# A Broadband H-plane Printed Horn Antenna with Sandwich Substrate Structure for Millimeter-wave Applications

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***Abstract*** **─** Antenna is a very important element and plays a key role in communication systems for radiating energy. Based on high data rate speed requirements and large volume multimedia applications, 3G, 4G and now 5G technologies have been introduced and implemented. This paper presents a low profile antenna with novel structure and large continuous bandwidth for 5G broadband and millimeter-wave wireless applications. It is an H-plane printed horn antenna with multi-layered sandwich substrate. There are two Rogers (RO3003(tm)) substrates that make a sandwich structure with eight stainless steel columns. The proposed antenna is expected to give an impedance bandwidth 20-45 GHz with S11 < -10dB and 8.64dBi gain at 28 GHz design frequency. ANSYS 18.2 HFSS simulator is used for designing and optimization of the profile antenna. A comparison between simulated and measured results confirms the validity of the proposed design.

***Index Terms*** **─** Millimeter wave antenna, 5G (fifth generation), wireless applications.

## I. INTRODUCTION

Fifth generation technology is a hot topic for researchers these days due to the current and upcoming multimedia high speed and large data volume challenges. Substrate integrated horn antenna is a low profile and compact millimeter wave antenna with ease of integration [1]. Horn antennas are directional with wider bandwidth feature that make them feasible for high gain broadband applications. This property makes the horn shape more attractive choice for researchers to design a substrate integrated horn shape patch antennas for high bandwidth packages which is a need of the hour for 5G applications. In substrate integrated horn patch antennas, bandwidth is improved by using different impedance transformers if mismatching occurs at the edges of dielectric slab [2],[3].

With the recent developments in communication systems, all wireless applications like multimedia or cellular applications, IOT (internet of things), ITS and other broadcast applications need high data rate large volume speed that is not fully supported by 4G technology [4].

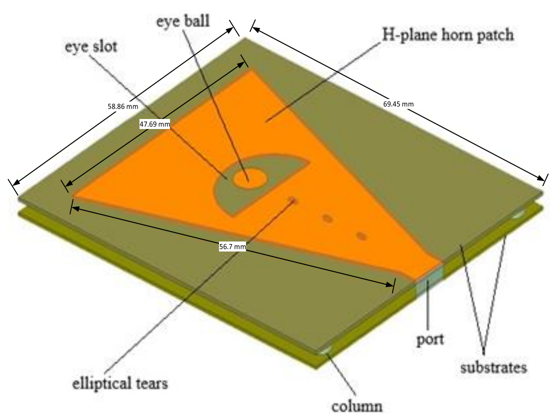


Fig. 1. Multilayer novel structure millimeter wave antenna.

So, ITU (International Telecommunication Union) issued new licensed high frequency bands in millimeter wave range for 5G and beyond applications [5]. Improvement of impedance bandwidth has been a hot topic for researchers in low profile micro strip antennas for high data rate 5G applications. There are various techniques that have been introduced to improve impedance bandwidths in past years including substrate integrated patches [1], slotted patches [6], [7] stacked patches [8], [9], [10] multilayers strip lines [11] and aperture coupled feed techniques [12], [13]. Multilayers technique has been used in most of these mentioned papers to improve bandwidths from 10.9% to 29% maximum.

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To overcome the multilayers alignment and high cost issues, a single-layered wideband planar antenna substrate based topology has also been presented in [14], [15], [16] to get improved bandwidth 12.4% to 25.5% maximum. For long range communication systems, a narrow beam antenna radiation pattern is required to get high gain while for short range communication systems; a wide beam pattern is useful for wide coverage [17]. For substrate integrated horn antennas, gain was enhanced using different correction structures like metal via arrays [18], SIW gap technology [19] and horn walls [20]. But these designs could give impedance bandwidth less than 20%. By adding electric and magnetic currents radiations, a stable and uniform radiation pattern [21] and end fire radiations [22], [23] are achieved.

The detailed literature review of the above mentioned papers traces a hypothesis to get wideband and high gain features. So, a broadband, low cost, low profile and a compact antenna is designed for wireless 5G applications. It is observed from literature review that the multi-layered and substrate integrated waveguide (SIW) structures are used for broadband and gain enhancement features respectively. So, in the proposed antenna design, a multi-layered topology is used with a sandwich structure. Instead of using a SIW structure, a sandwich structure is proposed. Two RO3003(tm) dielectric substrates make a sandwich structure with stainless steel columns without any holes as shown in Fig. 1. Furthermore, a sectoral H-plane slotted horn patch is printed on the top surface of the upper substrate to get a stable high gain radiation pattern with wide band feature. In comparison with the previous H-plane sectoral SIW horn antennas [1], [2] and [3], the proposed antenna gives better impedance bandwidth and gain.

In the first step, a broadband, high gain WR28 horn antenna is simulated for inspiration. In the 2nd step, an H-plane sectoral horn antenna is simulated on a single RO3003(tm) substrate. In the 3rd step, the proposed multi-layered sectoral H-plane slotted horn antenna is designed to get wide band high gain features. All antennas are optimized and simulated in ANSYS18.2 HFSS simulator. The proposed antenna is fabricated for measuring results.

The paper is organized as follows. Design of the proposed antenna and EM analysis is presented is Section II. Simulated and experimental results lie in Section III. The final summary is in Section IV.

## II. ANTENNA DESIGN AND EM ANALYSIS

### A. Antenna design

To design a millimeter wave antenna that can support wideband 5G wireless applications, the hypothesis through a detailed literature review creates a topology for an H-plane sectoral printed horn antenna with multi-layered sandwich substrate structure. Furthermore, the sandwich substrate structure with the air gap between two dielectric substrates affects the permittivity and height of substrate and increases the resonance frequency and operational bandwidth [24]-[28]. In [29], a millimeter wave SIW antenna is designed at 28 GHz for indoor applications. It has 11.6 dB gain and impedance bandwidth 24.5 to 29.5 GHz. Out of all these mentioned papers, the proposed antenna gives the large and wide bandwidth with high gain in E- and H-planes both.

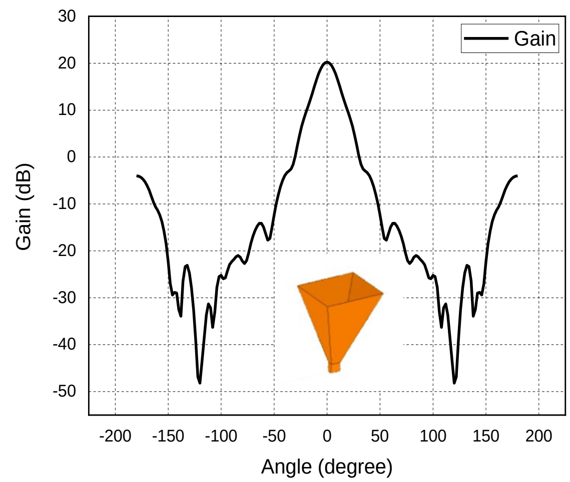



Fig. 2. Simulated full wave WR28 horn antenna gain.

In the first step, a WR28 horn antenna is simulated with the parameters and dimensions using design equations (1-6) [30]. Antenna parameters are calculated with reference to 20dBi high gain. The wide bandwidth and high gain characteristic of the full wave horn antenna gives a clear inspiration and hypothesis along with multi-layered topology from SIW H-plane sectoral horn antennas to design a multilayered sectoral H-plane printed horn antenna for wireless millimeter applications. It is observed from Fig. 2 that the full wave WR28 exhibits 20.23dBi gain at 28 GHz:

$$\left(\sqrt{2x}-\frac{b}{\lambda}\right)^2(2x-1)=\left(\frac{G_0}{2\pi}\sqrt{\frac{3}{2\pi}}\frac{1}{\sqrt{x}}-\frac{ba}{\lambda}\right)^2\left(\frac{G_0}{6\pi^3}\frac{1}{x}-1\right), \quad (1)$$

$$\frac{\rho_e}{\lambda}=x, \quad (2)$$

$$\frac{\rho_h}{\lambda}=\frac{G_0^2}{8\pi^3}\left(\frac{1}{x}\right), \quad (3)$$

$$x_{trial}=x_1=\frac{G_0}{2\pi\sqrt{2\pi}}, \quad (4)$$

$$a_1=\sqrt{3\lambda\rho_2}\cong\sqrt{3\lambda\rho_h}=\frac{G_0}{2\pi}\sqrt{\frac{2\lambda}{2\pi x}}, \quad (5)$$

$$b_1=\sqrt{3\lambda\rho_1}\cong\sqrt{2\lambda\rho_e}=\sqrt{2x\lambda}. \quad (6)$$

Where $G_0$ is the required gain, $\lambda$ is a wavelength, $a$ & $b$ are dimensions of wave guide, $a_1$ & $b_1$ are dimensions of the horn aperture and $\rho_e$ & $\rho_h$ are the distances from wave guide to the horn. The WR28 horn antenna parameters are calculated from all these equations (1-6).

**B. EM analysis**

The WR28 horn antenna parameters are relevant to a high directional gain as mentioned in Table 1. So, in the 2nd step these parameters and dimensions are used to print a sectoral H-plane un-slotted horn patch on a dielectric substrate to design a single substrate H-plane sectoral horn antenna as shown in Fig. 3. It is clear from the Fig. 3 that the horn patch is actually the one face of the full wave horn antenna. Dimensions of the substrate and printed horn patch are same as in Fig. 1 and are mentioned in Table 1. So, the printed H-plane sectoral horn patch has dimensions of one face of the full horn antenna.

Table 1: Horn antenna dimensions

| Description | Value | Unit |
|---|---|---|
| **f** | 28 | GHz |
| **a** | 7.11 | mm |
| **b** | 3.55 | mm |
| $\boldsymbol{\rho_e}$ | 56.7 | mm |
| $\boldsymbol{\rho_h}$ | 56.7 | mm |
| $\boldsymbol{a_1}$ | 47.69 | mm |
| $\boldsymbol{b_1}$ | 37.43 | mm |
| **Substrate length** | 58.86 | mm |
| **Substrate width** | 69.45 | mm |
| **Substrate height (each)** | 0.5 | mm |
| **Length of eye-slot centered curve** | 20 | mm |
| **Radius of eye ball-patch** | 3 | mm |
| **Major radius of slotted elliptic tears** | 0.5 | mm |

It is observed from Figs. 4 and 5 that the antenna gain is 5.8dBi with impedance bandwidth 26.6-30.6 GHz. This antenna gain and impedance bandwidth is not good enough, so in the 3rd step, a multi-layered topology is further used along with this H-plane sectoral horn patch to enhance the gain and wide bandwidth.

To increase the operational bandwidth with resonance frequency and gain, the multi-layered and slotted substrate topology is used with printed H-plane sectoral horn. A multi-layered sandwich substrate with H-plane printed slotted horn patch antenna is proposed. Patch has a crying eye with slotted tears. The slotted tears and crying eye gives a further boost to the bandwidth while keeping radiation pattern stable that makes it unstoppable below 10dB. Horn patch is at the top substrate and ground patch is connected below the bottom substrate.

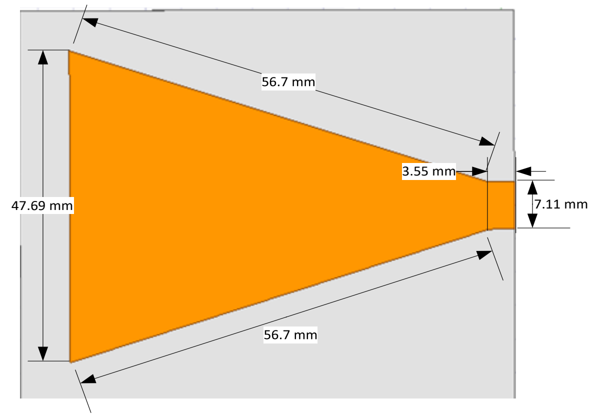



Fig. 3. Single substrate sectoral H-plane printed horn antenna.

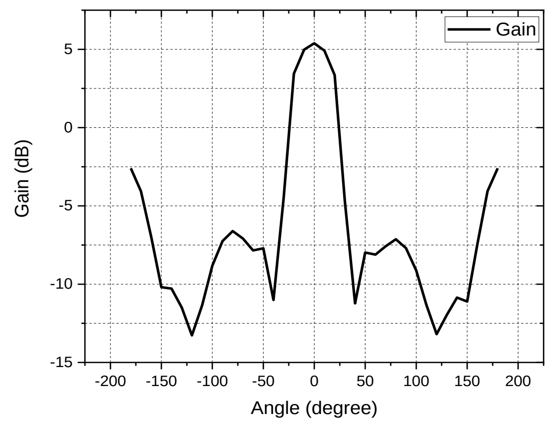



Fig. 4. Antenna gain of the single substrate H-plane sectoral horn antenna.

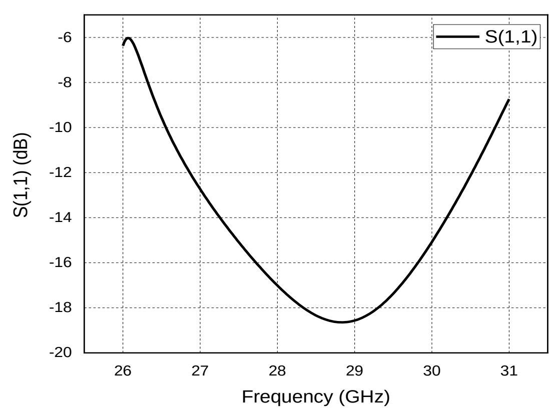
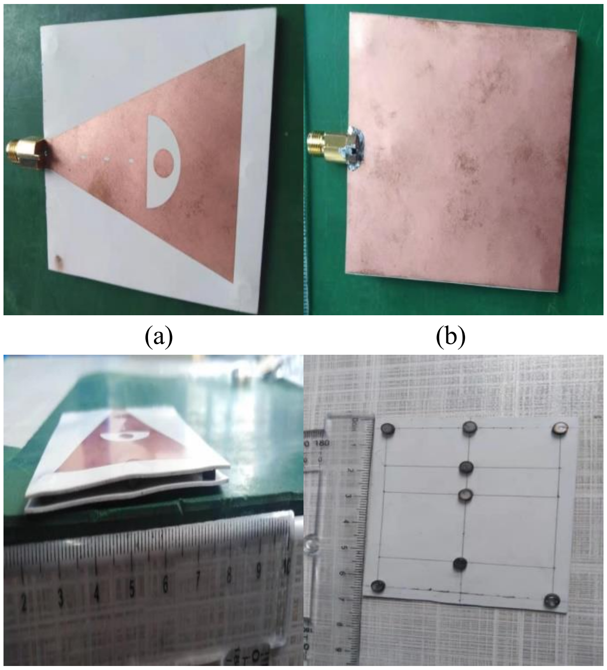



Fig. 5. Reflection coefficient of the single substrate H-plane sectoral horn antenna.



(a) (b)

(c) (d)

Fig. 6. Fabricated proposed antenna.

A 2.92 mm (K) female edge launch connector is used for excitation joining ground below the bottom substrate and patch on the top substrate Fig. 6. Both substrates make a sandwich with air gap of 1.5 mm and are supported by the stainless steel cylinders of the same dielectric constant as of air. Hence, the use of horn patch on a multi layered-substrate with cutting elliptic slots and an emotional eye collectively make a novel structure radiator. Both substrates have the same dimensions (58.86 mm × 69.45 mm). The stain less steel columns are fixed with a gum/bond at designated positions on the substrate as shown in Fig. 6 (d). It has 2 mm diameter and 1.5 mm height with dielectric constant 1. A high gain, narrow beam millimeter wave antenna with very large bandwidth is proposed for wireless 5G applications.

## III. SIMULATION AND EXPERIMENTAL RESULTS

The proposed antenna is a prototype as shown in Fig. 6. A single substrate sectoral H-plane horn antenna produces a directional gain and a bandwidth up to 4 GHz in millimeter wave range as shown in Figs. 4 and 5. The proposed antenna is further optimized with sandwich substrate structure and sectoral H-plane slotted horn patch to get high gain and very large bandwidth for wireless 5G applications. The antenna measurement was completed in an anechoic chamber using vector network analyzer. It produces a high gain of 8.64dBi with continuous large bandwidth at 28 GHz center frequency.

The simulated and measured radiation patterns of the proposed antenna at 28 GHz design frequency in E- and H-planes are shown in Figs. 7 and 8 respectively. The E-plane and H-plane simulated and measured radiation patterns are very consistent and stable. It is observed that the simulated and measured patterns are in well agreement with little discrepancies. The simulated and measured reflection coefficient is shown in Fig. 9. It is observed that the proposed antenna gives a very large continuous bandwidth 20 GHz to onward with S11 < -10dB. It produces a narrow beam radiation pattern which validates the proposed antenna a good candidate for 5G wireless communication systems within the premises even for commercial usage.

The overall antenna size is 69.4554 mm × 58.8685 mm × 2.5 mm. It is clear from simulated and measured results that there is no big evident influence on antenna performance. Figure 9 shows the simulated and measured S-parameters of the proposed antenna with little differences. There is a large impedance bandwidth below 10dB. A little discrimination is observed due to the soldering effect and high frequency millimeter wave connector. Although this profile antenna gives a large continuous band, so a small 5G operational band out of entire available band is considered for displaying results. The surface current distributions of the proposed antenna are shown in Fig. 10. Figure 11 shows the measured radiation patterns of the proposed antenna at 30 GHz, 32 GHz, 34 GHz, 36 GHz and 38 GHz within the operational band. It is observed that the radiation pattern is stable throughout the operational band with a little difference. The gain reduces over the entire band very little that is due to the radiation pattern deformation and impedance mismatching. The measured gain of the proposed antenna over the entire proposed band is 8.64 ± 0.65dBi. The measured antenna gain is shown in Fig. 12. Both simulated and measured results agree well and give a radiation pattern in the broadside direction like a waveguide horn antenna with large impedance bandwidth. The validity of the proposed antenna design is confirmed through a comparison between simulated and measured results.

In comparison with the reference papers [1], [2] and [3] where an H-plane sectoral SIW horn antenna was designed, the proposed antenna gives a high gain antenna element with better impedance bandwidth 20 GHz to onward. The very large continuous bandwidth, i.e., 20 GHz to 45 GHz and onward with a high gain stable radiation pattern makes this profile antenna an attractive candidate for 5G broadband and millimeter-wave wireless applications. A comparison of the proposed antenna with full horn antenna and single substrate printed horn antenna is presented in Table 2.

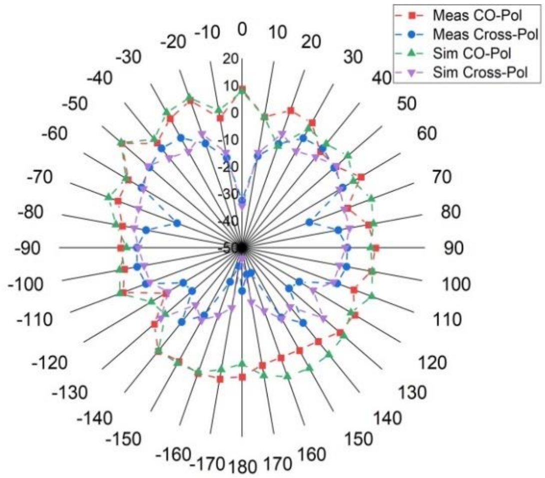



Fig. 7. Radiation patterns of the proposed antenna at 28 GHz in E-plane.

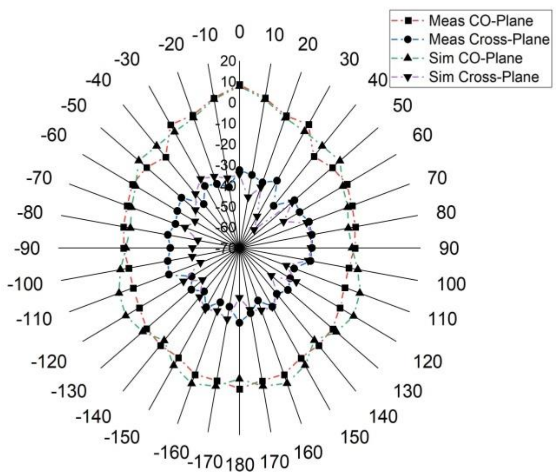



Fig. 8. Radiation patterns of the proposed antenna at 28 GHz in H-plane.

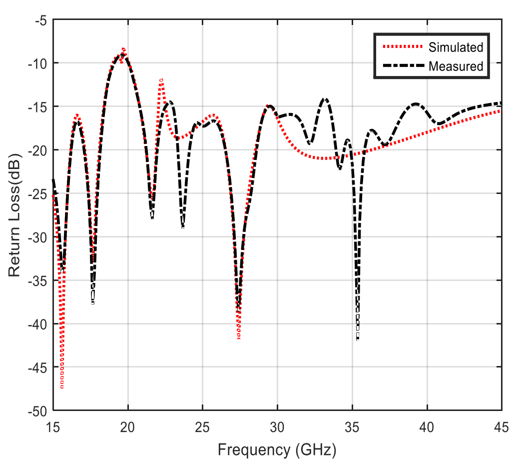



Fig. 9. Reflection coefficient of the proposed antenna.

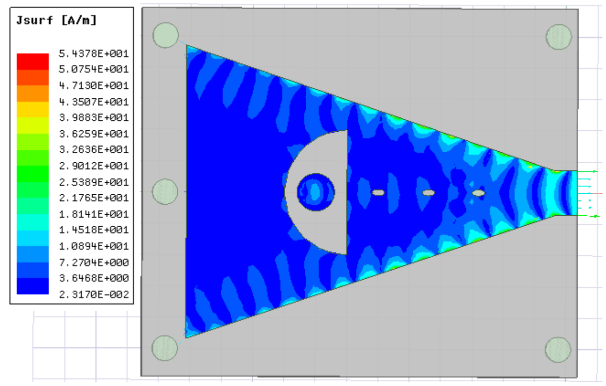



Fig. 10. Surface current of the proposed antenna.

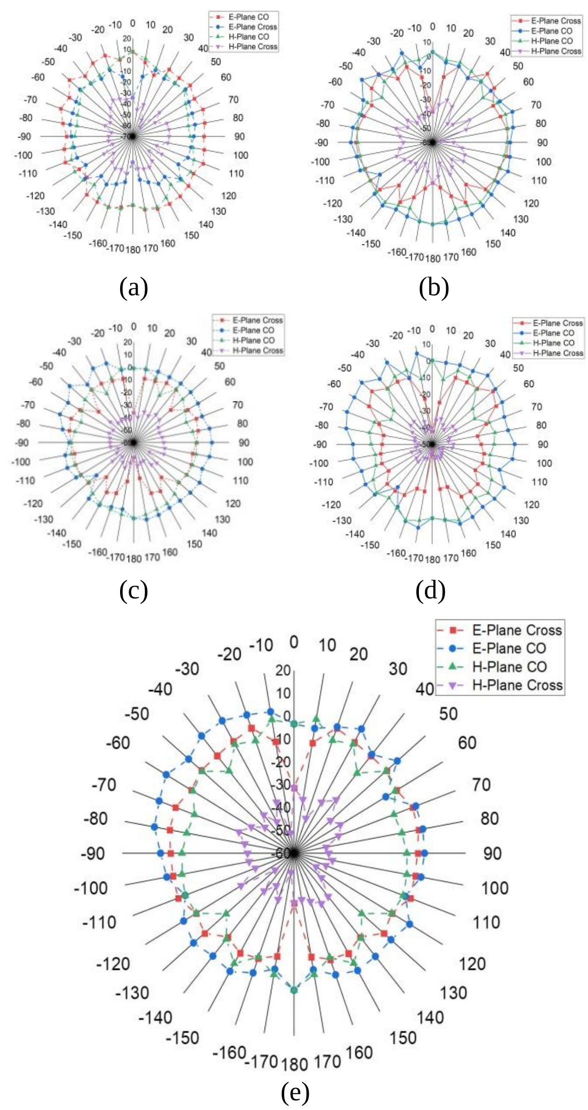



Fig. 11. Measured radiation patterns of the proposed antenna in E- and H-planes: (a) at 30 GHz, (b) at 32 GHz, (c) at 34 GHz, (d) at 36 GHz, and (e) at 38GHz.

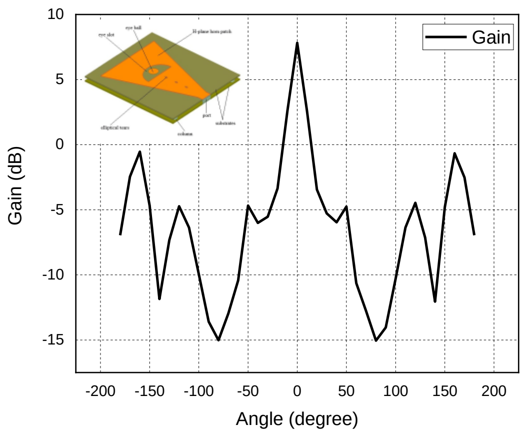



Fig. 12. Measured antenna gain of the proposed antenna.

Table 2: Comparison of antennas

| No. | Antenna Description | Frequency | Gain (dB) | Bandwidth |
|---|---|---|---|---|
| 1 | WR28 full horn antenna | 28 GHz | 20.2 | 18-40 GHz |
| 2 | Single substrate printed horn antenna | 28 GHz | 5.8 | 26.5-30.8 GHz |
| 3 | Proposed multilayered antenna | 28 GHz | 8.64 | 20-45 GHz (onward) |

## VI. CONCLUSION

In this article, an H-plane sectoral printed horn antenna with a novel multi-layered sandwich substrate is proposed for wireless 5G millimeter wave applications. The sectoral H-plane printed horn topology is used to get high gain radiation pattern. The multi-layered sandwich substrate structure gives a large continuous bandwidth from 20 GHz to onward. The proposed antenna exhibits measured bandwidth (20 GHz to 45GHz or onward) below -10dB reflection coefficient. The antenna has a sufficient measured gain of 8.64dBi in E- and H-planes both. It is experimentally demonstrated that the proposed antenna can be used for different wireless 5G millimeter wave indoor and outdoor applications.

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