stages are presented at 60 GHz on the XZ and YZ planes as given in Fig. 6. From the radiation patterns portrayed, it is observed that good directional properties with high boresight gain are obtained for the final considered structure on both the XZ and YZ planes compared to the designs 1, 2, and 3.



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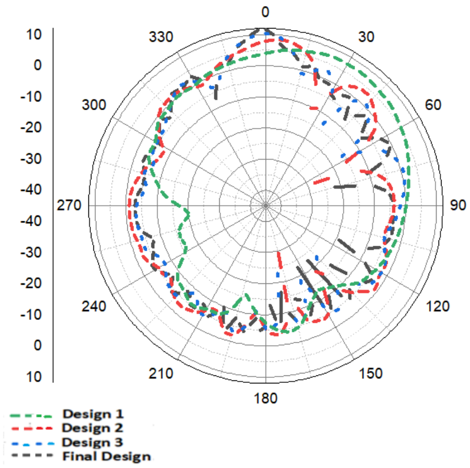
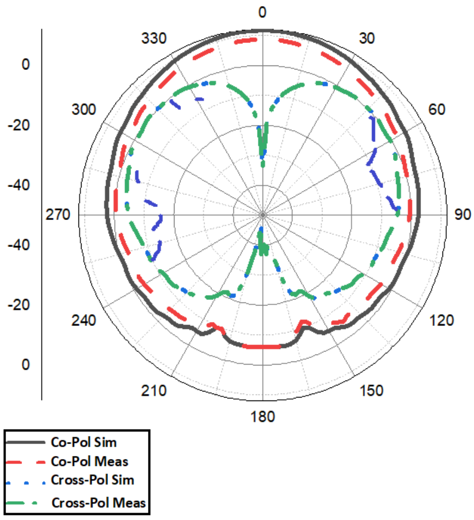


(b)

Fig. 6. Radiation patterns of various designs at 60GHz on: (a) XZ plane; (b) YZ plane.

The simulated and measured radiation patterns of the final planar antenna on the E and H planes are given in Figs. 7(a) and 7(b). From the obtained radiation patterns, it is concluded that the pattern on E plane is mainly towards the broadside direction in the upper hemisphere, which is required for many wireless applications. Similarly, on H plane, the pattern is orientated towards boresight direction. The antenna radiation pattern measurement setup in the anechoic chamber is shown in Fig. 7(c).



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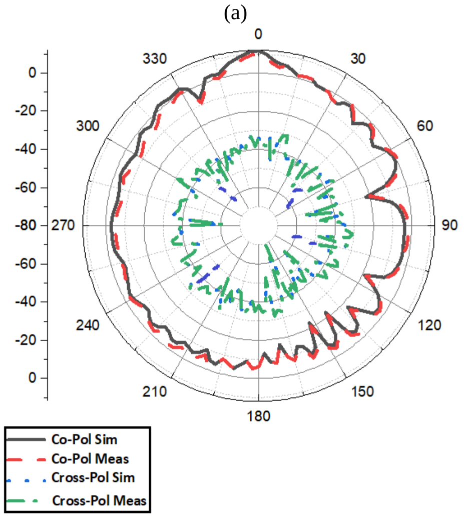

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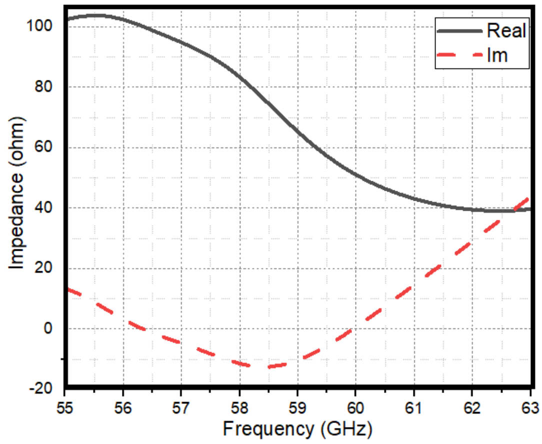

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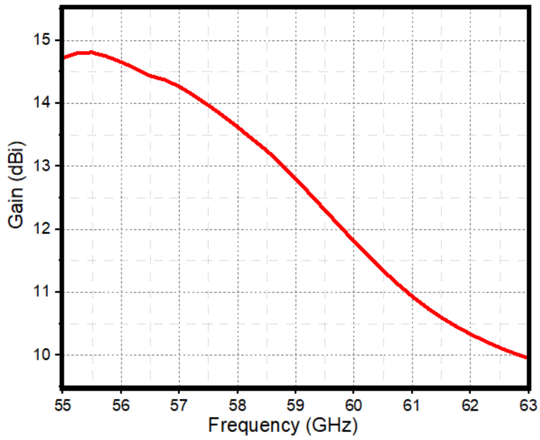

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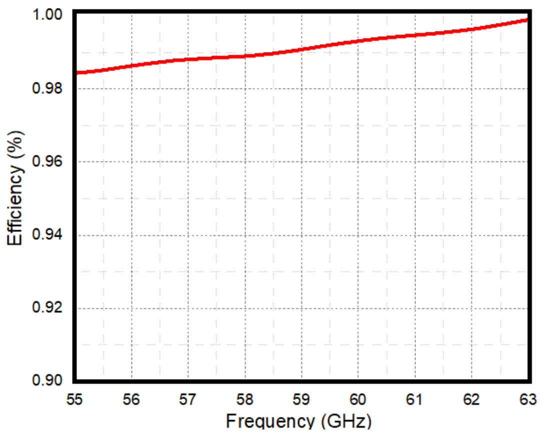
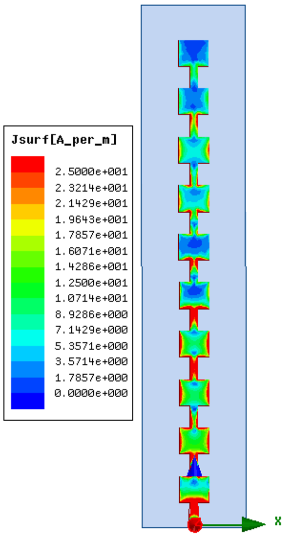


(f)

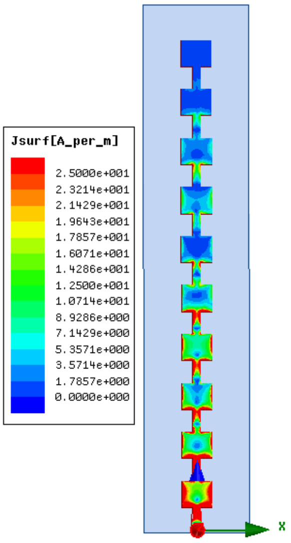
Fig. 7. Radiation patterns on: (a) E-plane; (b) H-plane; (c) Measurement setup at 60 GHz; (d) Impedance characteristics: (e) Peak gain plot; (f) Radiation efficiency plot.

Furthermore, the impedance characteristics of the proposed antenna are given in Fig. 7(d). The peak gain plot is presented in Fig. 7(e), from which it is observed that a maximum gain of 14.7 dBi is obtained near 55.5 GHz. Similarly, the efficiency plot is obtained and is portrayed in Fig. 7(f), where the efficiency is more than 98 % in the entire operating band.

The surface current distribution of the final proposed antenna at various frequencies is shown in Fig. 8, where it is observed that a considerable amount of surface current is distributed near the feed structure and the current gradually reduces towards the end of the structure.



(a)



(b)

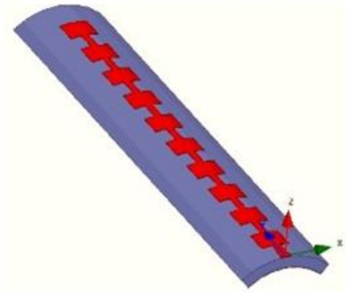
Fig. 8. Surface current distribution at: (a) 55 GHz; (b) 62.5 GHz.

III. CONFORMAL SERIES-FED ANTENNA STRUCTURE

The earlier section presented the design and development of a novel series-fed antenna structure resonating at 60 GHz. However, the main objective of the proposed work is to analyse the performance of the antenna on conformal structures and verifying its compatibility on bent-like surfaces. There are numerous applications where conformal antennas can be used in a real-time scenario. The applications include aircrafts, missiles, radar, vehicle tracking, etc. This section presents a discussion of the proposed conformal antenna structure and its performance observation on a bent structure and a cylindrical body.

In various wireless applications like guided missiles, radar, aircraft, satellites, etc., the antennas suitable for insertion into conformal structures are desired. Therefore, the performance of the antenna is verified with the conformal structure as shown in Fig. 9(a). The resulting S_{11}-parameters of the proposed conformal antenna are given in Fig. 9(b), from which it is observed that the antenna resonates exactly at 60 GHz with huge impedance bandwidth from 52 GHz to 62.25 GHz. The 2D radiation patterns of the proposed conformal antenna are given in Fig. 9(c), from which it is observed that the antenna exhibits good broadside radiation characteristics on the XZ plane and directional characteristics on the YZ plane. From Fig. 9(c), it is noted that a peak gain of more than 10 dBi is obtained at 60 GHz.

In the present case, a cylindrical glass structure of radius 4.25 mm and length 37.5 mm is considered and on which the proposed series-fed microstrip antenna is attached as shown in Fig. 10.



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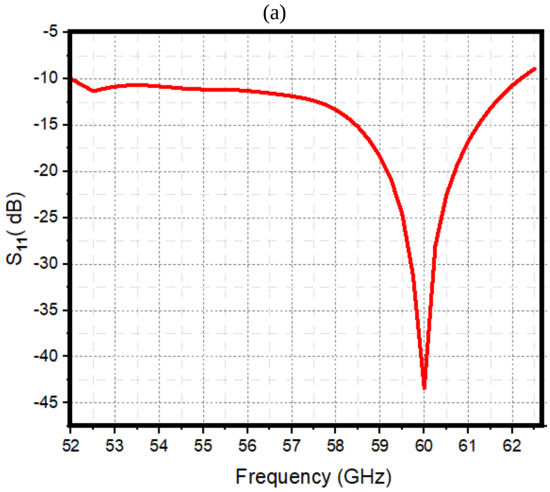

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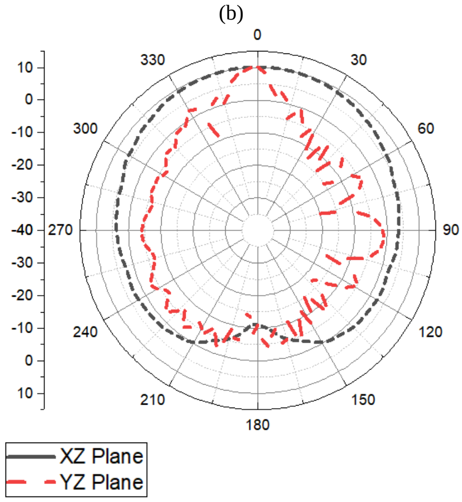
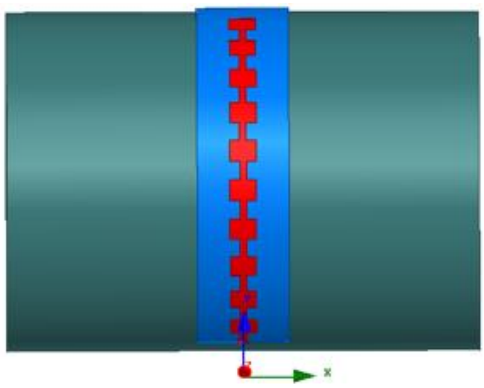
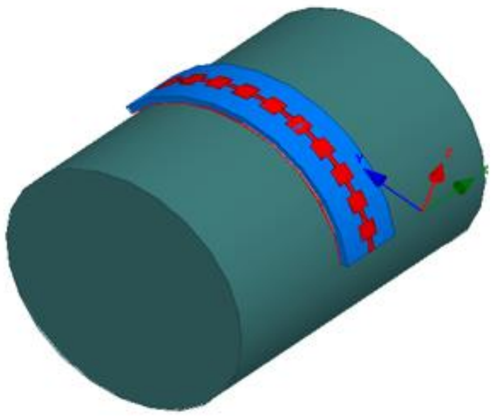


(c)

Fig. 9. (a) Proposed conformal antenna: (b) S_{11}-parameter; (c) 2D pattern at 60 GHz.



(a)



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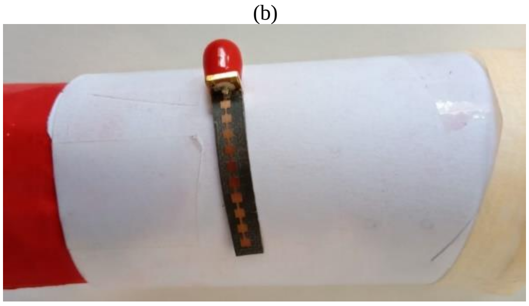


(c)

Fig. 10. Conformal antenna in 60 GHz simulation set-up: (a) Front view; (b) Side view; (c) Fabricated conformal antenna.

The antenna's S-parameters are given in Fig. 11(a), from which it is observed that the proposed centipede antenna on the cylindrical glass drum resonates at 59.5 GHz. The measured results are found to be almost matched with the simulated results. This means that when the antenna is employed on a planar structure, a 60 GHz resonance is obtained, whereas when the antenna is mounted on a conformal structure, the resonance frequency is slightly reduced, making the antenna to resonate at 59.5 GHz. The radiation patterns on the XZ and YZ planes of the proposed centipede-shaped microstrip antenna when employed on the cylindrical drum are shown in Fig. 12.

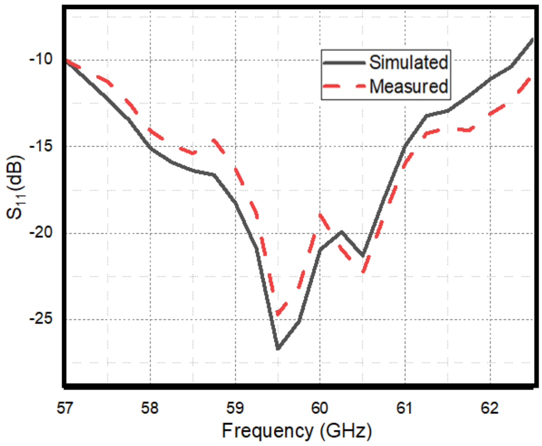
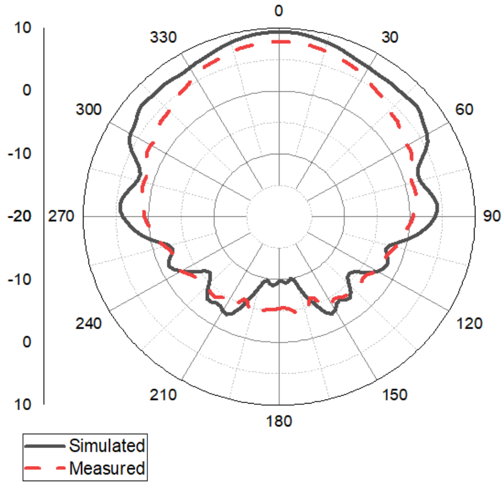
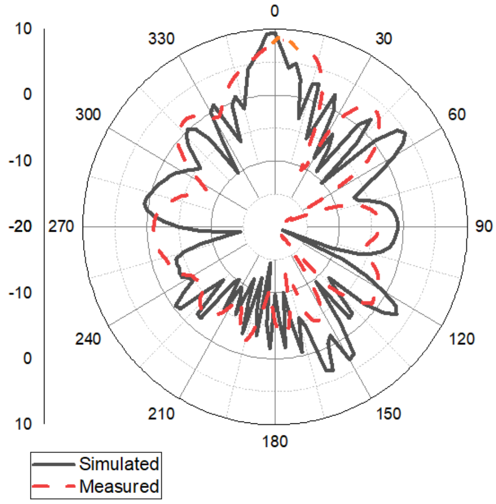


Fig. 11. S-parameters of the conformal antenna mounted on a cylindrical structure.

From the portrayed radiation patterns, it is observed that the proposed conformal antenna exhibits almost similar radiation patterns as when employed on the planar structure. It is found that the pattern on the XZ plane is nearly omnidirectional in the upper hemisphere and on the YZ plane; the radiation pattern is directional with good boresight direction characteristics. However, a slight disturbance is observed in the radiation patterns.



(a)



(b)

Fig. 12. Measured and simulated antenna radiation pattern on cylindrical drum on: (a) XZ plane; (b) YZ plane.

The proposed work is compared with some similar works in the literature (Table I). The antenna proposed in [6] uses the concept of the Febry-Perot cavity resonating at 60 GHz with 5.6 GHz bandwidth and the antenna size is 25×25 mm^2. The antenna mentioned in [7], operating at 60 GHz, gives a bandwidth of 2.5 GHz and the antenna is 35×25 mm^2. This antenna uses the concept of an open end microstrip to give characteristics of boresight gain. The antenna mentioned in [8] is a printed lens antenna that resonates at 60 GHz with a pattern beam offset at 15 ^{0}. However, this antenna gives a gain of 4 dBi. The antenna developed in [9], is suitable for conformal textile applications with a gain of 7 dBi. However, the size of this antenna is 100×100 mm^2. The double-layered antenna discussed in [11] gives bandwidth from 53.9 GHz to 66.3 GHz and the antenna size is 30×30 mm^2. The antenna discussed in [12] resonates at 60 GHz with a bandwidth of 6.5 GHz and the antenna size is 13×20 mm^2. From the table, it is observed that the antenna is compact giving gain more than 14.7 dBi at 55.5 GHz with a compact size of 7×35 mm^2. Additionally, the performance of the antenna is verified in the conformal structure, making it suitable for real-time applications such as aircrafts, missiles, etc.

TABLE I. COMPARISON WITH EXISTING SIMILAR WORKS.

Ref.	Type of Antenna	Operating frequency	Impedance Bandwidth	Gain	Type of radiation pattern	Size
[6]	Reflecting surface with Fabry-Perot cavity	60 GHz	5.6 GHz	16 dBi	Directional with narrow beamwidth	25×25 mm^2
[7]	Open end microstrip	60 GHz	2.5 GHz	11.5 dBi	Directional towards boresight	35×25 mm^2
[8]	Printed plastic lens	60 GHz	--	4 dBi	Beam offset to 15 ^{0}	15×15 mm^2
[9]	Textile conformal antenna	60 GHz	57 GHz to 64 GHz	7 dBi	Directional towards boresight	100×100 mm^2
[11]	Double-layered microstrip antenna	60 GHz	53.9 GHz to 66.3 GHz	11.8 dBi	Directional	30×30 mm^2
[12]	Textile conformal antenna	60 GHz	6.5 GHz	13.4 dBi	Directional towards boresight	13×20 mm^2
Proposed work	Series-fed microstrip antenna	60 GHz	57 GHz to 62 GHz	14.7 dBi	Hemispherical on the XZ plane and directional on YZ plane	7×35 mm^2

IV. CONCLUSIONS

In the present work, the design and development of a novel series-fed patch antenna resonating at 60 GHz is presented. This antenna gives good impedance bandwidth from below 57 GHz to 62 GHz with stable radiation characteristics in the hemispherical boresight direction. As a case study, the performance of this antenna conformal geometry is verified on a cylindrical glass surface of radius 4.25 mm and length 37.5 mm. The developed conformal antenna is also shown to give good resonant properties at 60 GHz with good boresight radiation characteristics, thus enabling the antenna to be suitable for applications like radar, aircraft, etc. at mm wave frequencies.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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