H-Plane Sectoral Horn Antennas in Substrate-Integrated Waveguide Technology

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November 2017

Abstract
This dissertation aims to study, design and manufacture substrate-integrated waveguide (SIW) H-plane sectoral horn antennas to be used as standard gain antennas in Instituto de Telecomunicações / Instituto Superior Técnico and enhance the existing standard gain antennas collection. In this context, the SIW technology allows to build horns much lighter and as robust as the standard gain pyramidal horns. Moreover, this technology allows to design compact planar structures. In order to fulfill these objectives, one pair of SIW H-plane horns have been designed and manufactured. This pair of antennas have a gain of about 10 dBi in the microwaves L-band. A coaxial-to-waveguide transition have been integrated in the prototypes. The design and the free space simulations were performed using the CST MWS software. After manufacturing the antennas, its performance was measured using an anechoic chamber and a vector network analyzer, and thus allowing a comparison of experimental and simulated results. A good agreement has been obtained.

Keywords: H-plane sectoral horn antenna, Substrate-integrated waveguide (SIW), Standard gain antenna, Coaxial-to-waveguide transition, L-band

1. Introduction
Antennas are essential elements of any wireless communication system. This element allow for the transfer of a signal in a wired system to electromagnetic waves that propagate through free space and can be received by another antenna responsible for the reciprocal process of transforming a wave into a signal that can be processed. The antenna characteristics required to provide a good performance depend strongly on the specific system and application.

Measuring the radiation pattern and gain of prototypes in an anechoic chamber is a meticulous process. This process is usually made by the use of standard gain antennas that receive radiation from (or transmit radiation to) the antenna under test (AUT). Standard gain antennas are used for gain reference and antenna measurements. These antennas have their characteristics well defined and when comparing its results with the results of the AUT, it is possible to take conclusions about its characteristics. The most common type of standard gain antenna is the horn.

At Instituto de Telecomunicações / Instituto Superior (IST) in the anechoic chamber facility there are a number of standard gain horns covering most of the range of microwaves. The covered range starts at 1.72 GHz up to 75.8 GHz and it is divided by smaller bands according to the EIA standard WR waveguide system, with each band having a pair of antennas. These antennas are pyramidal horns. It is important to note that the IT/IST has only one antenna in the L band, below the lowest band covered by a pair of existing horns. This last horn is very large, taking considerable dimensions and weight.

It is also important to say that this anechoic chamber is designed to have an operation frequency above 2 GHz. Studying antennas in this chamber below the certified frequency is also possible but the chamber have more reflections, and therefore the results are less accurate. However, results with acceptable accuracy can be obtained below 2 GHz. Taking this in consideration, adding the fact that the L-band horn is heavy and large, constitute two reasons which why the IT/IST acquired only one horn in this band.

To minimize the possibility of reflections on the walls of the chamber, it is required that the gain of the antenna is as large as possible resulting in a narrower beamwidth. To achieve large gains, the antennas have to be electrically large. In the anechoic chamber specifications, the antennas have to be in the farfield of each other to achieve accurate
results. The distance between the two positioners is approximately 5 meters. One of the rules of farfield that has to be respected is

\[ d \geq \frac{2D^2}{\lambda} \]  

(1)

where \( D \) is the largest physical linear dimension of the antenna and \( \lambda \) is the wavelength of the radio wave. For this reason, the standard gain horn can not be electrically large. There is a trade-off between these incompatible requirements, large and small dimensions and a compromise has to be achieved. A good compromise corresponds to horn with a gain of about 10 dB. In summary the objectives of this thesis is to design, fabricate and test one pair of SIW H-plane horns to be used in the frequency ranges 1.12-1.73 GHz. These antennas need to be as small and light weight as possible, provide a gain of about 10 dBi and linear polarization in the principal E and H planes.

In this context, the substrate-integrated waveguide (SIW) technology allows to build horns of acceptable weight and as robust as the pyramidal horns and our goal is to manufacture one pair of standard gain horns in order to enhance the existing collection.

2. State of The Art

2.1. Horns in Free Space

The horn is a waveguide which has been flared to a larger opening. The type, direction and the flare angle can have a big effect on the overall performance of the element as a radiator. The variety of shapes and sizes is connected to many practical applications such as communication systems, electromagnetic sensing, radio frequency heating, testing and evaluation, biomedicine, and a reference source for other antenna testing. Sectoral and pyramidal horn antennas are associated with rectangular waveguides, where the fundamental mode is the \( \text{TE}_{10} \), while circular waveguides feed conical horns and the fundamental mode is the \( \text{TE}_{11} \). [1]

An electromagnetic horn can take many different forms, four of them are shown in figure 1. Probably the most commonly occurring horn is the rectangular pyramidal family (figure 1c). A special case is sectoral horns, which are flared in only one plane and thus radiating a broad beam in the plane orthogonal to the flare. The conical horn allows any polarization of the exciting dominant \( \text{TE}_{11} \) mode and it is well-suited for circular polarization.

Flaring a waveguide provides a directive radiation pattern and a smooth transition from the input to free space. The surface across the face of the horn is called the aperture and is a reference for calculating the radiated fields. For horns with aperture dimensions greater than about one wavelength, the radiation characteristics may be calculated with reasonable accuracy by using equivalent currents (equivalence principle) and an approximation to the aperture field [2].

2.2. H-Plane Horn Antennas

The H-plane sectoral horn is one whose opening is flared in the direction of the H-field while keeping the other constant, and its shown in figure 2a. The horn is fed from a rectangular waveguide of interior dimensions \( a \) and \( b \), with \( a \) the broad wall dimension. The aperture is of width \( a_1 \) in the H-plane and height \( b_1 = b \) in the E-plane. The H-plane cross section in figure 2b reveals the geometrical parameters. In figure 3 it is represented the spherical coordinate system used and in grey is drawn the aperture of the horn included in the plane \( xy = 0 \). The dimensions \( a_1 \) and \( L_h \) (or \( \rho_1 \) or \( \rho_2 \)) must be determined to allow construction of the horn.

2.2.1 Radiated Fields

Huygen’s equivalent principle can be applied to the aperture across the opening to obtain equivalent current on the aperture, and then farfield region and electric vector potential can be achieved by integrating equivalent aperture magnetic and electric currents over the aperture. Assume aperture fields are associated with transverse electric fields of waveguide through a quadratic phase item, and substitute this relationship into magnetic vector potential and electric vector potential result in a two-dimensional Fourier transform. Farfield electric field and magnetic field can be now obtained. The horn antenna pattern on E-plane and H-plane can be computed from [3].

2.2.2 Directivity

The maximum radiation is directed nearly along the z-axis (\( \theta = 0^\circ \)) and the directivity for the H-plane

Figure 1: Different configurations of electromagnetic horn antennas [1]
(a) H-plane sectoral horn overall geometry

(b) H-plane cross section

Figure 2: H-plane sectoral horn and coordinate system (Adapted from [1])

Figure 3: Spherical coordinate system for a horn aperture (Adapted from [2])

The optimum directivity occurs when [1]

\[ a_1 \approx \sqrt{3\lambda\rho_2} \]  

2.3. SIW Technology

A very promising candidate for the development of microwave circuits and components is substrate-integrated waveguide (SIW) technology [4–6]. SIW structures are constructed by using two rows of conducting cylinders or slots embedded in a dielectric substrate that electrically connect two parallel metal plates (see figure 4), and allow the application of the regular rectangular waveguide components in planar form, as well as printed circuit boards (PCB), active devices and antennas. SIW structures exhibit propagation characteristics similar to those of rectangular metallic waveguides, knowing that the radiation leakage can be neglected due to the short space between the metallic vias. SIW modes correspond with the TE_{m0} modes, with \( n = 1, 2, \ldots \). SIW does not support TM modes due to the gaps between metal vias. The longitudinal surface currents are determined by transverse magnetic fields [7].

Having in mind this similarity between SIW and rectangular waveguide, some relations have been achieved regarding the geometrical dimensions of the SIW and the effective width \( w_{eff} \) of the rectangular waveguide. One of the most popular relations was derived in [8]:

\[ w_{eff} = w - \frac{d^2}{0.95s} \]  

provided that the spacing between the posts \( s \) is sufficiently small, where \( w \) is the transverse spacing and \( d \) is the diameter of the metal vias (see figure 4). This approximation is valid for \( s < \lambda_0\sqrt{\epsilon_r}/2 \) and \( s < 4d \). Relation 3 was later improved in [5], including the effect of \( d/w \):

\[ w_{eff} = w - 1.08\frac{d^2}{s} + 0.1\frac{d^2}{w} \]  

which is very accurate when \( s < 3d \) and \( d/w < 1/5 \). Other relation was presented in [9] which implies that when \( d < s/4 \), the width \( w_{eff} \) is bigger than the width \( w \) of the SIW and vice versa:

\[ w = \frac{2w_{eff}}{\pi} \cot^{-1} \left( \frac{\pi s}{4w_{eff}} \right) \left( \frac{s}{2d} \right) \]  

2.4. SIW Antennas

Several configurations have been proposed and the first SIW antenna was based on a four-by-four slotted SIW array operating at 10 GHz [10]. A different topology is the leaky-wave antennas, introduced
in [11] and exploits one of the fundamental characteristics of the SIW, the property to generate radiation leakage when the longitudinal spacing of the metal vias is sufficiently large.

Apart from the classical waveguide-based antennas, with apertures either on the top or on the side wall, other antenna configurations have been proposed in the literature. In [12] it is presented a modified Vivaldi radiator that consists of a dual V-type tapered slot antenna which is a good topology to be integrated in SIW technology. A cavity SIW antenna has been proposed in [13] and consists of a slotted SIW cavity fed by a coplanar waveguide.

Compact, patch oscillator antennas were proposed in [14]. It was used a square SIW cavity where the antenna was etched on the metal layer on one side of the substrate, and the antenna feed network and active device were placed on the other side, minimizing unwanted effects on the radiation pattern of the antenna.

2.4.1 SIW Horns

One of the advantages of combining SIW and horns is the physical adaptation. This solutions permit a reduction in size and weight of components. The horns have to be H-plane sectoral horn because of the planar requirement to take benefit of the capability of SIW.

Some of the limitations associated to the use of substrate are low efficiency as frequency is increased due to dielectric loss, strong mismatch due to the use of thin substrate layers, high reflection at the end of the aperture caused by the impedance difference between the air and the dielectric, and low gain.

There are common techniques to improve the horn performance and to reduce its dimensions, for example to include a loading or a lens over the horn aperture, optimized transitions, or including air vias in the structure. An H-plane sectoral horn antenna in SIW technology is presented in [15]. This antenna was also combined with a dielectric loading with rectangular and elliptical shape, integrated in the same substrate, which allows high gain and narrow beamwidths both in the E-plane and in the H-plane. Usually, dielectric lenses are used since metal-plate lenses introduce a polarizing effect and their edges cause diffraction. This solution is easy to implement as the lens can be created by extending the same dielectric slab where the horn is built. These horns are known as lens-corrected horns and the lens focuses the radiation frontwards, increasing the front-to-back-ratio and reducing the phase error. This antenna has been used to form a one-dimensional mono-pulse antenna array to obtain higher gain.

Other rectangular dielectric loaded SIW H-plane sectoral horn antennas have been fabricated and tested in [16] and resulted in improved gain and beamwidth. The length of the horn was reduced further which resulted in an increase of gain and also narrow beamwidths in the E-plane and H-plane.

An highly efficient empty substrate-integrated waveguide H-plane sectoral horn is presented in [17]. The antenna is integrated with a planar substrate and is fed by a microstrip line. It is composed of a partially empty substrate layer stacked between two cover metallic plates. The structure does not depend on substrate characteristics and this new methodology improves the performance of conventional substrate-integrated waveguide horn antennas.

The design rules for SIW horn antennas follow the same principles as free space horn antennas. To ensure the single mode excitation of a H-plane SIW horn, the width of the feeding waveguide a should be such as \( \lambda_0 / (2\sqrt{\epsilon_r}) < a < \lambda_0 / (\sqrt{\epsilon_r}) \) and the height b smaller than a, and in order to excite the fundamental mode, b can be as small as desired. However, SIW Horns are not well matched when the substrate thickness b is much smaller than the free space wavelength \( \lambda_0 \), and usually the available substrates are much thinner than the wavelength yielding poor matching and undesired back radiation. The previous lens approach presented is not feasible for \( h < \lambda_0 / 10 \) because of the effect of the lens is negligible. In [18], a structure that consists of a transition printed in the same SIW substrate which improves both the radiation and the matching performances of conventional SIW horns is presented. The horn shape is further optimized by reducing its dimensions required for a given directivity and the transition is adapted to improve more the front-to-back ratio in [19]. The proposed transition is designed to match a H-plane SIW horn built in a thin substrate (thickness < \( \lambda_0 / 10 \)) at the Ku-band. In general, for thicknesses smaller than \( \lambda_0 / 6 \), the mismatch between the aperture and the air results in unwanted radiation and poor matching, what is frequently encountered at frequencies lower than 20 GHz. The existing thicker substrate than \( h > 2.5 \) mm are not well suited for manufacturing SIW structures because the via metallization is then challenging, and for these reasons the SIW technology is mainly used in the millimeter-wave region. The solution proposed is based on a printed transition etched after the horn aperture, maintaining the most important features of the SIW technology, namely its compactness and ease of manufacturing.

Other technique is to integrate metal rectangular patches and dielectric loading into the aperture.
of the horn antenna proposed in [20] to a H-plane horn. This results in an increased gain, narrow E-plane beamwidth, and reduced sidelobes and backward radiation. To minimize the sidelobes while maintaining compact size and easy fabrication, the rectangular patches are added in front of both the top and bottom layers of the dielectric loaded SIW H-plane horn.

Recently, two novel designs of SIW H-plane horn antenna have been presented in [21]. The structure is a transition with double square loop and further improved with rotated double square loop. This technique improves the mismatch between the horn and free space and the bandwidth performance can be improved to a large extent by optimizing the dimensions of the double square loop and rotation angle.

3. Design of H-Plane SIW Horns

The system is constituted by the aggregation of three parts: the waveguide, the horn and the feed.

To ensure the single mode TE$_{10}$ excitation of a H-plane SIW horn, the dimension of the feeding waveguide $a$ should respect this requirement. Basic behavior of a waveguide depends upon the dimensions of the waveguide and the dielectric constant. The cutoff frequency for both the TE$_{mn}$ and TM$_{mn}$ modes of a waveguide are given by

$$ f_{c_{mn}} = \frac{c}{2\pi} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} $$  \hspace{1cm} (6)

The dimension $a$ determines the cutoff frequency of the fundamental mode TE$_{10}$,

$$ a = \frac{c_0}{2f_{c_{10}}\sqrt{\epsilon_r}} $$  \hspace{1cm} (7)

In order to avoid a high dispersion zone, lower power capacity and greater attenuation, the lowest working frequency of the waveguide is commonly chosen 20% above the cutoff frequency of the fundamental mode. Higher values of $b$ lead to the lower attenuation and greater power capacity. However, if $b > a/2$, the second mode will be TE$_{01}$ and the frequency band for unimodal mode is smaller. For this reason, normally it is decided that $b = a/2$ or slightly lower. To avoid leaving the frequency range of the unimodal mode, the guide is used of about 90% of the cutoff frequency of the second mode. The equation 7 becomes:

$$ a = \frac{1.2c_0}{2f_{min}\sqrt{\epsilon_r}} $$  \hspace{1cm} (8)

For a conventional hollow rectangular waveguide, it is considered that $\epsilon_r = 1$, and the antenna will operate in the L band, the minimum frequency of use is 1.12 GHz and the cutoff frequency is 933 MHz. The dimension $a$ then takes the value of 160.7 mm. The cutoff frequency of the second mode (2x933MHz = 1.866 GHz) is above the intended maximum frequency of use which is 1.73 GHz.

3.1. Metallic H-plane Horn in FR4 Substrate

The FR4 plates physical limitations. The plates have dimensions 420x350 cm$^2$ and thickness of 1.6 mm. It has to be decided to which side the horn is going to flare, to the one that is wider or not. On this study, it was decided to take 40 mm for the length of the waveguide and so it gives two options of dimensioning the horn: 1)380x350 or 2)420x310. The thickness depends on how many plates are going to be used, having in mind they are going to be placed on the top of each other. In between the plates, a planar radiating element would be placed. The options are 2 plates together, 4 or 8, knowing that having 8 plates it is equal to a thickness of 12.8 mm, a considerable value of thickness. In table 1 it is presented the gain for different number of plates and the corresponding thicknesses.

The gain is improved when using a thicker substrate, which is not suitable for our project. To end this study of the use of FR4 substrate, it is going to be calculated the number of plates that would be necessary to have a reasonable gain. With 32 plates of FR4, it gives a thickness of 51.2 mm and a gain of 3.6 dBi is achieved. With a two blocks structure transition and this number of plates, a gain of 7.57 dBi can be achieved. This is an acceptable gain value but the antenna is not feasible due to the complexity of the process of bonding so many substrate plates.

3.2. Metallic H-plane Horn in Foam Substrate

The optimization of a classical metallic horn has to be made before the design of the SIW structure. Due to the equivalence between the two structures, the metallic structure has to be studied first.

A design has to be made to achieve our requirements and to respect our limitations. The plates available have dimensions 1250x600 mm$^2$ and thicknesses from 40 mm to 80 mm in intervals of 10 mm. The rule of farfield (equation 1) has also to be respected for a 5 meters measurement distance, corresponding to the distance between positioners in

<table>
<thead>
<tr>
<th>#Plates</th>
<th>Thickness [mm]</th>
<th>Gain [dBi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.6</td>
<td>-14.1</td>
</tr>
<tr>
<td>2</td>
<td>3.2</td>
<td>-10.9</td>
</tr>
<tr>
<td>4</td>
<td>6.4</td>
<td>-7.71</td>
</tr>
<tr>
<td>8</td>
<td>12.8</td>
<td>-4.46</td>
</tr>
<tr>
<td>32</td>
<td>51.2</td>
<td>3.6</td>
</tr>
</tbody>
</table>
the anechoic chamber. Using the rule, the largest physical linear dimension of the antenna is 658 mm (for the smaller wavelength). It means that we can assume that our plate maximal dimensions are 658x600 mm$^2$.

Having our physical limitations in mind, and respecting the reference level of -10 dB for the reflection coefficient, an optimized horn has been obtained from simulations. The $L_H$ is 414 mm resulting in a good reflection coefficient. The dimensions are presented in figure 6. It is important to state that at the initial frequency 1.12 GHz the $S_{11}$ takes -9.37 dB and after 1.13 GHz, the $S_{11}$ is always below -10 dB. The gain is 9.98 dBi and the HPBW is 111° for the E-plane and 29° for the H-plane.

Figure 5: $S_{11}$ results of the H-plane foam optimized horn

Figure 6: CST model and dimensions of the L-band H-plane metallic horn

3.3. SIW H-plane Horn in Foam Substrate

First of all, a comparison between horn with metallic walls and SIW horn has to be made to ensure that there is a good equivalence between models. The distance between pins in SIW is the same as the diameter of pins (1 mm) resulting in the design most similar to a classic metallic horn. As it is expected, the $S_{11}$ results are very similar and they are shown in figure 7.

The distance between pins is now progressively increased to verify the conclusions taken before when studying the distance between pins on the waveguide model. The values of $s$ are in wavelengths and the wavelength is the smaller over the range. It means for the highest frequency, 1.73 GHz it gives a wavelength of 173.41 mm. For lambda/16, it gives a good $S_{11}$ over the frequency range, but at frequency 1.33 GHz, it is slightly above the -10 dB level. For lambda/15 the $S_{11}$ is completely different. It was concluded that this results are not in conformity with the conclusions taken before for a waveguide study. Before, it was concluded that for values of $s$ starting at lambda/6 to smaller values of spacing that the transmission and reflection in SIW is acceptable.

Figure 7: Comparison of $S_{11}$ results of classical and SIW models

4. Horns with Coaxial-Waveguide Transition

The rectangular waveguide is a non-TEM mode wave propagating structure, where the wave is transmitted in a TE or TM mode. A coaxial line supports a TEM mode. The coaxial to waveguide transition converts the TEM mode of the coaxial line into the TE$_{10}$ mode of the waveguide and vice-versa. Two classical approaches in designing coaxial-to-waveguide transitions are the electric (or right-angle) probe and the magnetic (or in-line) probe. To achieve an optimum impedance match, the optimization concerns finding the best location, height and diameter of the probe.

Figure 8: Electric probe coaxial-to-waveguide transition

The most common classical approach of coaxial-to-waveguide transition is the right-angle transition, also known as electric probe. The inner conductor of a coaxial cable is incorporated in the waveguide by using a simple antenna probe reaching into the waveguide to excite the $TE_{10}$ mode, and the shield of the coaxial cable is connected to
the waveguide side as shown in figure 8. A back-short is positioned some distance D away from the probe, and it will work as a short-circuit. The electromagnetic energy that was propagating the wrong way is reflected back to the probe where it combines with the incident wave. The time-varying electric field generated by the probe is going to propagate down the guide. The right-angle type of transition can provide low reflection coefficient across the full waveguide frequency band. The distance D is usually smaller than a quarter of a guided wavelength at center frequency. The coaxial cable is typically 50 ohm impedance, whereas the impedance of the \( TE_{10} \) mode in a rectangular waveguide is of the order of few hundred ohm. To enhance the matching, some tuning must be applied and can be achieve by including tuning screws. Tuning screws are positioned in a point to reduce the reflection in a certain frequency but compromising the reflection in other frequencies. It enhances the bandwidth in a narrow frequency range. For free space, the probe height would be 1/4 wavelength, a quarter-wave monopole. The height and the diameter of the probe are parameters that can be varied to optimize the design. To provide a better match and enhance bandwidth, the center coaxial pin is widened gradually as it extends into the waveguide.

The classical approach was tested without bringing good matching to our horn. A modification to this configuration was also tested including a disc load, but also without good results. Finally, a configuration with variable diameter transition (figure 9) in now interfaced in our L-band classical horn.

With this final transition, it was decided to test with different pins distances. Accordingly to the previous SIW optimization of the previous chapter, the results are better for lambda/16 and a verification is needed. In figure 11 it can be seen that the space between pins can be increased to lambda/10 = 17.34 mm. This confirms that the optimization of the SIW horn was not correct. A numeric error related to the waveguide port position in CST is the cause of this problem, and it was not understood and corrected at that time.

![Figure 10: \( S_{11} \) of the L-band optimized transition](image1)

![Figure 11: Comparison of \( S_{11} \) results of the optimized horn with transition for different pin distances](image2)

During the manufacturing process of the L-band SIW horn, it was noticed that the metal support that is going to hold the antenna in the positioner is not large enough to incorporate the horn. This forced a reduction of the foam thickness from 80 mm to 70 mm. The horn dimensions as well as the transition dimensions are the same, but the antenna performance is different. The gain reduced and the \( S_{11} \) is now not less than -10 dB at some frequencies. Simulations were done to try to enhance the reflection coefficient without success and the best results were achieved with the same dimensioned transition. Results are shown in figure 13 (pink curve). Also during the manufacturing process it was noticed that using copper wire of 1 mm diameter as pins was a complex and hard task to do, so it was decided to use copper wire of 1.5 mm diameter without significant influence on the antenna performance.

![Figure 9: Probe with variable diameter](image3)
5. Prototypes and Experimental Results

5.1. Prototypes

One pair of H-plane SIW horns were produced. The working frequency is in L-band. The spacing between pins is equal to \( \lambda/10 = 17.341 \text{ mm} \) of the highest frequency. Respecting this spacing between pins, for each side of horn, it is needed an integer number of pins. It results in a slightly smaller spacing between pins for each side. Referring to our final horn dimensions in figure 6, for \( a = 165.1 \) it is needed 11 pins and it results in \( s = 16.51 \text{ mm} \). For \( L_1 = 167 \text{ mm} \), 11 pins are also needed but with \( s = 16.7 \text{ mm} \). Finally for the flare side equal to 461 mm, it is needed 28 pins with \( s = 17.07 \text{ mm} \). The total number of pins is equal to 85 and it was used copper wire of diameter 1.5 mm as a metal pin. The foam used is 2 plates of roofmate, one with 30 mm thickness and another of 40 mm, placed together.

It was decided to give a margin of 5 mm in each side between the pins center and the edge of the copper plates. The initial plan to build the prototype was to join the foam as also the copper plates together and then proceed to weld the pins on both sides of the antenna. Due to the heat of the weld procedure, the foam started to melt more than what was expected. Because of this problem, it was decided to first, weld all pins and after this, incorporate the foam that was cropped exactly to be inserted from the horn aperture to the bottom. The horn with the welded pins and foam can be seen in figure 12a. The transition was inserted inside the foam and incorporated at the same time the foam was incorporated. The SMA connector was welded to the horn top face then joined to the brass transition with a 1.5 mm screw that can be seen in figure 12b.

![SIW horn with substrate](image1)

![Coaxial-to-waveguide transition](image2)

Figure 12: SIW horn prototype and coaxial-to-waveguide transition

5.2. \( S_{11} \) Results

In this section it is presented the experimental \( S_{11} \) measured to both L-band SIW horns. In both measurements, pieces of foam that absorbs electromagnetic radiation were place under the horn to avoid reflections from the floor. In figure 13 it is presented a comparison of both experimental and simulated \( S_{11} \) for both prototypes (1 and 2). As it can be seen the results have good agreements to what was expected. As it can be observed, the reflection coefficient is not less than -10 dB for all frequencies.

![Figure 13: Comparison of simulated and measured \( S_{11} \) results](image3)

5.3. Radiation Pattern Results

This section present experimental radiation pattern results obtained in an anechoic chamber. The results only present patterns regarding the H-plane and E-plane or the horizontal plane and the vertical plane.

The gain-transfer method provides a simple yet accurate solution for measuring antenna gain. This method utilizes a gain standard with well-known performance characteristics (gain and \( S_{11} \)). This method consists of performing two measurements of received power. In the first measurement, the standard gain horn is used to receive and in the second measurement it is used the AUT. The transmit antenna is the same during both measurements. The gain of an AUT is determined in conjunction with the following equation [22]:

\[
G_{AUT} = \frac{P_{AUT} G_{SGH}}{P_{SGH} \left( 1 - |\Gamma^2_{AUT} | \right)} \left( \frac{d_{AUT}}{d_{SGH}} \right)^2
\]

\( G_{AUT}, P_{AUT}, d_{AUT}, d_{SGH} \) and \( |\Gamma^2_{AUT} | \) are the unknown gain, received power, distance between transmit antenna and AUT and reflection coefficient associated with the AUT, respectively. \( G_{SGH}, d_{SGH} \) and \( P_{SGH} \) are the known standard antenna gain, distance between standard gain antenna and AUT and received power associated with the standard gain antenna, respectively. A pyramidal horn is used as standard gain antenna.

In figure 14 it is presented the gain over frequency for three cases: prototype 1, prototype 2 and for the simulated model. A gain of 9.54 dBi was achieved at center frequency for the simulated model, comparing to a gain of 10 dBi (prototype 1) and of
9.97 (prototype 2) achieved from the measurements. The maximum difference between simulated and experimental gain results is about 1 dB. Taking into account that the working frequency is substantially below the minimum certified frequency of use of the anechoic chamber (2 GHz) used in the measurements, this difference is acceptable.

A comparison between simulated and measured radiation pattern (gain scale) of prototype 1 at center frequency (1.40 GHz) is presented in figure 15. It is necessary to point out that for angles above about 130 degree (and below about -130 degree) the positioner blocks the radiation of the AUT and therefore the measured results are strongly corrupted. In the E-plane, except in the mentioned block region the agreement between simulated and experimental results is very good. In the H-plane the agreement is good in the main lobe, but is not good for angles above 90 degree (below -90 degree) where the difference is mainly caused by the poor performance of the absorbing material used in the walls, ceiling and floor.

It was observed that the cross-polarization level is below -30 dB in the -10 dB beamwidth region of the main lobe.

6. Conclusions and Future Work

Two substrates emerged as possible solutions for our antennas. When using FR4 it was noticeable that a horn would need a very thick substrate to have an acceptable gain. Some solutions were designed with lower thicknesses, and none of them gave good performance. For this reasons, the foam was selected for our project.

The L-band horn was designed in a classical metal form and then converted to SIW and it maintained the same characteristics. A coaxial-to-waveguide transition was designed and optimized to give the best performance. A final solution was designed with 70 mm thickness of foam and a gain of 9.54 dBi was achieved at 1.4 GHz. The $S_{11}$ is acceptable, but it is slightly above -10 dB at a few frequencies.

One pair of H-plane SIW horns was manufactured and the experimental results are in good agreement with the simulated ones. This pair of antennas have working frequency range in the L-band and gain of about 10 dBi in the central frequency. A coaxial-to-waveguide transition has been integrated in the prototypes. The SIW horns weights 3.4 Kg comparing to 11.6 Kg of correspondent pyramidal FMI model.

Although most of the proposed objectives have been achieved, there are still some aspects to be improved. It is suggested for future work to realize a detailed study on how to enhance the horn impedance matching using the capability of tuning screws and to measure the horn gain and radiation pattern in an anechoic chamber that is certified for the used frequency range.

It was also observed with the experimental measurements the reflections effects that occur inside the chamber for frequencies lower than 2 GHz, the limit which the anechoic chamber is certified.

To conclude, our work contributed with one pair of L-band standard gain horns to be used in IT/IST far field anechoic chamber facility and it was confirmed that SIW technology allows to fabricate lighter structures.

Acknowledgements

I would like to thank my supervisor Professor Custódio Peixeiro for all support, dedication, knowledge and guidance, provided continuously during the development of the present work.

I also would like to thank Mr. Jorge Farinha and Mr. António Almeida for the knowledge, experience and ability for the construction and tests of the prototypes.

References


