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Development of a Wideband and High Gain ESIW H-plane Horn Antenna

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ABSTRACT: In this paper, a new structure of an Empty Substrate Integrated Waveguide (ESIW) H-plane Horn Antenna with improved gain and impedance bandwidth is introduced. Using ESIW technology, by removing the dielectric material of the SIW structure, the dielectric loss is eliminated and in turn, antenna gain is improved. The flaring area of the ESIW horn is also divided into a few rectangular waveguide sections with proper length and width to improve its impedance bandwidth. Moreover, adding radiating slots significantly reduce Half Power Beamwidth (HPBW) of the E-plane pattern of the ESIW horn. In addition, by adding a slot array at the right position of the structure, the radiating fields of both the horn aperture and the slot array are properly combined and in turn, radiation performance of the ESIW horn is improved. Additionally, by adding non-radiating slots on both sides of the structure, impedance bandwidth is significantly enhanced. The most important feature of the proposed horn antenna is its two-dimensional (2-D) structure, while both gain and impedance bandwidth are improved. The introduced horn antenna is successfully simulated by High Frequency Structure Simulator (HFSS) software and the results are verified by CST. The obtained results show that it provides 14.1 dBi gain with 98% radiation efficiency and 11.3% impedance bandwidth over the frequency range of 25.5 GHz up to 28.5 GHz.

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1- Introduction

Empty Substrate Integrated Waveguide (ESIW) technology was first introduced in [1]. This technique is a special type of SIW technology, in which the dielectric part of the structure is removed, leading to eliminating dielectric loss of the structure, and so antenna efficiency is improved. In addition, the ESIW technique reduces the weight of the antenna structure. Additionally, the existing design rules and regulations for both SIW and ESIW methods are nearly the same, and the only difference is their construction procedure [2-4].

Using ESIW technology instead of the conventional SIW method in designing of H-plane horn antenna led to increase impedance bandwidth and radiation efficiency. Additionally, adding non-radiation slots along the flaring area of the SIW horn significantly increases its impedance bandwidth [5, 6]. Dielectric loading at the end of the ESIW H-plan horn increases its directivity, but antenna size is enlarged and radiation efficiency is also decreased [7]. In general, the most disadvantage of H-plane SIW horn antennas is their large HPBW of E-plane pattern, which reduces gain over the operating bandwidth [8]. In [9], by adding a rectangular waveguide at the end of radiating aperture of a horn and loading it by a dipole array on the both sides of the structure, the HPBW of both E-plane and H-plane are highly improved. In this design, the radiation from the horn and the applied dipole arrays are combined to increase the antenna gain. Although the use of dipole arrays in this antenna leads to improve radiation performance, the final structure is not planar [9]. A reflector plate around the radiating aperture of the SIW horn with a suitable size would increase antenna gain [10, 11]. In [12], the flaring area of the SIW horn antenna is divided into five rectangular waveguide sections with different length and width. The length of the last one is determined in such a way that in addition to stimulating the first mode, the third mode is also propagated, and sos by proper combination of amplitude and phase of different propagating modes of the applied sections, radiation performance of the SIW horn including gain and impedance bandwidth is highly improved.

In this paper, the radiation characteristics of the ESIW H-plane horn antenna including impedance bandwidth and E-plane HPBW is simultaneously improved by adding both radiating and non-radiating slots. Adding radiation slots with appropriate size, nearly half a guided wavelength, and their positions on the top and bottom side of the structure leads to increase antenna gain, but due to the low inherent bandwidth of these slots, the impedance bandwidth of the ESIW horn is poor. To improve the impedance bandwidth of the horn, non-radiating slots with proper length are also added at the proper position on both sides of the structure. The obtained simulated results show that the proposed new ESIW H-plane horn antenna provides 14.1 dBi gain with 98% radiation efficiency and 11.3% impedance bandwidth over the frequency range of 25.5 GHz up to 28.5 GHz, while the antenna structure is kept in planar form.

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2- Antenna Design Concept and Structure

The design procedure of the proposed antenna is provided in five steps. At first, a conventional SIW H-plane horn antenna is designed at the desired frequency. Next, by removing the dielectric material of flaring area of the horn, the conventional ESIW H-plane horn antenna is obtained. In the next step, to improve impedance matching and achieve higher frequency bandwidth, the flaring area of the horn is divided to three rectangular waveguides with appropriate length and width. Afterwards, by adding the radiating slots on both sides of the structure, antenna gain is improved. Finally, non-radiating slots are added on both sides of the substrate to increase the impedance bandwidth. The proposed design procedure of the ESIW H-Plane horn antenna is summarized in Fig. 1.

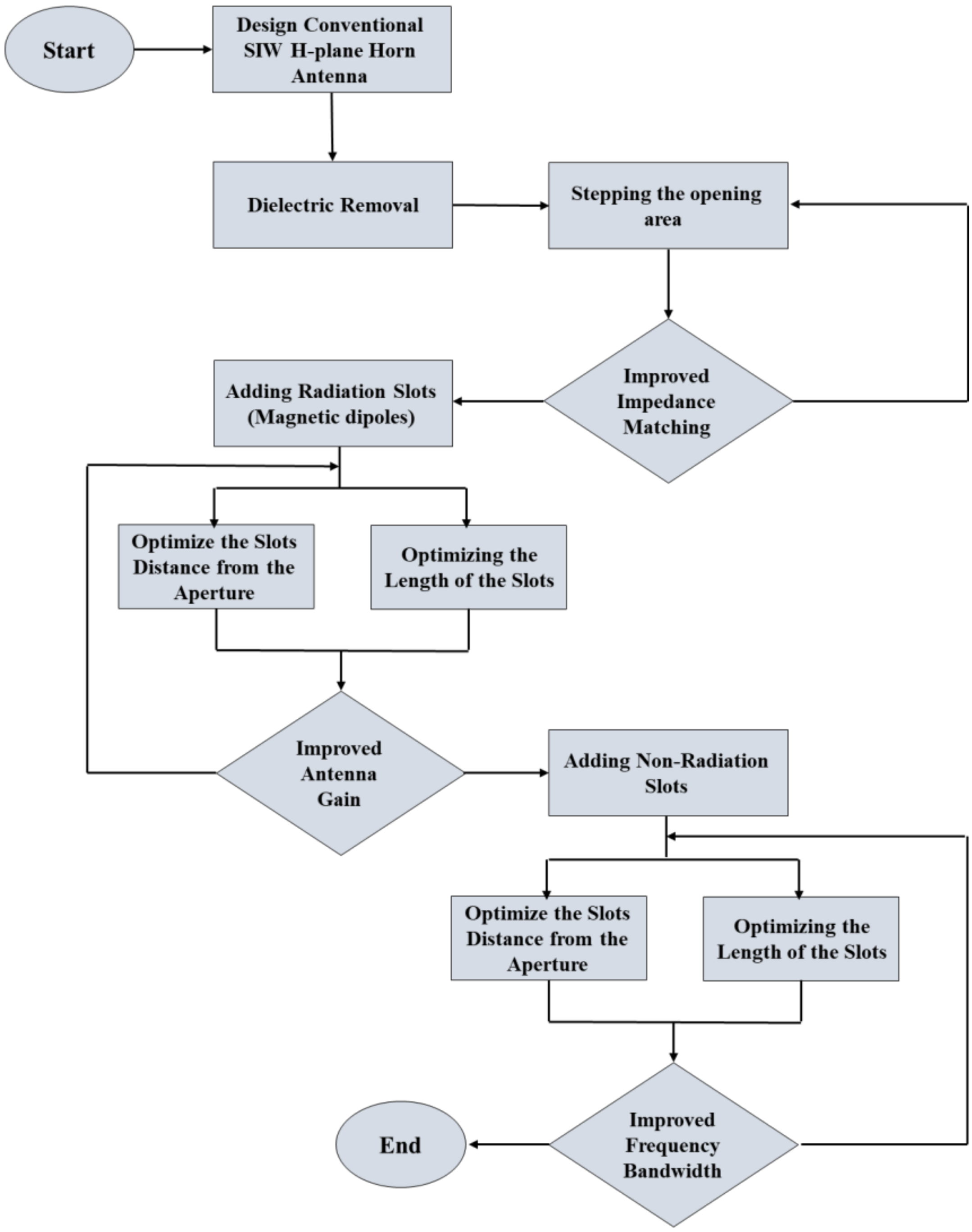


Fig. 1. The proposed procedure design of the ESIW H-plane horn antenna.

The proposed final ESIW horn antenna is shown in Fig. 2, in which the dielectric material of the flaring area is removed. The radiating and non-radiating slots are also located on the top and bottom sides of the structure. The geometrical parameters of the proposed antenna are summarized in Table 1, in which L_{sr} is the length of the radiating slots and L_{snr} is the length of the non-radiating slots. The antenna is made using TLY062 substrate with dielectric constant of 2.2 and thickness of 1.578 mm. The proposed antenna is simulated using HFSS software and its radiation performance including return loss, impedance bandwidth, radiation patterns, and antenna gain is reported.

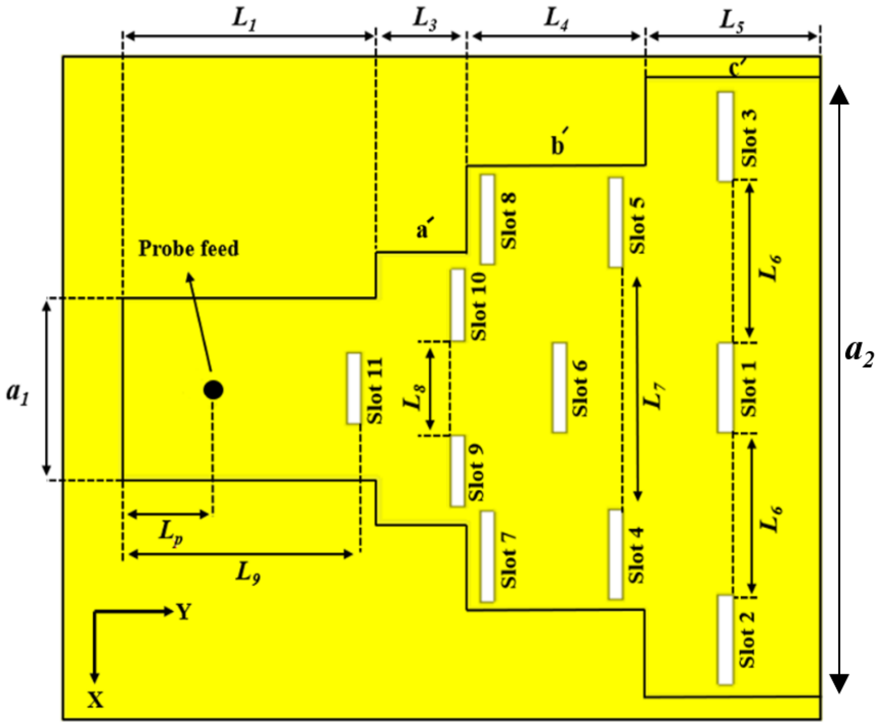


Fig. 2. The geometry of the proposed ESIW H-plane horn antenna.

Table 1. The geometrical parameters of all horn antennas.

parameter	value (mm)	parameter	value (mm)
a_1	7.6	L_1	9
a_2	26	L_2	15.4
a_3	11.2	L_3	3
a_4	14.9	L_4	6
a_5	18.6	L_5	6
a_6	22.3	L_6	6.8
L	24.4	L_7	10.2
L_p	3	L_8	4
d	0.8	L_9	10.4
p	1.25	L_{sr}	4.5
R_2	1.15	L_{snr}	3

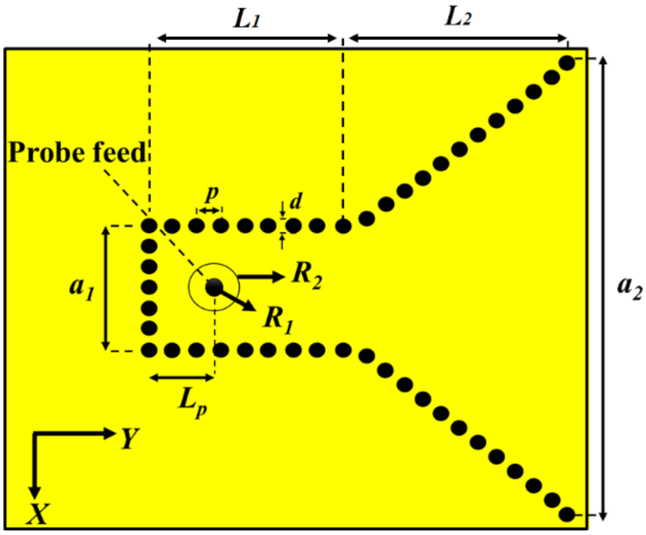


Fig. 3. The geometry of the conventional SIW H-plane horn antenna.

2- 1- Conventional SIW H-plane Horn Antenna

Fig. 3 shows the designed conventional SIW H-plane horn antenna, in which the antenna is excited by a 50 Ω coaxial line with inner and outer radius of R_1 and R_2, respectively [5]. To reduce the radiation loss of the SIW structure, the diameter of the metallic via-holes, d, and the distance from each other, p, have to be determined using equations (1) and (2) [6]. Additionally, to prevent the exciting of the higher modes and only propagating the dominant mode, TE_{10}, the length of the first part of the structure, a_1, is evaluated by equation (3). Since the antenna is an H-plane horn, to achieve the best directivity, the width of the radiating aperture, a_2 is calculated by equation (4), in which λ_g is guided wavelength, L_1 and L_2 are the length of the rectangular waveguide and the flaring area of the horn, respectively [13].

$$p < 2d \tag{1}$$

$$d/\lambda_0 < 0.1 \tag{2}$$

$$\frac{\lambda_g}{2} < a_1 < \frac{3\lambda_g}{2} \tag{3}$$

$$a_2 \approx \sqrt{3\lambda_g (L_1 + L_2)} \tag{4}$$

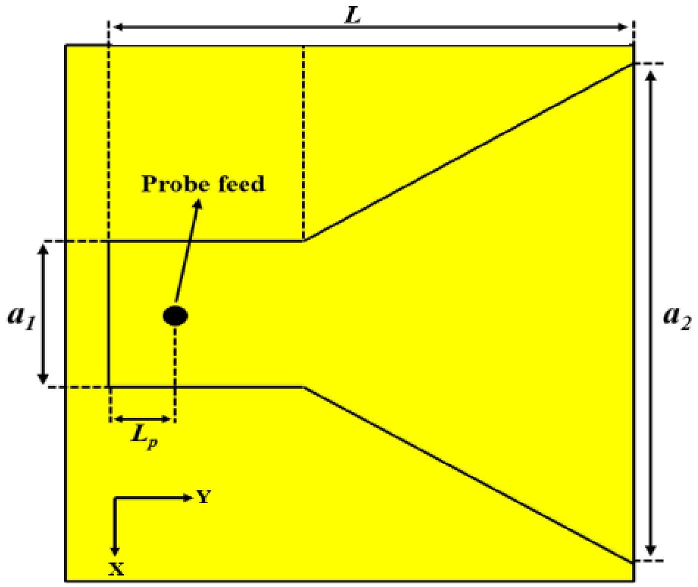
2- 2- Conventional ESIW H-plane Horn Antenna

In order to improve the antenna gain and its impedance bandwidth, first the dielectric material of the SIW H-plane horn is removed. Fig. 4 shows the detailed structure of the ESIW horn. The simulated S_{11} of both the SIW and ESIW H-plane horn antenna is plotted in Fig. 5 versus frequency. It can be seen that by removing the dielectric part, the operating frequency is slightly shifted up and impedance bandwidth is improved [5].

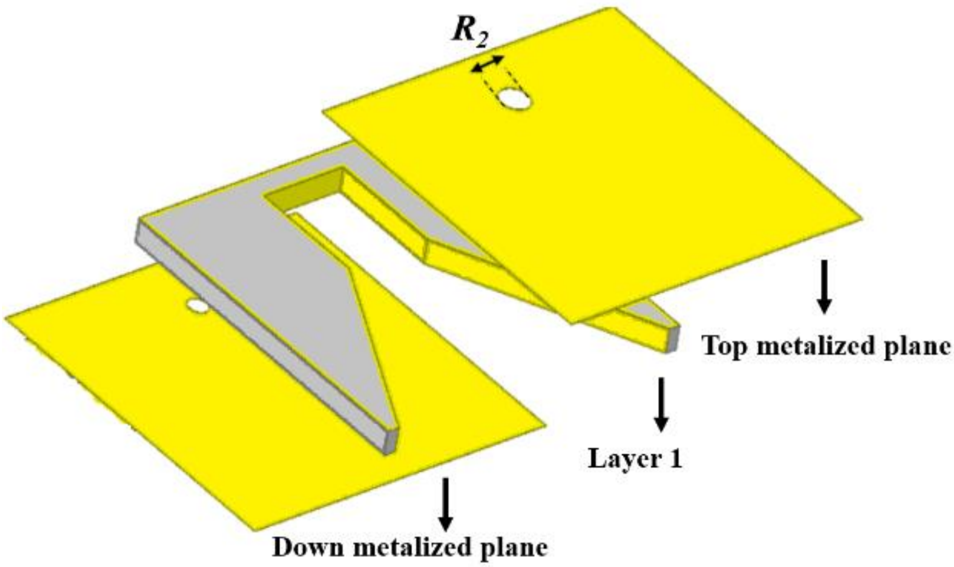
The characteristic impedance of the SIW structure is determined by equation (5), in which η_0, h, W and f_c are free space characteristic impedance, substrate thickness, waveguide width, and waveguide cut-off frequency, respectively. Equation (6) also calculates the cut-off frequency of the SIW waveguides, in which ε_r, c and a are dielectric constant, free space light and width of the waveguide, respectively [14]. In general, one way to increase the bandwidth of SIW H-plan horn antenna is to increase the characteristic impedance of the structure [15], so according to equation (5), by removing the dielectric material, wave impedance is increased and in turn impedance bandwidth is improved. Fig. 6 shows the H-plane radiation pattern of the conventional SIW horn at 27.8 GHz and ESIW horn at 28.7 GHz. It can be seen that by removing the dielectric part of the structure, the beamwidth of the H-plane pattern is considerably lowered and in turn, antenna gain is improved.

$$Z_{SIW} = \frac{K\eta h}{\beta W} = \frac{\eta_0 h}{W\sqrt{\varepsilon_r}\sqrt{1-\left(\frac{f_c}{f}\right)^2}} \tag{5}$$

$$f_c = \frac{c}{2a\sqrt{\varepsilon_r}} \tag{6}$$



(a)



(b)

Fig. 4. The geometry of the conventional ESIW H-plane horn antenna, a) top view, b) antenna perspective.

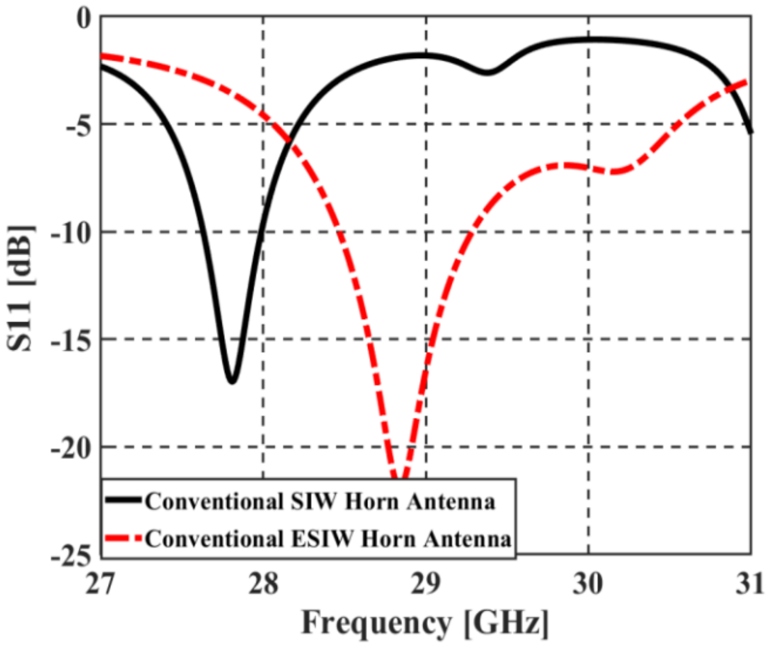


Fig. 5. The simulated S_{11} of the SIW and ESIW H-plane horn antenna versus frequency.

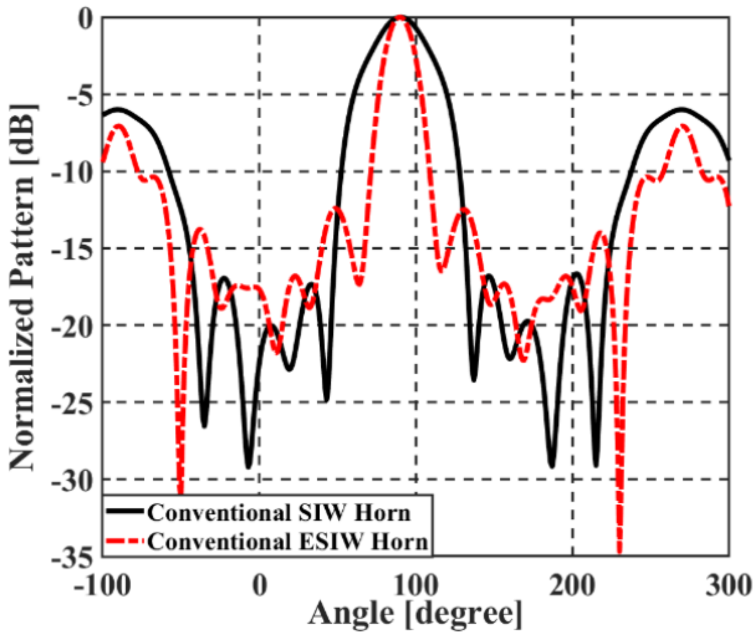


Fig. 6. The simulated H-plane radiation pattern of the conventional SIW at 27.8 GHz and ESIW antenna at 28.7 GHz.

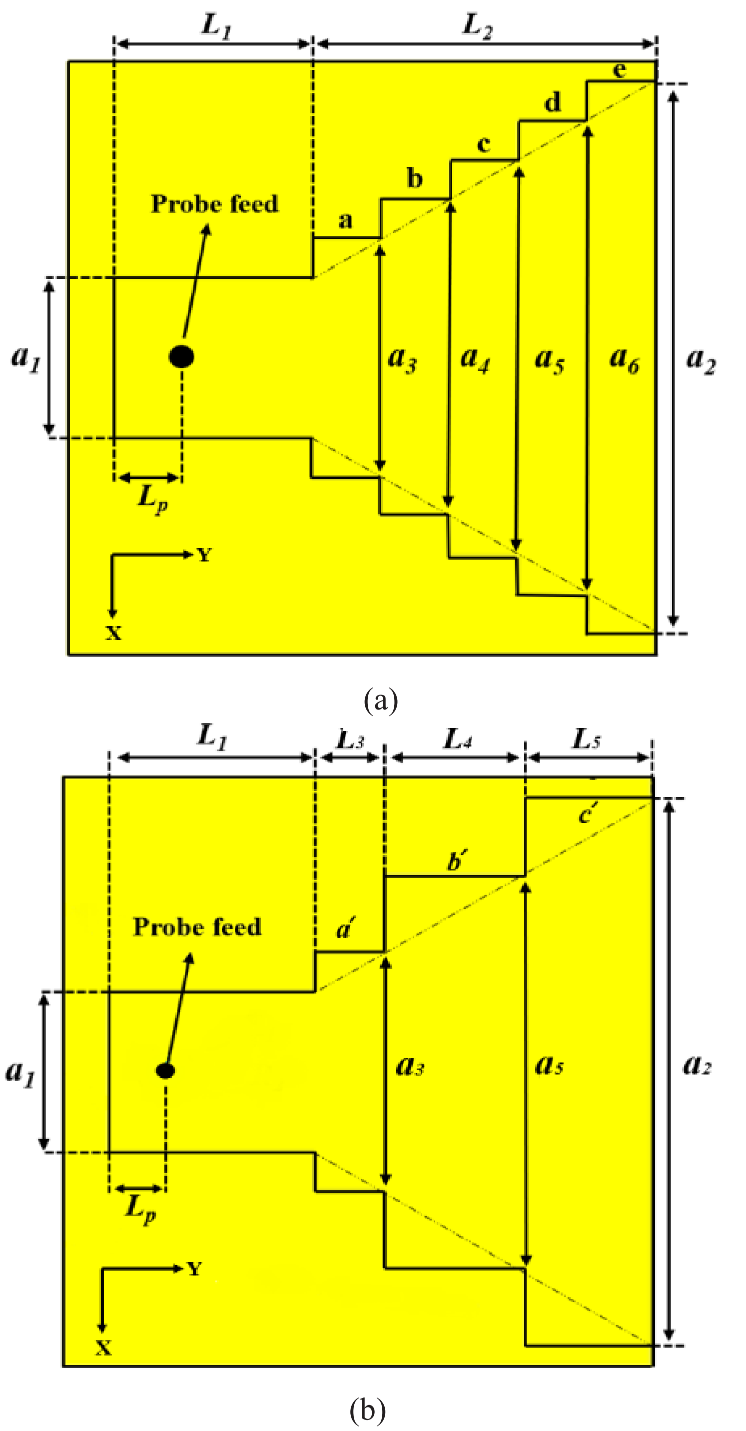


Fig. 7. The geometry of ESIW H-plane horn using staired flaring area, a) with five sections, b) with three sections.

2- 3- Modified ESIW H-plane Horn, Using Staired Flaring Area

Fig. 7(a) shows the modified ESIW H-plane horn antenna, in which the flaring area is divided into five rectangular waveguides designated by a to e with the same lengths but different widths [12]. Fig 7(b) also shows this type of horn with three sections, in which the lengths of the rectangular waveguides are different.

The radiation performance of these two ESIW horns are studied and our simulation investigations show that the obtained bandwidth in case of the horn with three sections is more than that of the horn with five sections in the flaring area. Moreover, since waveguide width W is the most important parameter which affects the wave impedance of a waveguide, therefore by adjusting the width of these three parts of the flaring area of the ESIW horn, impedance bandwidth

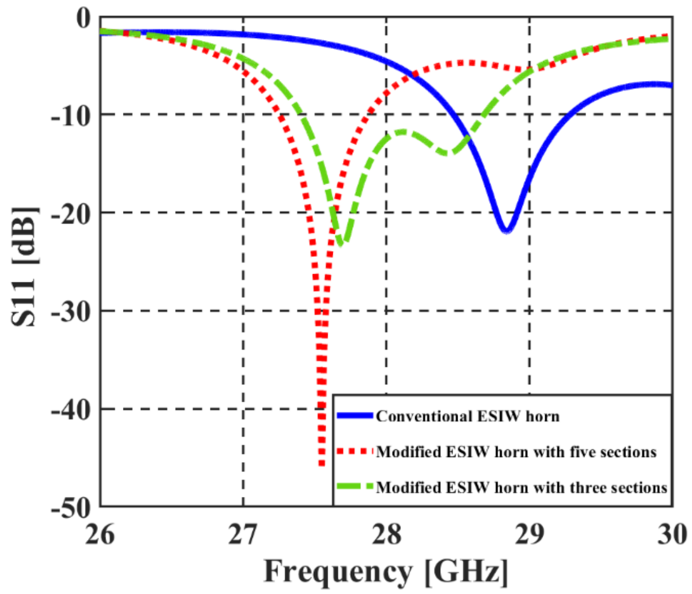


Fig. 8. The simulated S_{11} of different horns, including conventional, modified ESIW with five and three sections in flaring area.

could be improved. The simulated reflection coefficient, S_{11} of the different horn antennas including conventional ESIW horn, ESIW horn with five sections and ESIW horn with three parts of rectangular waveguides, are plotted in Fig. 8 versus frequency. It can be seen that apart from a shift up in frequency range of the staired SIW horn with three sections in the flaring area, it provides much more impedance bandwidth compared to those of other horns.

2- 4- Adding Radiating Slots to the Modified ESIW Horn with Three Sections

Adding radiating slots on the top and bottom sides of the modified horn antenna with three sections in the flaring area, as shown in Fig. 2, leads to enhance antenna gain due to combining the radiation of the horn aperture and the added slots. By adjusting the position and the length of the applied slots, the radiation pattern of both structure aperture and slots are properly combined in E-plane leading to obtain lower HPBW, and thus antenna gain is improved. Our simulated investigations show the best condition with the highest gain is achieved by eight slots. These slots are numbered slot 1 to slot 8 in Fig. 2, which are etched on both sides of the structure to obtain symmetrical patterns. These eight radiating slots are placed in area with weak surface current distribution and their length is designated by L_{sr} which is determined by equation (7) at the center frequency of 26.5 GHz, in which ε_r, f, c, and a are dielectric constant, operating frequency, speed light in free space and waveguide width, respectively [16].

Fig. 9 shows the simulated distribution of the surface current and radiated electric near to radiating aperture by adding the radiating slots. It can be seen that by placing these radiation slots in the appropriate location and choosing the right length for them, $L_{sr} \approx \lambda_g / 2$, the radiation fields of the horn aperture and the added slots are combined in a such a way to enhance the antenna characteristics.

In order to study the effect of the radiating slot length L_{sr} on antenna gain, a parametric analysis is carried out and antenna gain is studied. The simulated antenna gain versus different lengths of the radiating slots L_{sr} at 26.5 GHz is plotted in Fig. 10. It can be seen that the proposed antenna provides the highest gain of 13.9 dBi for the L_{sr} = 4.5 mm.

Fig. 11 shows the simulated radiation patterns of the modified ESIW horn with three sections in flaring area with and without the radiating slots at 26.5 GHz. It can be seen that by adding eight radiating slots, HPBW of E-plane pattern is reduced nearly 50 degrees, and Front to Back Radiation (FTBR) and Side Lobe Level (SLL) are also highly improved.

2- 5- Adding Non-Radiating Slots to ESIW Horn with Three Sections

Although eight radiation slots in the ESIW horn with three sections of rectangular waveguide in the flaring area increase antenna gain, it also provides poor impedance bandwidth. This is confirmed in Fig. 13 in which the simulated S_{11} is presented. It can be seen in this case that the obtained bandwidth of the modified ESIW is only 2.64%. To increase the impedance bandwidth, according to Fig. 2, three non-radiating slots are etched on both sides of the substrate. The length of these slots, L_{snr}, is less than the radiating slots, L_{sr}, and their positions are placed in area with strong surface current distribution. These three slots are numbered slot 9, to slot 11, and are shown in Fig. 2.

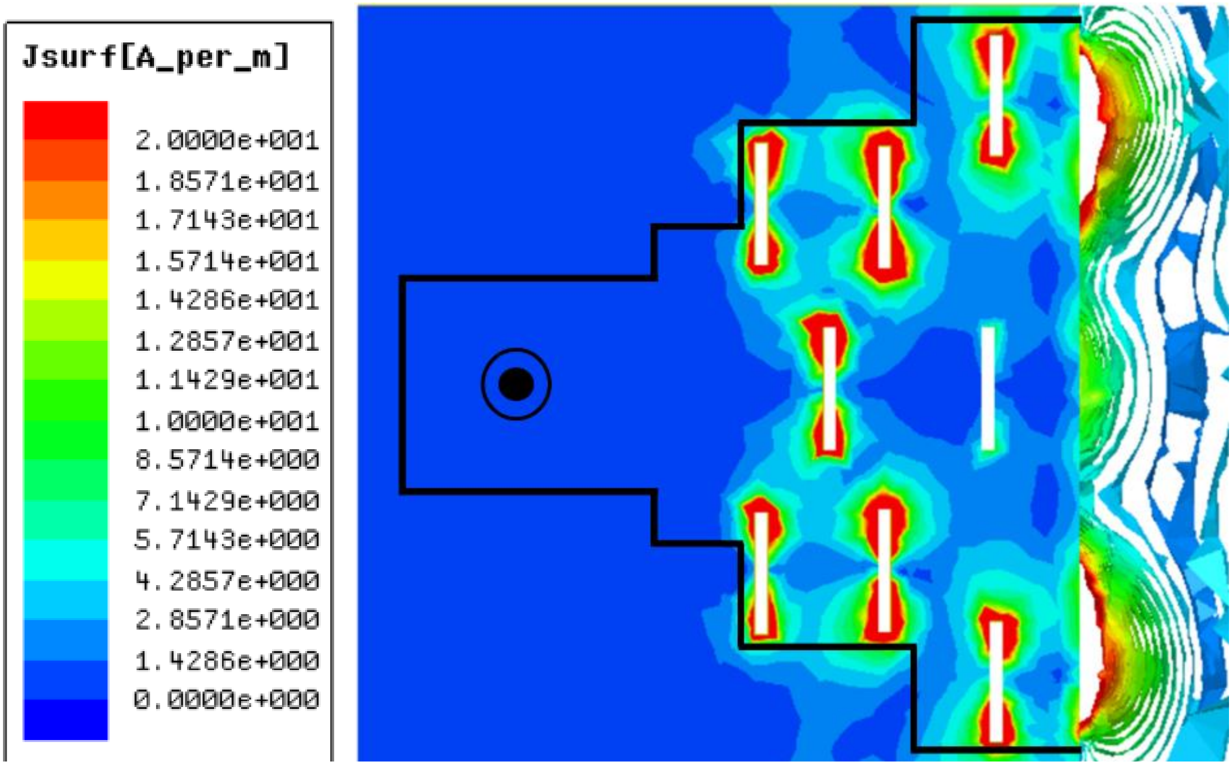


Fig. 9. The simulated distribution of the surface current and electric field from the antenna by adding radiation slots

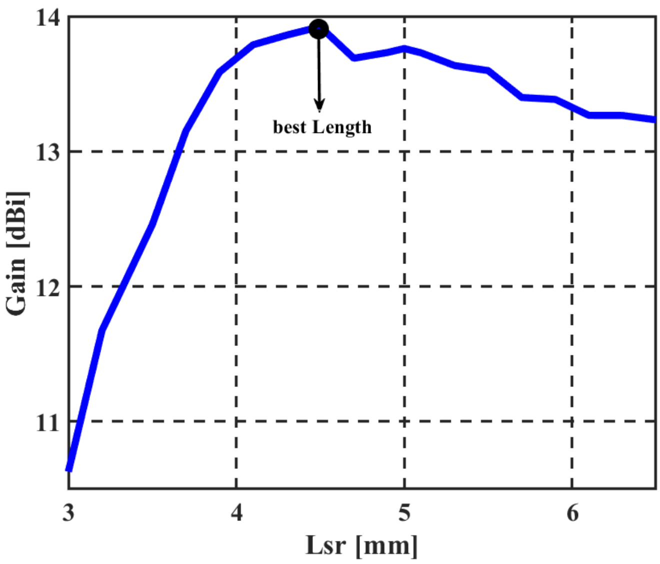
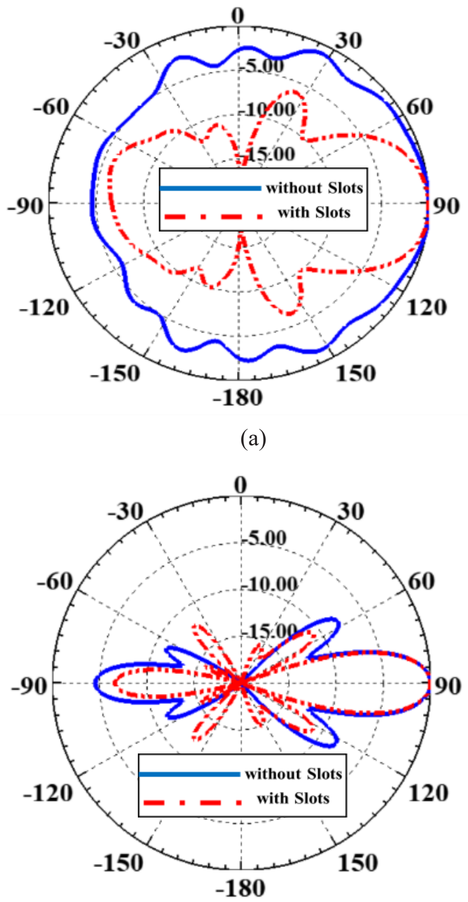


Fig. 10. The simulated antenna gain versus different lengths of the added radiating slots at 26.5 GHz.



(a)

(b)

Fig. 11. The simulated radiation pattern of modified ESIW with three sections in flaring area with and without radiate at 26.5 GHz, a) E-plane, b) H-plane.

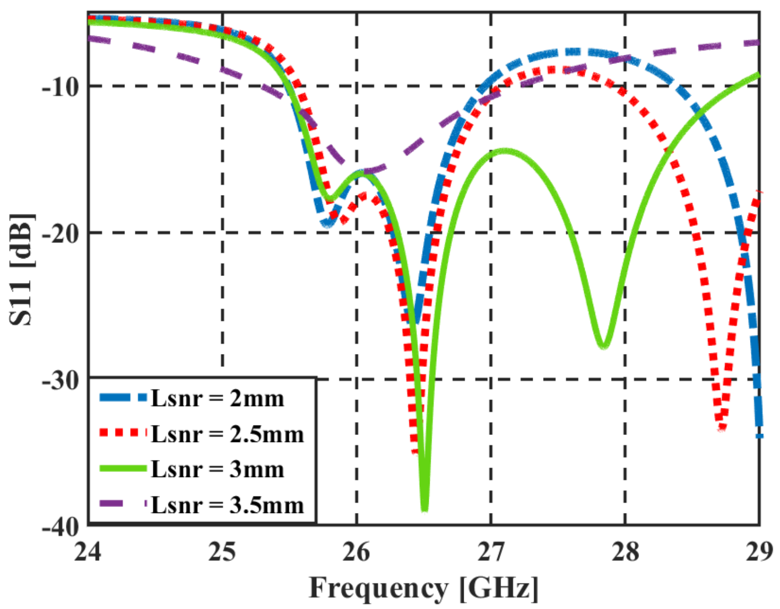


Fig. 12. The simulated S11 parameter of the antenna for different lengths of non-radiation slots.

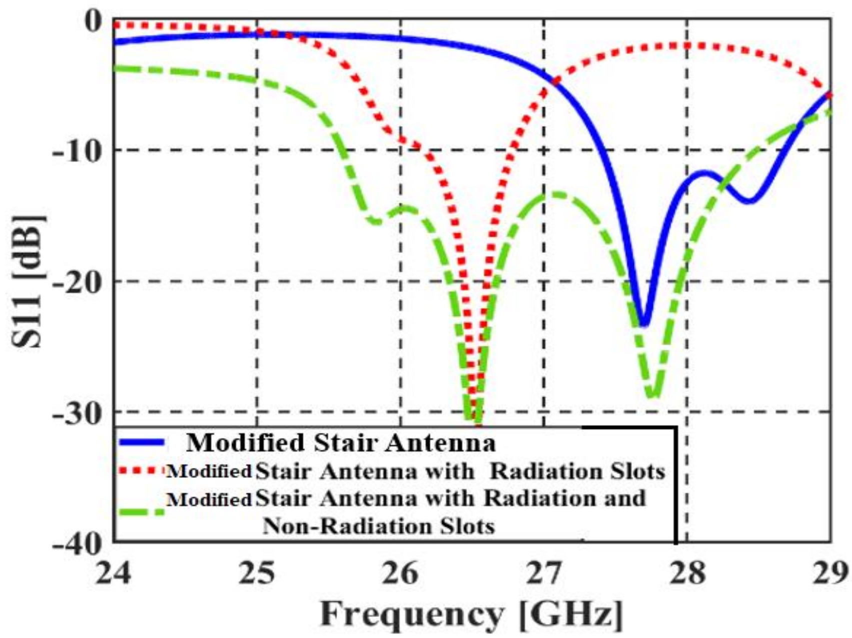


Fig. 13. The simulated S11 of the modified SIW horn with three sections in flaring area with and without non-radiating slots.

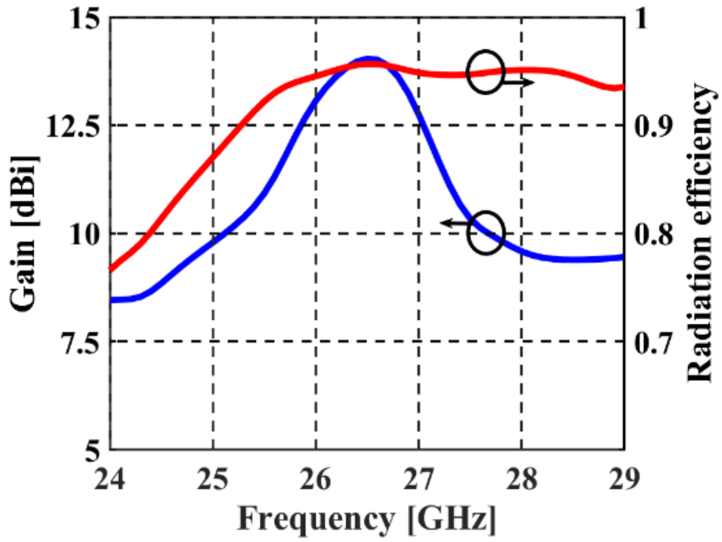


Fig. 14. The simulated gain and radiation efficiency of the proposed antenna versus frequency

To study the effect of the length of the non-radiation slots, L_{snr}, on the impedance of the proposed antenna, a parametric study is carried out. The results are plotted in Fig. 12 for reflection coefficient S_{11} of the proposed versus frequency. It can be concluded that by choosing L_{snr} = 3 mm, the horn antenna provides the highest bandwidth.

Fig. 13 shows the simulated S_{11} of the modified SIW horn antenna with three sections in the flaring area with and without non-radiating slots. It can be seen that in case of adding non-radiating slot impedance bandwidth is highly improved and it covers the frequency range of 25.55 GHz up to 28.5 GHz for S_{11} less than -10 dB, which provides nearly 11.1% impedance bandwidth. Additionally, the variation of the simulated gain and radiation efficiency of the proposed antenna are plotted in Fig. 14. The antenna gain along the operating bandwidth varies from 9.3 dBi to 14.1 dBi with at least 98% radiation efficiency.

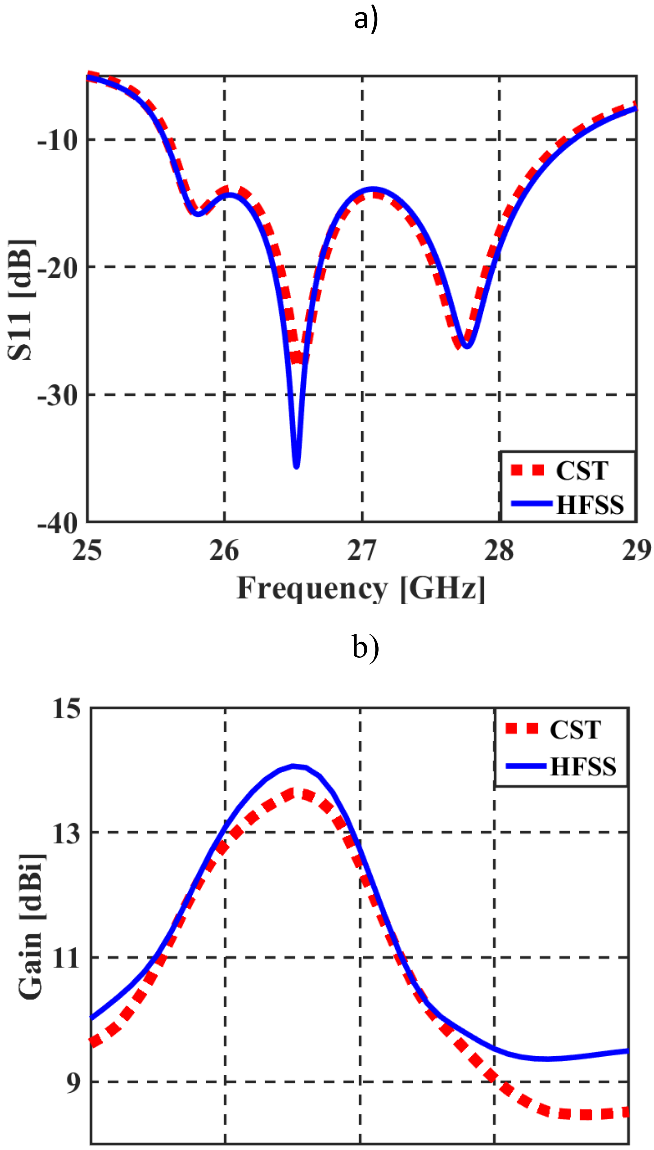


Fig. 15. The simulated S_{11} and gain of the ESIW with two types of slots using HFSS and CST.

To verify the results of the proposed ESIW antenna with both types of the applied slots, the final structure is numerically investigated using CST software. The simulated results S_{11} and antenna gain, including those using HFSS software is plotted in Fig. 15(a) and Fig. 15(b) versus frequency. It can be concluded that both results agree well. The detailed radiation characteristics of the proposed horn antenna are summarized in Table 2. Table 3 also shows the radiation performance of the proposed ESIW horn antenna with the results of the SIW structures, which have been recently published works in literature. It can be seen among the considered SIW horn H-plane horn antennas with planar structures, our proposed ESIW antenna in this paper provides higher gain and bandwidth.

3- Conclusion

This paper presents a new type of Empty Substrate Integrated Waveguide (ESIW) H-plane Horn Antenna to provide high gain and broadband impedance bandwidth. By removing the dielectric material of the SIW horn antenna, the dielectric loss is eliminated, and in turn antenna gain is enhanced. The flaring area of the proposed ESIW horn is also divided into a few rectangular waveguide sections with proper length and width to improve its impedance bandwidth. Two types of slots are symmetrically added on both sides of the structure to obtain symmetrical patterns. At first, a slot array using radiating slots with half a guided wavelength length at the right position is added. The radiating fields of the applied slot array

Table 2. The simulated radiation performance of the different ESIW H-plane antenna studied in this paper

Parameter	Conventional SIW Horn	Conventional ESIW Horn	Modified ESIW Horn with 3 sections	Modified ESIW horn with 3 sections and radiating Slots	Final ESIW Proposed Horn
Impedance Bandwidth (%)	1.22	2.8	4.64	2.64	11.3
Resonate Frequency (GHz)	27.8	28.7	27.5	26.5	26.5
Gain (dBi)	6.4	8.67	9.3	13.9	14.1
E-plane HPBW (degree)	119	107	107	55	48
H-plane HPBW (degree)	44	21	20	19	20
SLL_H (dB)	-16.7	-12.5	-7.8	-12.6	-11.1
FTBR (dB)	5.5	4.6	4.6	5	7

Table 3. The comparison table of the simulated radiation performance of the proposed antenna and those recently published in literature.

Reference	Size (λ_0^3)	FBW (%)	Maximum Gain (dBi)	Structure Type
[9]	2.2×1.5×0.58	5	14.1	Non-Planar
[17]	2.1×3.8×2.16	5	10.4	Non-Planar
[18]	2.3×1.6×0.25	0.66	10.11	Planar
[19]	7.6×3.8×0.12	4.6	9	Planar
This work	2.18×2.33×0.14	11.3	14.1	Planar

are properly combined with those of the radiating aperture of the ESIW horn leading to significantly reduce HPBW of the E-plane pattern of the ESIW horn, and hence antenna gain is improved. However, due to inherent resonant characteristics of the slot array, the obtained impedance bandwidth is poor. Therefore, the second type of slots named non-radiating are etched on both sides of the substrate to improve the impedance bandwidth of the new horn. The most important feature of the proposed ESIW horn antenna horn with three parts of the rectangular waveguides in the flaring area and the required slots is its planar structure, which fascinates integration with other devices and circuits. The introduced new ESIW horn antenna is successfully simulated by HFSS software and the results are verified using CST obtained. The simulated results show that the proposed antenna provides 14.1 dBi gain with at least 98% radiation efficiency and 11.3% impedance bandwidth over the frequency range of 25.5 GHz up to 28.5 GHz. The obtained results show that our proposed ESIW horn antenna provides high gain and wideband impedance bandwidth, and it can be used in practical communication units.

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