Dielectric-loaded substrate integrated waveguide H-plane horn antenna with embedded air cavity

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1 | INTRODUCTION

The concept of substrate integrated waveguide (SIW) has attracted significant attention from its inception and become a well-established technology with immense potential [1]. Owing to the benefits of easy integration and low-cost fabrication, many SIW passive and active devices have been investigated for their use in the microwave and millimetre-wave systems [2–4]. Recently, SIW antennas have been extensively investigated and became an important research direction as a result of its advantages in terms of its radiation characteristics [5,6]. At the same time, owing to the inherent structural features and the filling medium in the waveguide, H-plane horn antennas suffer limitations such as the backward radiation, hindered gain enhancement because of the poor performance in the E-plane and impedance mismatch between the SIW section and the air space.

Various methods have been investigated for the improvements of the radiation characteristics of the SIW H-plane horn antennas [5–19]. In [6], a compact design using periodic printed metal strips to the horn on a thin substrate is presented. Although the narrow pattern in H-plane is realised at multiple frequencies, the E-plane pattern is difficult to control by applying such a technique because of high side lobe levels (SLLs). An easy approach that involves rectangular metal patches on the dielectric loading is described in [7]. This work shows that at 22.7 GHz, the SLL in E-plane of the normalised radiation pattern is reduced to −10 dB, and an improved gain of 10.1 dBi is obtained with the narrowest half-power beamwidth (HPBW) 50° in E-plane and 30° in H-plane. A simple solution for increasing the front-to-back ratio (FTBR) is achieved by etching air slots in the metal plates in [8], that act as magnetic current source. However, the improvement in the forward radiation is limited, as the gain is constrained by wide beamwidth.

Another recent example [9], where the improved radiation characteristics such as 13.97 dBi gain, 32 dB FTBR, −10 dB SLL and 44° HPBW in E-plane are realised at 20.5 GHz, in a structure combining the SIW H-plane horn antenna and a Yagi-Uda antenna array. With all its advantages, this structure carries limitations in terms of integration, demanding high precision and complex manufacturing process, and different external components accommodated on the restricted SIW size cavity.

By employing the dielectric loading [14], the beamwidth in E-plane can be reduced, and the gain can be enhanced. However, unexpected radiation occurs on the surface of the dielectric loading along the propagation direction, once the length of the dielectric loading exceeds certain limits, resulting in additional side lobes in both E- and H-plane. It can be concluded that for the SIW H-plane horn antenna, most reported designs can only achieve the gain enhancement through the improvement of H-plane radiation performance.

An SIW H-plane horn antenna with a sandwich-type dielectric loading is developed to provide superior radiation performance together with a simple design process. Over
multiple frequencies, the suggested antenna introduces a significantly improved E-plane performance for the SIW H-plane horn on thin substrate. Besides the standard printed circuit board (PCB) manufacturing, the proposed structure only requires horizontal drilling for a simple design procedure, offering high applicability in the planar integration without longitudinal transformation and extension.

2 | ANTENNA STRUCTURE

The geometry of the proposed SIW H-plane horn antenna illustrated in Figure 1 includes one single layer of PCB, TMM4 laminate with the dielectric constant \( \varepsilon_r = 4.5 \). To ensure a single-mode TE_{10} is transmitted in the antenna at the operating frequency of 24.15 GHz, the SIW width labelled \( A \) is calculated based on the design rules in [10]. The diameter \( d \) of the metal vias and the spacing \( S \) between adjacent metal vias are determined in the following text [11].

The lengths of the SIW rectangular cavity and the horn are shown as \( L_1 \) and \( L_2 \). Owing to the phase error caused by the path difference in the horn, the E-field at the aperture is not uniform. To reduce this effect, a supplementary SIW section of length \( L_4 \) is added [9]. As the bandwidth (BW) enhancement is not the focus in this design, a coaxial connector with a transition pin is utilised to feed the SIW directly. The distance from the SIW back wall to the centre of the pin is labelled \( L_0 \), and the radius of the insert pin and the corresponding outer shield is \( R_1 \) and \( R_2 \).

The extension of the dielectric loading, with the length \( L_3 \) and the same width \( D \) as the horn aperture, is achieved by stripping the copper-clad of the top and bottom PCB sides.

![Coaxial connector with transition pin](Image)

**FIGURE 1** The geometry of the proposed antenna

**TABLE 1** Dimensions of the proposed antenna (unit: mm)

| SIW Horn Antenna | Proposed Loading |
|------------------|------------------|
| Symbol | Value | Symbol | Value |
| \( L_0 \) | 2 | \( A \) | 6 | \( b \) | 3.175 |
| \( L_1 \) | 9 | \( D \) | 16 | \( b_1 \) | 0.8 |
| \( L_2 \) | 13.5 | \( S \) | 1 | \( b_2 \) | 1.1875 |
| \( L_4 \) | 2.5 | \( d \) | 0.8 | \( L_3 \) | 34 |
| \( R_1 \) | 0.15 | \( R_2 \) | 1.3 | \( L_5 \) | 6 |

3 | MAIN CONCEPT AND FIELD ANALYSIS

3.1 | Design idea

Based on our study and the previously mentioned references, we propose a design of a SIW H-plane horn antenna with a rectangular dielectric loading where a rectangular air cavity is inserted horizontally. This air cavity has the role to create the perfect electric conductor (PEC) boundaries to modify the field distributions of the surface waves in the dielectric slabs stacked on both sides. It also provides the physical distance between two dielectric slabs that contributes to the gain enhancement of the broadside radiation.

To ensure that each surface wave antenna works at the fundamental TM_{00} mode, there is a required value for the thickness of a given dielectric material [12,13]. Figure 2 shows the relation between the dielectric thickness and the first two surface wave modes for the dielectric constant \( \varepsilon_r = 4.5 \). In our
3.2 Field analysis

In support of our design concept and hypothesis that the two surface waves can be realised by horizontally inserting the air cavity in the middle of the dielectric slab, an initial study of the field propagation (Figures 3–9) in a preliminary dielectric loading unit, consisting of two dielectric slabs separated by an air cavity, has been completed. Two excitations, a TE_{10} mode (Figure 3), followed by SIW horn feeding (Figure 7) are used. The electric and magnetic fields inside the air cavity only and the entire unit are presented. The radiation characteristics are evaluated versus the length of the preliminary dielectric unit for the two different feeding methods, revealing their similarities. The length of the air cavity is L_{air} and the thicknesses of two dielectric slabs are identical and thin enough to only support the TM_{0} mode.

3.2.1 TE_{10} feed case

The preliminary dielectric unit fed by TE_{10} mode (wave port excitation in HFSS) is illustrated in Figure 3. The field distribution within the air cavity and inside the unit are given in Figures 4 and 5. For the field distribution within the air cavity, Figure 4a represents the vector plot of the E-field in yz plane, and Figure 4b represents the vector plot of the H-field in xz plane.

For the field distribution inside the preliminary dielectric unit, the free space wavelength \( \lambda_0 \) is about 12.4 mm and the normalised propagation constant \( \beta/\kappa_0 \) is 1.2026. It is seen that the thickness of the dielectric slab should be smaller than 0.13\( \lambda_0 \) to eliminate the impact of the second TE_{1} mode.

For the field distribution inside the entire preliminary unit fed by TE_{10} mode in the free case, Figure 5a presents the vector plot of the E-field in yz plane, and Figure 5b presents the vector plot of the H-field in xz plane.

The inspection of these field indicates that the wave propagation in the dielectric slabs resembles that of a surface wave supported by a grounded dielectric slab [13]. This is because the two surface waves in the top and bottom slabs are out of phase and force the E-field in the air cavity to be aligned to the y-axis, perpendicular to the propagation direction z. Hence the air-dielectric interfaces inside the air cavity behave as PEC boundaries that support the two surface waves in the two slabs. Thus, one can consider such a system to have two surface waves coupled together, with a lateral y-axis separation, behaving as a two-element antenna array, symmetrically distributed along the propagation direction.

The radiation characteristics versus the air cavity length L_{air} for the preliminary dielectric unit fed by TE_{10} mode in terms of the guided wavelength \( \lambda_{g} = 10.4 \text{ mm} \) of the surface wave is shown in Figure 6. For the L_{air} \leq 1.0\lambda_{g}, the side lobes do not appear, merging to the main lobe or back lobe. When these two dielectric slabs are directly fed by the TE_{10} mode, the directivity continuously increases from 7.3 to 14.8 dBi because the beamwidths in both planes keep narrowing when L_{air} increases. The higher FTBRs occur periodically about every
The preliminary dielectric unit fed by the dielectric filled SIW horn is shown in Figure 7. Figure 8a,b shows the E-field and H-field distributions of the entire preliminary dielectric unit. Compared with the field distributions in Figure 5a,b, similar field distributions are obtained. Specifically, when these two dielectric slabs are fed by the dielectric filled SIW horn, the air cavity in the middle also acts as the PEC boundaries for the two surface wave antennas. These findings show that properly sized length and thickness of the air cavity in the dielectric extension of the SIW H-plane horn antenna can result in narrower radiation patterns leading to the directivity improvement in the broadside radiation.

The impact of the air cavity length \( L_{air} \) on the radiation characteristics, for the SIW feeding, is illustrated in Figure 9 and is similar to the TE\(_{10}\) feed case, from Figure 6. The higher values of FTBR (emphasised by vertical dotted lines) appear around every half-guided wavelength and the directivity in broadside keeps increasing as the beamwidths in both planes become narrower.

![Figure 7](image1.png)

**FIGURE 7** The preliminary dielectric unit fed by the dielectric filled SIW horn

![Figure 8](image2.png)

**FIGURE 8** The field distribution of the entire preliminary dielectric unit. (a) Vector plot of the E-field in \( yz \) plane, (b) Vector plot of the H-field in \( xz \) plane

half-guided wavelength (marked by the dotted vertical lines) with an overall increasing trend from 12 to 20 dB as the \( L_{air} \) in the range from 1.0\( \lambda_g \) to 3.0\( \lambda_g \). As the thickness of the air cavity is fixed, the SLLs in E-plane have minor variations around −10 dB.

3.2.2 | SIW horn feed case

The simulation for the preliminary dielectric unit directly fed by the dielectric filled SIW horn is shown in Figure 7. Figure 8a,b shows the E-field and H-field distributions of the entire preliminary dielectric unit. Compared with the field distributions in Figure 5a,b, similar field distributions are obtained. Specifically, when these two dielectric slabs are fed by the dielectric filled SIW horn, the air cavity in the middle also acts as the PEC boundaries for the two surface wave antennas. These findings show that properly sized length and thickness of the air cavity in the dielectric extension of the SIW H-plane horn antenna can result in narrower radiation patterns leading to the directivity improvement in the broadside radiation.

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**FIGURE 9** Radiation characteristics versus air cavity length \( L_{air} \) for the preliminary unit fed by the SIW horn

For a more intuitive understanding and observation of the E-field radiation, a comparative field simulation among the basic SIW H-plane horn antenna called plain structure, the SIW H-plane horn antenna loaded with a rectangular dielectric extension called loaded structure, and the proposed structure has been conducted. All antennas have the same dimensions for the SIW section and are operated at the same frequency. The loaded and proposed structures have the same loading length \( L_3 \) of 34 mm.

The plots of the magnitude of E-field in E- and H-plane are shown in Figure 10. Figure 10c clearly illustrates a reduction in the side radiation, marked as an angle \( \theta_c \), as a result of the phase difference between the radiating sources compared to Figure 10b. The normalised radiation patterns of all structures are illustrated in Figure 10d,e. They show that the benefits of the embedded air cavity correct the low directivity and high SLL in both planes when the loading structure is simply extended.

4 | PARAMETRIC STUDY OF THE PROPOSED ANTENNA

In this section, we present the proposed final structure where the dielectric loading utilises a length \( L_3 \) of dielectric in front of the horn that is optimised to 6 mm and illustrated in Figure 1, for achieving a better radiation performance [14]. Two variables, the length \( L_{air} = L_3 - L_5 \) (from Figure 1) and thickness \( b_1 \) of the rectangular air cavity are investigated for their impact.

4.1 | Impact of the air cavity length

The normalised radiation parameters HPBW, SLL, FTBR, and directivity of the proposed antenna with the length \( L_{air} \) increasing from 0 to 3.0\( \lambda_g \) are illustrated in Figure 11. The height \( b_1 \) of the air cavity is fixed at 0.8 mm.

As expected, a general trend of reduction in both E- and H-plane HPBW’s occurs as \( L_3 \) increases. The minimum
obtained HPBW values are 36.3° in E-plane and 28.7° in H-plane for the length $L_{air} = 3.0\lambda_g$. As for the effects on side lobes, the SLL in E-plane keeps decreasing as $L_3$ increases from $1.34\lambda_g$ to $3.0\lambda_g$, reaching about $-13.6$ dB. Furthermore, the lowest $-20$ dB SLL in H-plane occurs when $L_{air} = 2.11\lambda_g$.

The impact on the directivity and FTBR caused by the length of dielectric loading is shown in Figure 11. Steady improvement of the peak directivity can be achieved by increasing the length $L_{air}$. The highest directivity $15.68$ dBi is achieved when $L_{air} = 3.0\lambda_g$. On the other hand, the FTBR values are all above $20$ dB when the air cavity length is longer than one guided wavelength. The highest FTBR at $35$ and $33$ dB are reached when $L_{air}$ are $2.11\lambda_g$ and $2.69\lambda_g$ (marked as dotted lines) respectively.

### 4.2 Impact of the air cavity height

The HPBW and SLL with different height $h_t$ of the air cavity ranging from $0.03\lambda_0$ to $0.17\lambda_0$ are illustrated in Figure 12. Considering the fabrication rules and manufacturing accuracy, the values of $h_t$ beyond this range are not included. The length...
A coaxial Huber + Suhner’s PC 3.5-mm connector with characteristic impedance 50 \Omega and a transition pin (73-Z-0-0-168) is used to feed the SIW.

To observe the radiation performance of the proposed antenna at multiple frequencies, the measurement was performed in a frequency range from 22 to 27 GHz. The measured HPBWs and SLLs in normalised value in this frequency range are shown in Figure 14. The measured HPBW in E- and H-plane are below 37.5° and 30.8° respectively with a continuing narrowing trend as frequency increases, reaching 30° and 23° at 27 GHz. All SLL values in E-plane are maintained below –10 dB with two lowest points – 12.6 dB and –13.06 dB at 23.6 GHz and 25.8 GHz. For H-plane, the SLL is reduced to –20 dB and –23 dB at the frequencies 22 and 24.5 GHz.

The measured realised gain and FTBR from 22 to 27 GHz are also plotted in Figure 14. The realised gain is enhanced to around 13.5 dBi in this frequency range with 13.4 dBi at 24.15 GHz. Specifically, higher realised gain above 15 dB can be obtained at 23 GHz, 25 GHz, and 26 GHz due to the better matching to the 50 \Omega port impedance. From 22 to 24.6 GHz, the FTBR is above 20 dB, with 38.8 dB peak value occurring at 23.6 GHz.

The measured and simulated radiation characteristics show a discrepancy in SLLs in both E- and H-plane around 24.15 GHz. This is due to the manufacturing accuracy and drilling issues. The offset in both dielectric slabs and air cavity, and the rough surface caused by the drilling are shown in Figure 13d. Simulations were conducted to account for these imperfections and compared with the measurements. The simulated and measured radiation patterns with offset and rough surface at 24.15 GHz are shown in Figure 15. The simulated side lobes in H-plane are asymmetric, and the main lobe in H-plane has a 3° shift from the principal propagation direction agreeing with the measurement results. The SLL in E-plane increases as the rough surface is present. These findings indicate that the radiation characteristics could be improved if the surfaces of the dielectric extension are smooth.

5 | ANTENNA FABRICATION AND MEASUREMENT

A prototype of the optimised antenna shown in Figure 13 is fabricated by using a commercially available PCB manufacturing.
The measured and simulated reflection coefficient $S_{11}$ show a good agreement as plotted in Figure 16a. Two measured frequency ranges around 24.2 GHz and 26.3 GHz with $S_{11}$ below $-10$ dB are obtained, which are close to the simulation. The narrow BW is a result of the proposed antenna being directly fed by the coaxial connector, as this feeding technique limits the BW of operations [7–9]. To confirm that the antenna itself is a wideband structure, we performed a simulation, given in Figure 16a, of the proposed antenna illustrated Figure 16b, where a different excitation by a rectangular waveguide was utilised. The simulated reflection coefficient $S_{11}$ of the proposed antenna excited by a rectangular waveguide (wave port in the HFSS simulator) with a pair of tuning vias increases the relative BW above 20.5%, as shown in Figure 16b. The normalised radiation patterns at 23.35 GHz, 25.85 GHz and 27 GHz are plot in Figure 17, indicating that our proposed structure contributes to stable radiation characteristics in multiple frequencies.

A summary of recent articles related to designs on one single PCB layer is listed in Table 2. In the case of wideband, the best radiation performance is selected for a single frequency. It can be concluded that from the literature, for typical SIW H-plane horn antennas, poor performance in E-plane always exists, limiting the gain improvement. Even if some designs show narrowed HPBW in E-plane [18,19], the corresponding SLLs are all above $-10$ dB. Additionally, although the antennas proposed in [7,9] provide E-plane SLL at $-10$ dB, the E-plane HPBWs is still wide in [7], and the solution presented in [9] requires a complicated fabrication process. By comparison, our proposed new structure can not only improve the gain with superior radiation performance but also offer a simple design solution in one thin substrate.

6 | CONCLUSION

A new type of SIW H-plane horn antenna is presented where a dielectric loading with an embedded rectangular air cavity is proposed. The gain enhancement is achieved by suppressing the radiation pattern in both E- and H-planes using thin and high dielectric material. For achieving the high directivity of a single antenna, a unique and simple loading structure is developed to control the phase distribution of the radiating sources. To obtain a good radiation performance in multiple frequencies, the parameters of the proposed antenna are analysed and optimised. A prototype of the proposed antenna is fabricated, and the measured radiation patterns validate the simulation results. At the designed frequency 24.15 GHz, the
HPBs 34.3° in E-plane and 27.6° in H-plane are obtained, agreeing well with the simulations. From 22 to 27 GHz, high gain and narrow radiation patterns in both planes can also be maintained. The proposed antenna offers an easy option for improving the radiation characteristics without a complex design process.

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