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Development of Low Profile Substrate Integrated Waveguide Horn Antenna with Improved Gain

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ABSTRACT

In this paper, a new low profile Substrate Integrated Waveguide (SIW) probe-fed H-plane horn antenna with improved gain is proposed. It consists of two waveguides, including a rectangular and a tapered one, in which both the first and third modes of the structure are simultaneously excited leading to a uniform field distribution along the radiating aperture of the antenna and in turn, its directivity is improved. Moreover, using a coaxial probe to excite the antenna, spurious radiation due to the feeding network is suppressed. The antenna structure is numerically analyzed using a software package, and a prototype is made using a single thin substrate layer. A good agreement is obtained between simulated and measured results. The measured results show 10.48 *dBi* gain which is 4.9 *dBi* higher than the gain of a conventional SIW horn obtained at 27.8 *GHz*. The introduced antenna is compact and can be used as a single antenna or as an element of a large antenna array.

KEYWORDS:

Aperture Antenna, Horn Antenna, Substrate Integrated Waveguide (SIW)

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1- Introduction

Rectangular metallic waveguide horn antennas have been widely used in many applications because of their unique radiation properties such as high gain, wide bandwidth, and symmetrical patterns. However, their implementation in planar form is difficult due to the bulky geometry and especially their three-dimensional structures. These difficulties have been resolved in recent years by introducing Substrate Integrated waveguide (SIW) structures [1–5].

The SIW structures essentially offer the familiar advantages of metallic rectangular waveguides, such as high-quality factor and low loss, while preserving the added advantages of microstrip structures, including low profile, light weight, and low cost. Moreover, the SIW structures are also superior for the design of millimeter wave circuits such as filters, resonators, and antennas due to compatibility with planar structures.

H-plane horn antenna is one of those structures, which has been made using SIW technology recently. Various techniques have been reported to improve the radiation performance of these antennas. In [6–9], dielectric loaded SIW horn antennas and arrays have been introduced to obtain high gain. Although using a thin substrate would lower gain and increase backward radiation, still the dimension of the antenna is large. Also, because the effect of dielectric lens is eliminated for a substrate thickness of $h \leq \lambda_0/6$, this technique is not useful [10] for a thin substrate. In [10], printed transition structures are placed in front of the aperture to overcome this weakness, and backward radiation is improved up to 15 *dBi*. In [11], the loading dielectric slab in front of the aperture of the SIW horn provides a lossless guiding structure and corrects phase of the wave and peak gain of 7.9 *dBi* is obtained.

In [12], an H-plane horn antenna with embedded metal-via is introduced and the antenna gain is improved up to 7.75 *dBi* at 35.4 *GHz*, in which the antenna size is $3.48\lambda_0 \times 1.9\lambda_0$ mm^2 using a thick substrate. In [13], a broadside horn antenna is implemented by the SIW technology.

In this paper, a low profile H-plane horn SIW antenna is designed and studied using a thin substrate with $h<\lambda_0/10$ working at 27.8 *GHz*. The proposed antenna is simulated using High-Frequency Structure Simulator (HFSS) and it is shown that the antenna directivity is improved compared to that of the conventional horn.

2- Antenna structure

Geometry and size parameters of a conventional H-plane SIW horn excited by a coaxial probe are illustrated in Fig. 1-a. The structure consists of one rectangular SIW waveguide and another tapered one which supports the propagation of fundamental mode TE_{10} of the SIW structures with the radiating aperture length of d_1.

The structure of the modified SIW horn made by one rectangular and two tapered sections is shown in Fig. 1-b. The length of the different tapered parts is labeled by L_4 and L_5 with angles θ_2 and θ_3 with respect to the horizontal line, respectively. θ_2 and θ_3 are chosen in such a way that both horns provide the same radiating aperture width.

Both antenna structures are made using a thin single layer Rogers 4003 substrate with ε_r=3.55, tangent loss of 0.0027 and thickness of h=0.813 *mm*. They are fed by a 50 Ω coaxial line with the inner radius of R_1 and external radius of R_2. The distance between two adjacent vias d and the radius of each

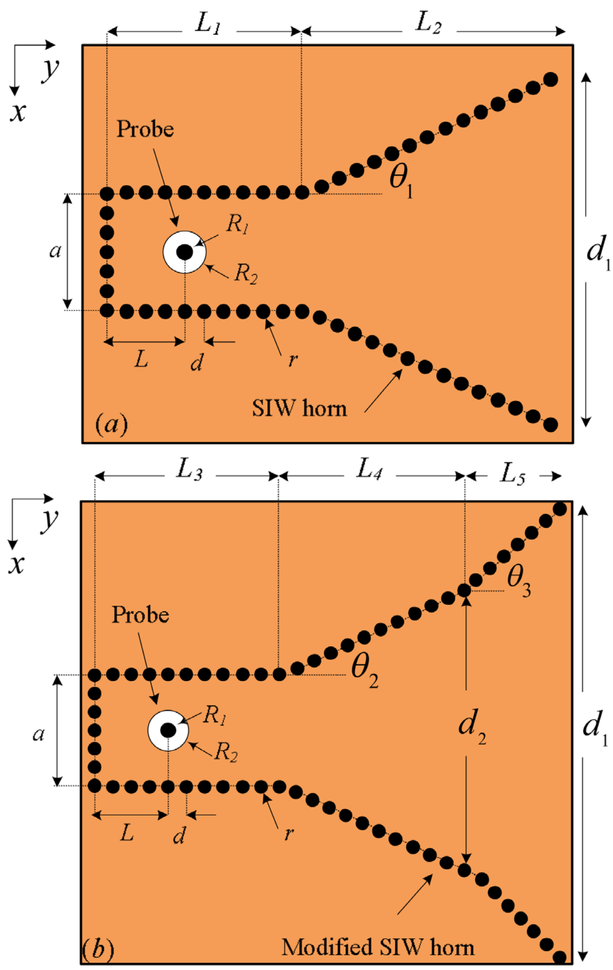

Fig. 1. SIW horn antenna structures, a) conventional horn, b) modified horn

one r are chosen based on the designed rules in Eqs. (1) and (2) to ensure eliminating spurious radiation from the gap between nearby vias.

$$d \le \lambda_g / 20 \quad (1)$$

$$r \le d/2 \quad (2)$$

in which λ_g is waveguide length in SIW structure.

Angles θ_1 and θ_2 of the first part of both horn antennas are chosen based on the designed rule of ordinary horns to provide maximum gain [15]. The opening aperture of the SIW horn using angle θ_3 in modified horn as shown in Fig. 1-b leads to exciting higher modes of the structure, especially the third one. By choosing appropriate values for L_5, the combination of first and third modes makes uniform field distribution on the radiating aperture and in return, the gain of the modified horn is improved [11].

To increase the gain of the modified horn, a grounded metal reflector with a thickness of 0.5 *mm* is placed around the radiating aperture as shown in Fig. 2-a. This would lower both SLL and backward radiation and therefore, the antenna gain is improved. Also, in order to further increase the antenna gain, a grounded pin is added in the middle of the aperture as shown in Fig 2-a. This technique adjusts field distribution on the radiating aperture to be uniform and not only increases the antenna gain but also improves SLL of the modified horn.

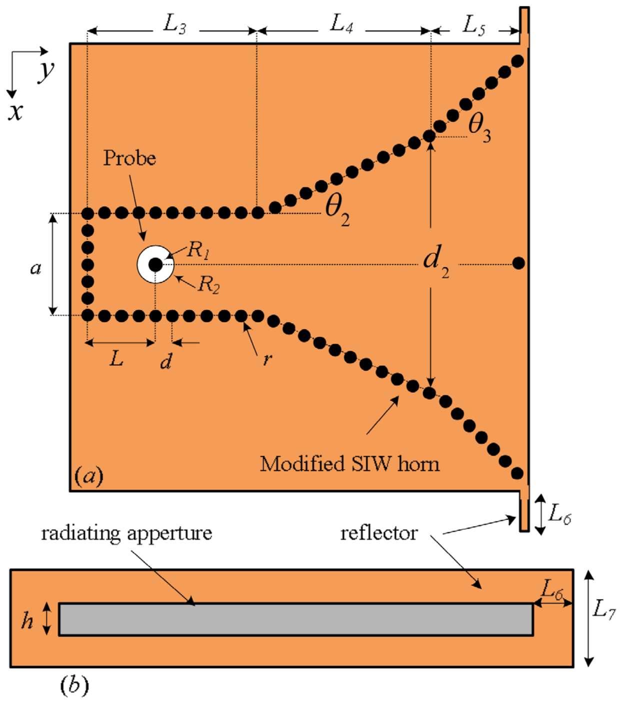

Fig. 2. Modified SIW horn antenna with reflector and pin b) radiating aperture and reflector

3- Results and discussion

The proposed antenna structure is numerically investigated using HFSS. The detailed geometrical parameters of both conventional and modified horns are summarized in Table 1.

3- 1- Field distribution on the aperture

The simulated electric field distribution of different types of horn antennas are shown in Fig 3. The magnitude of the electric fields is a half cycle of sinusoidal variation along the radiation aperture for conventional horn which confirms TE_{10} mode of the structure. For the modified horn due to the excitement of the first and third modes, there is a portion of a cycle of sinusoidal variation with negative values along the aperture [11]. Adding the pin with a radius of 0.25 *mm* at the proper place along the aperture would suppress negative values and the effective width of the radiating aperture is increased compared to that of the conventional horn leading to uniform field distribution. Removing the negative portion of field distribution would also lower SLL and in turn, the antenna directivity is improved. Moreover, the reflector around the aperture would improve FBR and consequently antenna directivity is improved.

From the point of view of an array structure, the modified horn with a pin can be considered as a two-element antenna array with element spacing of $0.85\lambda_0$ and therefore the antenna gain is improved.

3- 2- Simulation results

The simulated reflection coefficient of different types of horns is shown in Fig. 4 versus frequency. It can be seen that all antennas resonate around 28 *GHz*, whereas the modified horn with reflector and pin demonstrate best matching condition at 27.6 *GHz* with S_{11}=-42 *dB*.

Far-field radiation patterns of different antennas, including E- and H-plane patterns are plotted in Fig. 5. It can be seen that all antennas provide nearly the same E-plane patterns, except the modified horn with reflector which offers lowest SLL and best FBR among different antenna types. It can be seen that the H-plane pattern beamwidth of the modified horn is 30°, which is 10° narrower than that of the conventional horn..

3- 3- Parametric study

To study the effect of the length of the second

Table 1. Geometrical parameters of horn antennas

Conventional Horn				Modified Horn					
Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
θ1	22.4°	d1	17.3	θ2	15.85°	L5	2.1	r	0.4
L	1.4	a	5	θ3	51°	d	1	R1	0.4
L1	3	r	0.4	L	1.8	d1	17.3	R2	0.95
L2	14.9	R1	0.35	L3	3.3	d2	12.1	L6	0.8
d	1	R2	0.9	L4	12.5	a	5	L7	6.2

All units are in mm, except for θ in degree

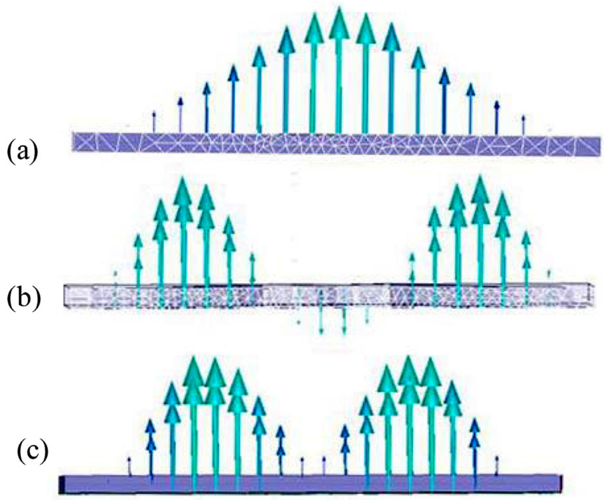

Fig. 3. Simulated electric field distribution along the radiating aperture, a) conventional horn, b) modified horn without a pin, c) modified horn with a pin

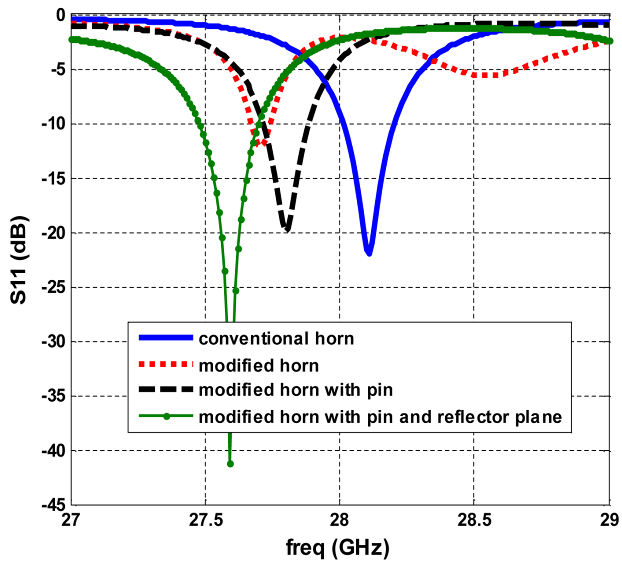

Fig. 4. Simulation results of S_{11} for different types of SIW horns versus frequency

tapered waveguide L_5 on the radiation performance of different horns, a few simulation processes were carried out and antenna directivity and H-plane SLL were studied. In this study, the width of the radiating aperture is kept constant as the width of the conventional horn. This is done by adjusting θ_2. It is shown that for θ_2 up to 34º, only TE_{10} mode is excited at the first tapered part of the modified horn [15] and θ_3 is calculated by Eq. (3).

$$\tan\theta_3 = \frac{d_1 - d_2}{2L_5} \tag{3}$$

The variations of directivity and SLL versus L_5 are shown in Fig. 6. It can be observed that by increasing L_5 from 1 mm up to 1.6 *mm*, only the first mode is excited and directivity of modified horn antenna has increased, whereas SLL approximately remains constant. Further, by increasing L_5 up to 2.1 *mm*, both first and third modes are excited and antenna gain and SLL have slightly increased. It is said that this is due to enhancing field distribution on the aperture for 1.6 $mm \le L_5 \le 2.1$ *mm*. In the case of $L_5 > 2.1$ *mm*, a combination of fundamental and the other modes cancels each other and field distribution is not uniform on the aperture. Therefore, the antenna gain is decreased.

Variation of directivity and SLL of the proposed antenna versus L_7 for different modified horns is shown in Fig. 7. It can be seen that by increasing L_7 from 0.81 *mm* up to 6.2 *mm* antenna directivity has increased, while SLL has decreased. Further, by increasing L_7 up to 9 *mm*, directivity and SLL remain constant.

Simulated results show that all horn antennas are radiating linearly polarized wave with an acceptable

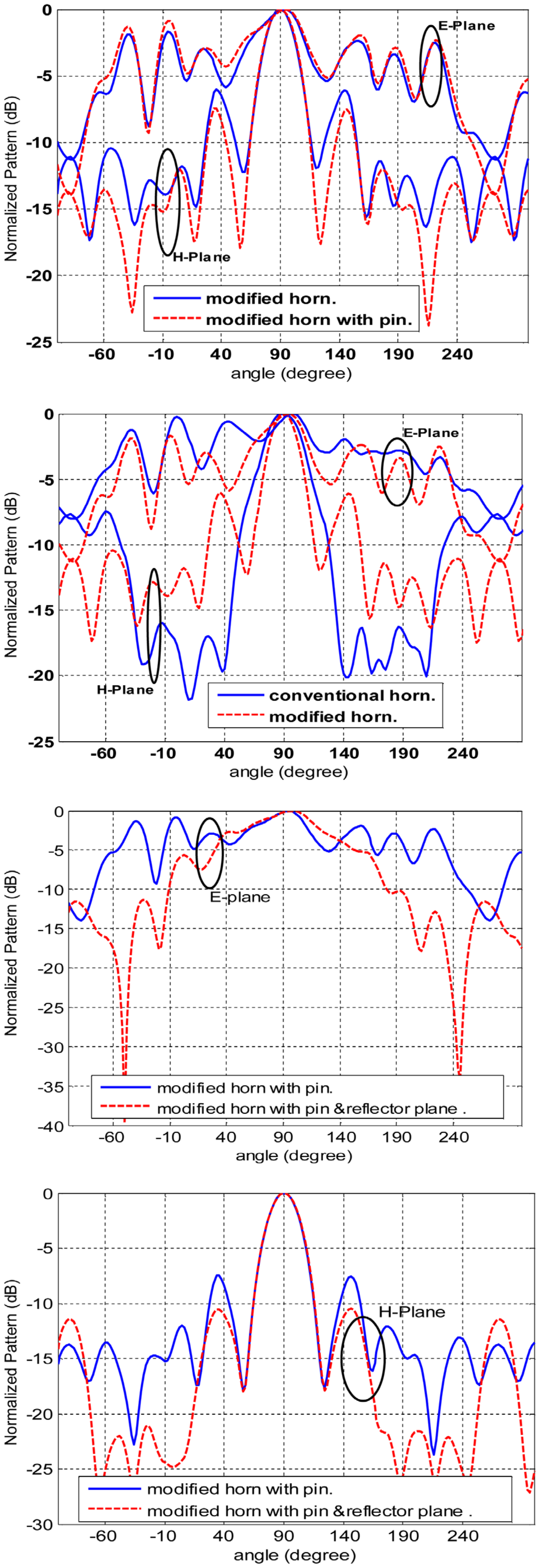

Fig. 5. Simulation radiation patterns of the different type horns

Cross Polarized Level (CPL).

3- 4- Measured results

A prototype of the modified antenna is made using Rogers 4003 substrate. A photo of the fabricated modified horn with reflector and pin is shown in Fig. 8. The antenna is tested in an anechoic chamber using Agilent E8361 Network Analyzer. The setup measurement is shown in Fig. 9.

Measured results for S_{11}, including simulated ones of modified H-plane horn with reflector plane and pin are illustrated in Fig. 10. A good agreement is obtained between measured and simulated results. Measured resonant frequency is 27.8 *GHz* with -22.5 *dB* reflection coefficient.

Antenna gain is measured by gain comparison method using a standard antenna. The variation of measured gain, including simulation results, are plotted in Fig. 11. It can be seen that peak gain of 10.4 *dBi* is obtained at 27.8 *GHz*.

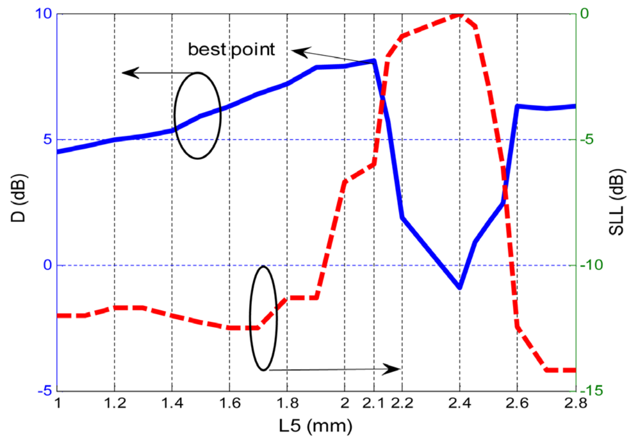

Fig. 6. Simulation results of directivity and SLL versus L_5 for modified horn at 27.8 *GHz*

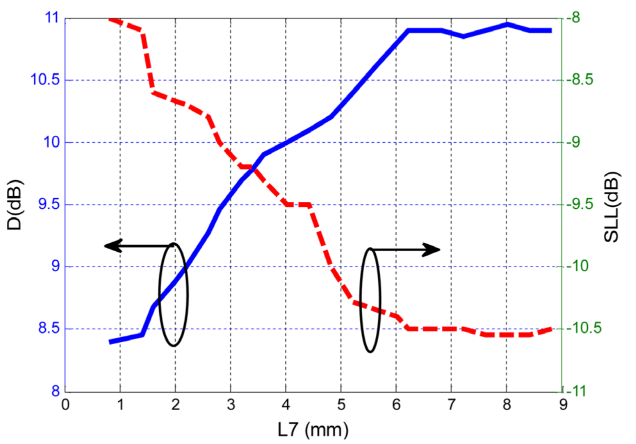

Fig. 7. Simulation results of directivity and SLL versus L_7 for the modified horn at 27.6 *GHz*

Measured far-field radiation E- and H-plane patterns are plotted in Fig. 12-a and Fig. 12-b, respectively. A good agreement between simulation and measured results are obtained and SLL is less than 10 *dB* for both patterns.

The detailed measured radiation performance and antenna size of the proposed antenna, including a few recently published antennas are summarized in Table 2 for comparison.

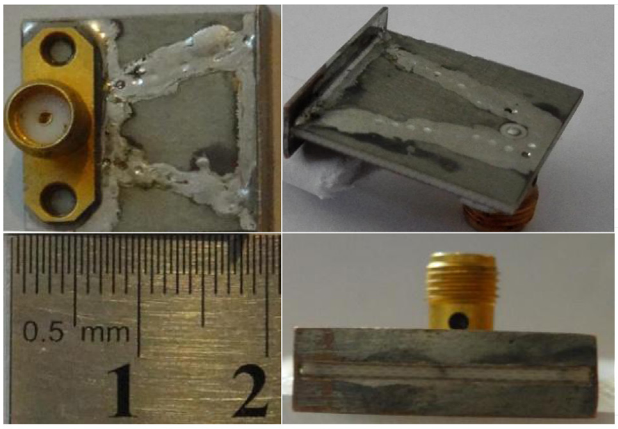

Fig 8. Photo of the fabricated antenna

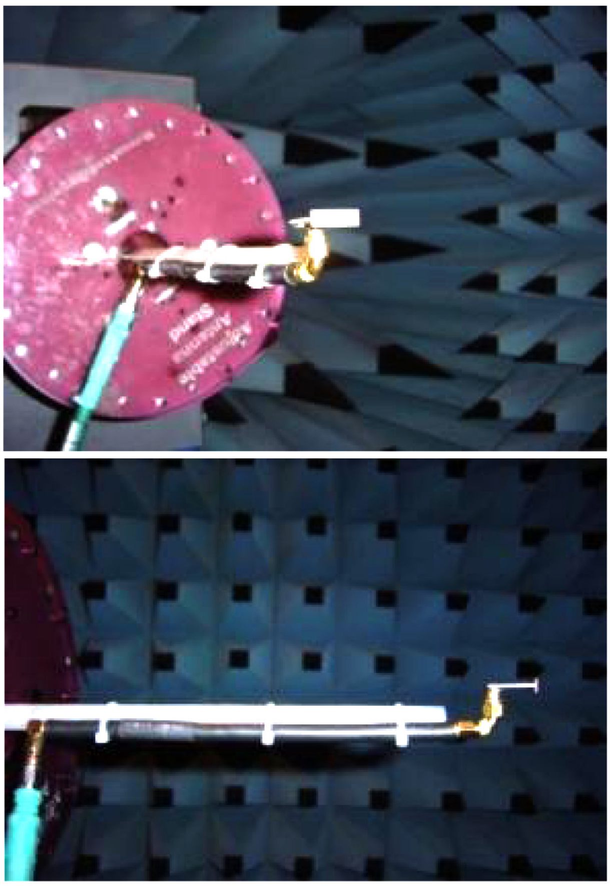

Fig. 9. Experimental setup for measurement of the performance of the proposed antenna

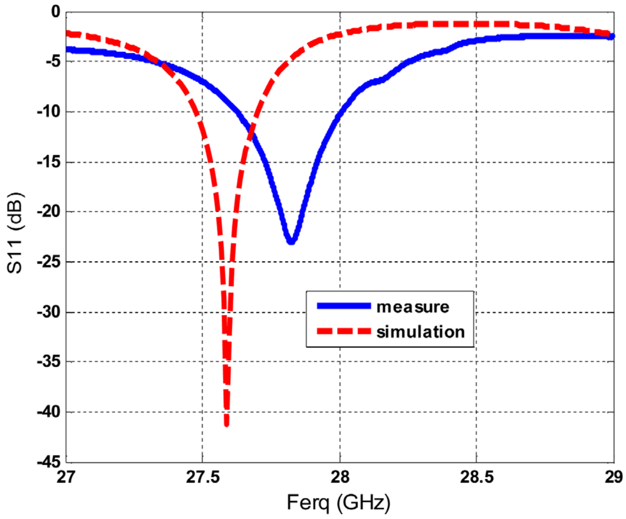

Fig. 10. Measured and simulated results of S_{11} for modified H-plane horn with pin and reflector plane

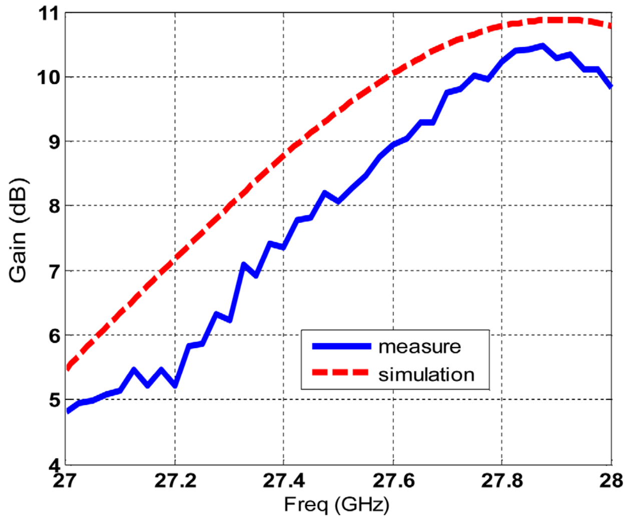

Fig. 11. Measured and simulated antenna gain versus frequency

4- Conclusions

In this paper, a new low profile high gain modified Substrate Integrated Waveguide (SIW) probe-fed H-plane horn antenna is introduced. The transition part of the proposed horn consists of two taper waveguides in which the first and third modes of the structure are simultaneously excited leading to a uniform field distribution along the radiating aperture. A reflector grounded plane is sited around the aperture to improve SLL and backward radiation of the antenna. The antenna structure is numerically investigated and a prototype of the structure working at 27.8 *GHz* is made by a thin substrate and successfully tested. The measured results agree well with those obtained by

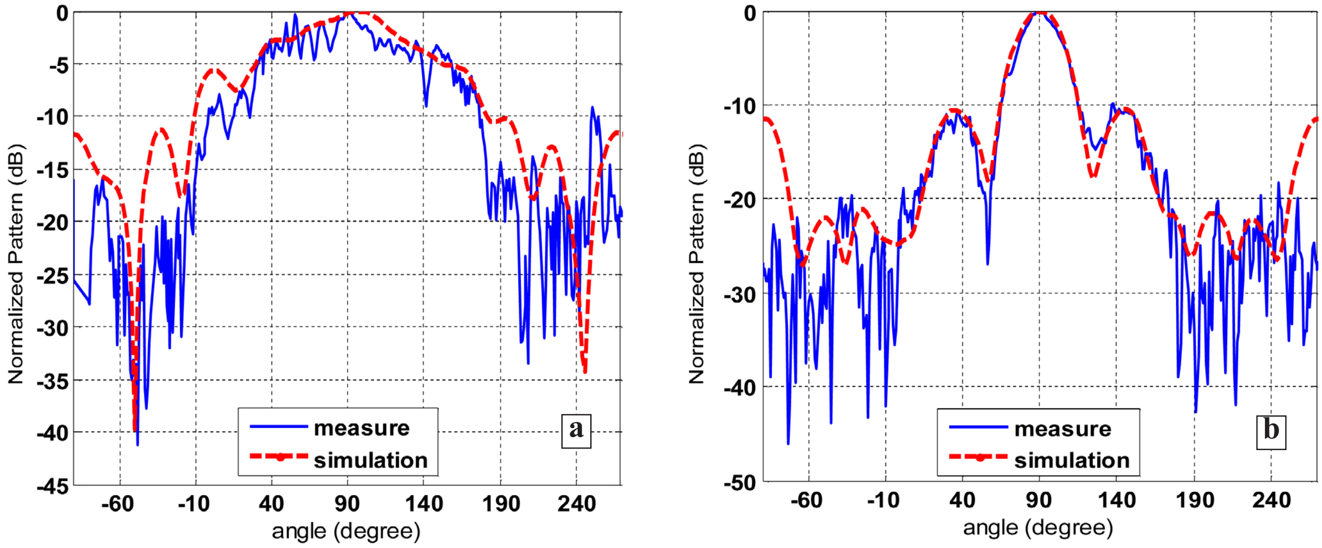

Fig. 12. Measured and simulated patterns of the modified H-plane horn, a) E-plane, b) H-plane

Table 2. Comparison of radiation performance of the proposed horn and recently published ones

Related Ref.	Antenna size	Aperture size	Improvement Techniques	SLL (*dB*)	Gain (*dB*)
[6]	$5.2\lambda_0 \times 7\lambda_0$	$2.27\lambda_0^2$	SIW Power divider + 1×8 horn array	-9.63	15.65
[12]	$3.48\lambda_0 \times 1.9\lambda_0$	$0.34\lambda_0^2$	Embedded metal-via arrays	-9.53	7.78
[13]	$5.5\lambda_0 \times 1.6\lambda_0$	$5.12\lambda_0^2$	Dielectric loading	-10	16
[15]	$3.13\lambda_0 \times 1.5\lambda_0$	$0.37\lambda_0^2$	Dielectric loading & rectangular patches using thick substrate	-15.6	10.9
This paper	$1.6\lambda_0 \times 1.6\lambda_0$	$0.9\lambda_0^2$	Combining mode, pin and reflector	-10.5	10.4

simulation and 10.48 *dBi* gain is achieved which is 4.9 *dBi* higher than the gain of a conventional SIW horn antenna. The proposed antenna is compact and can be used as a single antenna or element of an array for feeding large antennas.

5- Acknowledgment

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