"NEW APPROACH TO THE DESIGN OF CORRUGATED HORN ANTENNAS"

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Abstract

In this paper, we present two new corrugated horn antenna designs in circular waveguide. The first one is a converter horn antenna from monomode circular waveguide TE_{11} to corrugated waveguide HE_{11} mode in a very efficient way. The conversion efficiency varies between 98 % and 99%.

The HE_{11} mode has highly desired radiation pattern characteristics for applications like satellite communications, radar, remote- sensing, etc, nevertheless, when the requirements are more stringent this mode is not good enough and we must look for other solution. This one corresponds to the fundamental gaussian beam, which has outstanding features, such as being a free space mode, having high matching efficiency with a reflector, no sidelobes, perfect symmetry, etc. The second horn antenna presented generates very efficient fundamental gaussian beams at the output (99%-99.9%). It is important to say that the input must look like a gaussian beam, an HE_{11} for instance, which presents a 98.4% of gaussian beam or similar.

We also show a new design in which we are working now, consisting in the junction of the two aforementioned designs. They form an unique horn antenna that results in the TE_{11} mode, from the fundamental gaussian beam mode.

These components have been analysed using the Mode Matching and the Generalised Scattering Matrix techniques and the Moment Method as well as the equations in [1] to get the far field radiation pattern. Our results have been checked against those obtained by other authors.

Introduction

In many applications a complete antenna system is required. Basically, it consists on a generator, a transmission line and finally an antenna. The generator has a monomode waveguide output, typically in rectangular waveguide but sometimes in circular waveguide. The transmission line transports the power from the generator output to the antenna input using a rectangular or circular waveguide. We will assume the TE_{11} mode as input power working in a circular monomode waveguide. This mode does not have a good radiation pattern and for large number of applications it can not be used as radiation source. So, it is necessary to transform it into another mode more adequate to radiate.

This mode conversion will take place by using the component that we present in this paper. This component use corrugated waveguide technology due to its high-performance, [2] [3] [4] : i.e. the high symmetry, wide bandwidth and robustness.

With this technology we can think of two possibilities, the first one is to get an HE_{11} mode which is the corrugated waveguide fundamental mode and the second one is to generate a free space fundamental gaussian beam mode.

The HE_{11} mode has good far field radiation features and can be used in applications ranging from reflector feeder to communications, radar, remote-sensing, radio links, atmosphere studies,....with very good results.

The fundamental gaussian beam [5] is obtained from HE_{11} mode [6] in order to improve the radiation features. This is very useful in critical applications where the high efficiencies and sensibilities are required. In quasi-optical transmission line applications which mirrors are involved this would be the only solution because it is necessary to use a free space mode to minimise the transmission losses [7], [8].

In this article, we show in detail the above horn antenna designs and their results. Furthermore, we also comment on an alternative design in which we are working at this moment to join the two antennas.

TE_{11}-HE_{11} Horn Antenna Converter

As we have already mentioned before, this device appears due to the necessity to obtain a good radiation pattern from a monomode circular waveguide TE_{11}.

The chosen profile is defined by two hyperbolas in which we fix a continuous derivative at the matching plane and a zero derivative at the output. In this way, we can join it with other devices.

Superimposed to the two hyperbolas we put a surface impedance adapter to match in adequate way the TE_{11} mode to the HE_{11} mode. This adapter has a corrugation depth variation from $\lambda/2$ to $\lambda/4$ (being λ the free space wavelength) in a length L_1. This one must be chosen in such way that the final radius just allows the propagation of the TM_{11} mode.

The equations defining the horn profile are the following :

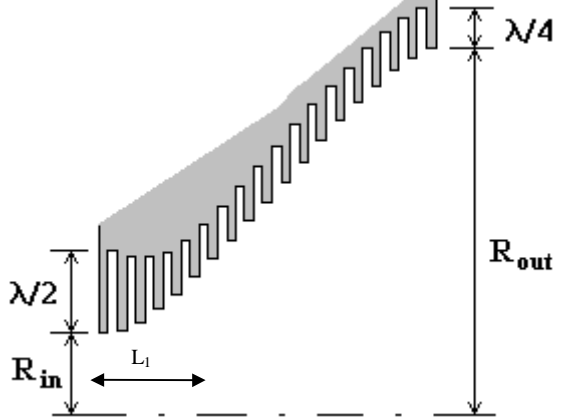$$r(z) = R_{in}\sqrt{1+\left(\frac{z}{\alpha \cdot k \cdot R_{in}^2}\right)^2}$$

$$f(z) = \begin{cases} r(z) & z < \frac{L}{2} \\ -r(L-z) + 2 \cdot r\left(\frac{L}{2}\right) & z \geq \frac{L}{2} \end{cases}$$

(1)

Figure 1 : Horn antenna converter TE_{11}-HE_{11} equations and picture.

α being a value approximately of 1.3 (it can be changed between 1.1 and 1.5) which controls de taper slope, k is the free space wave number, and L the total length which is calculated to achieve the correct output radius (between 0.65λ and 0.85λ) obtaining, in this way, approximately the HE_{11} mode. This means, there are a lot of possibilities, and we have to choose the best one for our particular application.

It is important to remind, that the HE_{11} mode composition changes with the parameters of the corrugation: period (p), depth (d) and duty cycle (w). In our design we have chosen the period equal to $\lambda/3$ and duty cycle equal to p/2. Then, it is very difficult to know, simply looking the output mixture if we are exciting or not an eigenmode of the corrugation waveguide. To show that we are exciting a pure corrugated waveguide eigenmode, one can add a straight corrugated waveguide, in order to see if the field structure keeps constant or not along the waveguide. Another possibility is to compare the far field pattern of the output mixture and the theoretical HE_{11} mode.

Furthermore, if we inspect equation (1) we can see that it depends on the k value, so the design and the working is completely independent of the chosen frequency value.

Now, we show the obtained result from the analysis of this antenna. Firstly, we can see the input far field pattern (TE_{11} mode) versus the output one (see figure 2), the improvements in the radiation pattern are evident.

The conversion efficiency to a HE_{11} mode of the field structure on the horn antenna output is 98.3%, so we can affirm that we have obtained a very good HE_{11}. Besides, in the far field radiation pattern we get an excellent characteristics like very low crosspolarization (-43 dB), no sidelobes (this is due to the relation between k and radius values) and very high symmetry between E and H planes. Another important feature is the total length, this one is 2.67 cm (2.67λ), so we have obtained a very good HE_{11} mode in a very short length.

In figure 3 we present the field lines of the TE_{11} mode and those from the output field structure of the horn antenna, as result we can see the horn antenna design gets an excellent lineal polarisation in the output mixture, this is very important in communications, radar, remote-sensing, low power testing applications.

TE_{11} far field pattern
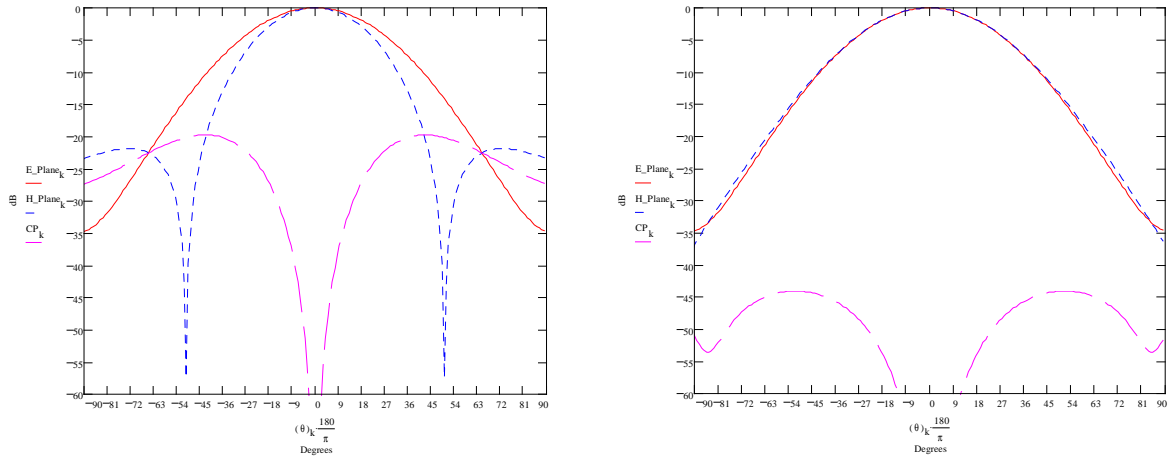Output mixture far field pattern

Figure 2: Far field radiation pattern of (a) TE_{11} mode and (b) HE_{11} mode, obtained at 30 GHz, with 7.9 mm output radius and a horn antenna length of 26.7mm.
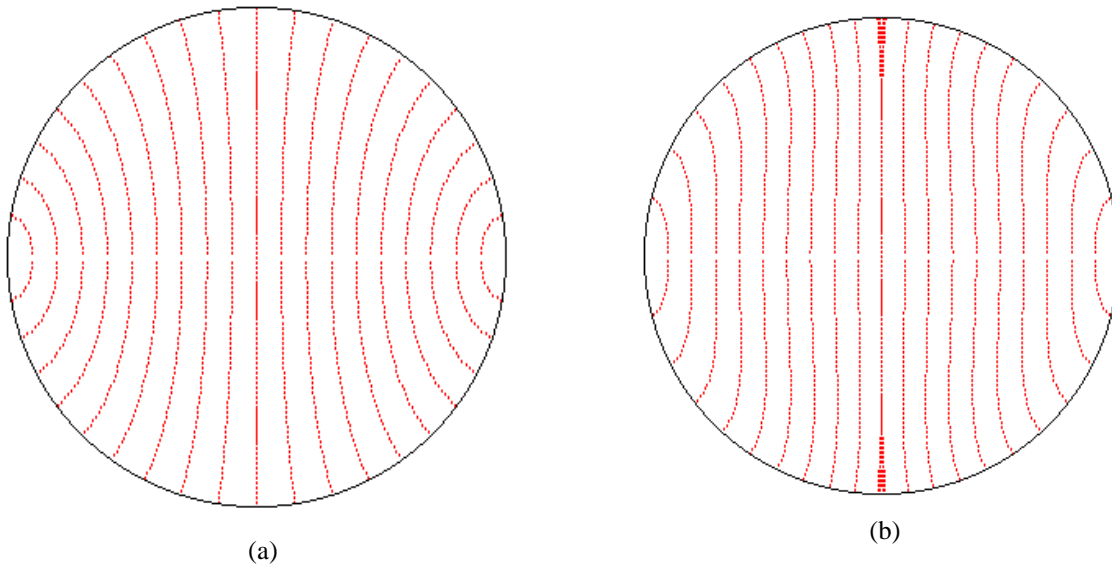

(a)

(b)

Figure 3: Field lines of the (a) input mixture (TE_{11} mode) and (b) output mixture.

In figure 4 we represent the bandwidth. To calculate it, we have used two different procedures, the first one consist on the relation between the frequency and the conversion efficiency to the HE_{11} mode and the second one the frequency versus the reflected power.

We show two different ways to calculate the bandwidth because the knowledge of the reflected power is not enough to determine the bandwidth. Also it is very important to analyse the conversion efficiency because this one must be larger than 97.5% to think over it like a good HE_{11} mode. Inspecting figure 4, we can determine that the bandwidth is about 20% of the working frequency and it is limited by the conversion efficiency parameter.

As we will see later, this component can be used also as first step to get a fundamental gaussian beam. In this case, the output of this converter does not have to be necessarily a pure HE_{11} mode, because it is not the final output of the system, besides, the second component improves the input mixture obtaining high efficient gaussian beams.

Summarising, we have proved that with this device good features are achieved, and can be used in a great number of applications requiring low crosspolarization, high efficiency, excellent symmetry pattern radiation and of course a bandwidth of about 20.
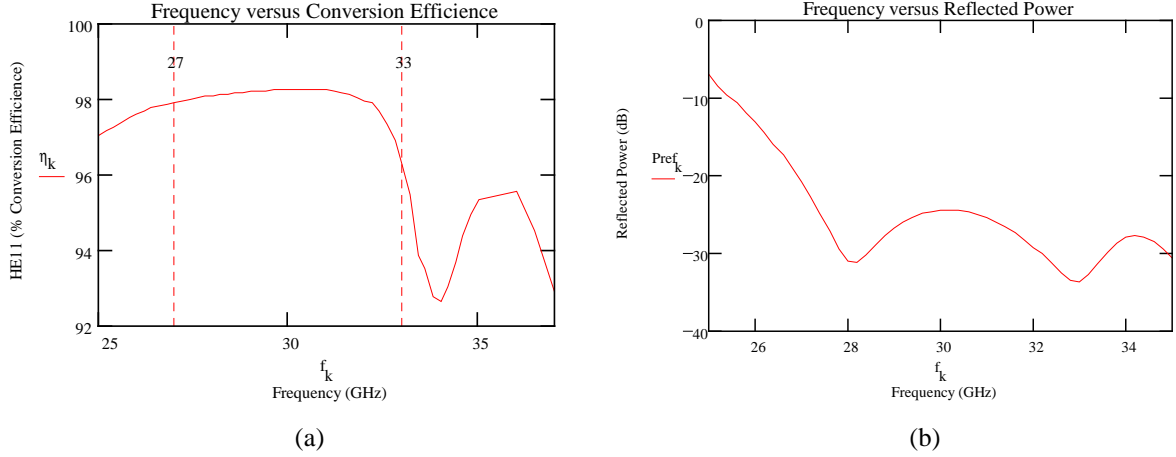
Figure 4 : Horn Antenna converter TE_{11}-HE_{11} bandwidth, related to (a) the conversion efficiency and (b) reflected power.

HE$_{11}$-Fundamental Gaussian Beam (Ψ_0^0) Antenna.

Nevertheless, sometimes, the HE_{11} mode is not good enough for some specific applications. For instance, if we need to improve some horn parameters like the gain, the reflector efficiency or the matching factor with the free space. In these cases, a high purity fundamental gaussian beam will be the preferred choice.

Before beginning to explain the component design, we should notice that the fundamental gaussian beam can be developed as a combination of circular waveguide TE_{1n} and TM_{1n} modes. The obtained results are shown in the figure 5, where the mixture of modes depend on the relation between the output radius (R) and the beam waist (ω_0) of the obtained fundamental gaussian beam.
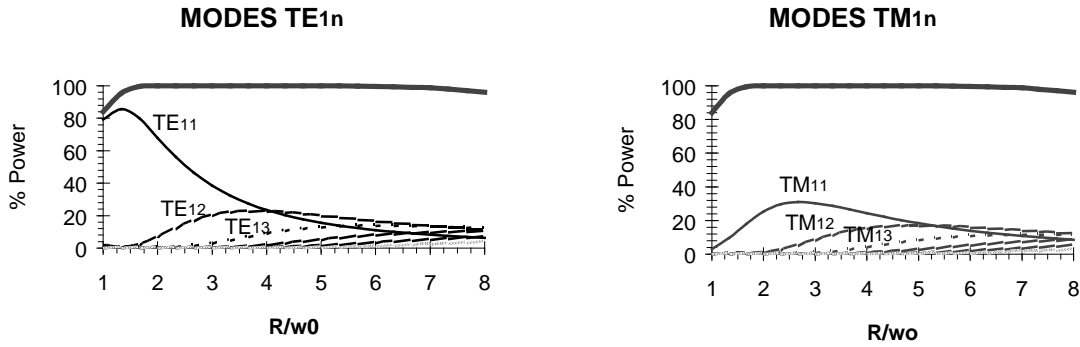

Figure 5 : Mode mixture of TE_{1n} (a) and TM_{1n} (b) necessary to get a fundamental gaussian beam.

These plots are independent of the frequency, so for a given value for R and ω_o (beam waist) the same amplitude mode mixtures to get a fundamental gaussian beam are always defined. Besides, the amplitude mixture is totally independent of the beam waist position, only a variation in the mode phases to obtain the gaussian expansion can be expected.

Once the theoretical mode mixtures to obtain the fundamental gaussian beam are known, we design the device which will produce them. This will be a corrugated horn antenna whose profile (see equation 2 and fig.6) is expanded in the same way that a gaussian beam. This component must be fed with an appropriate gaussian field distribution, i. e., the quasi-HE_{11} mode generated with the mode converter previously presented. This consideration is not critical, because this horn antenna improves, in an efficient way, the input mixture, obtaining high efficient fundamental gaussian beams. For instance, if the input mixture is varied between 80-20% and 90-10% of TE_{11} and TM_{11} respectively with a phase difference among 0 and 15 degrees the conversion to a fundamental gaussian beam is always bigger than 99%.

$$r(z) = r_0 \cdot \sqrt{1 + \left(\frac{\lambda z}{\pi \omega_0^2}\right)^2} \qquad (2)$$

where r_o is the input radius, λ is the free space wavelength and ω_o is the beam waist for the desired fundamental gaussian beam.

The profile and the corrugation depth of this horn are presented in figure 6, where $p \leq \lambda / 3$, $d = \lambda / 4$ and $w = p / 2$.

With this profile, figure 5 power mixture and phases are automatically generate to get a fundamental gaussian beam, then, we can select the desired total length. Only some little variations in the total efficiency conversion (existing an optimal value) and the antenna gain are obtained.

Analysing the output mixture versus the real fundamental gaussian beam, we can absolutely determine the position of the beam waist (which defines phase centre) and the beam waist value (ω_o) of the generated fundamental gaussian beam. Furthermore, looking for the relation output radius value (R) and obtained beam waist (ω_o) in figure 5, the difference between practise and theoretical results can be observed.
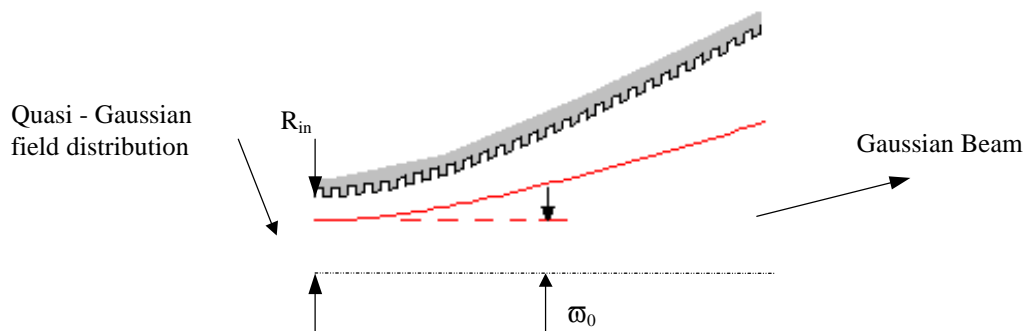

Figure 6: HE_{11} mode to fundamental gaussian beam horn antenna profile.

The far field radiation pattern obtained with this horn antenna taking as input is the previous HE_{11} mode (see figure 2) are shown in the following picture. The used length is 100mm, the output radius 41mm and the frequency 30GHz.
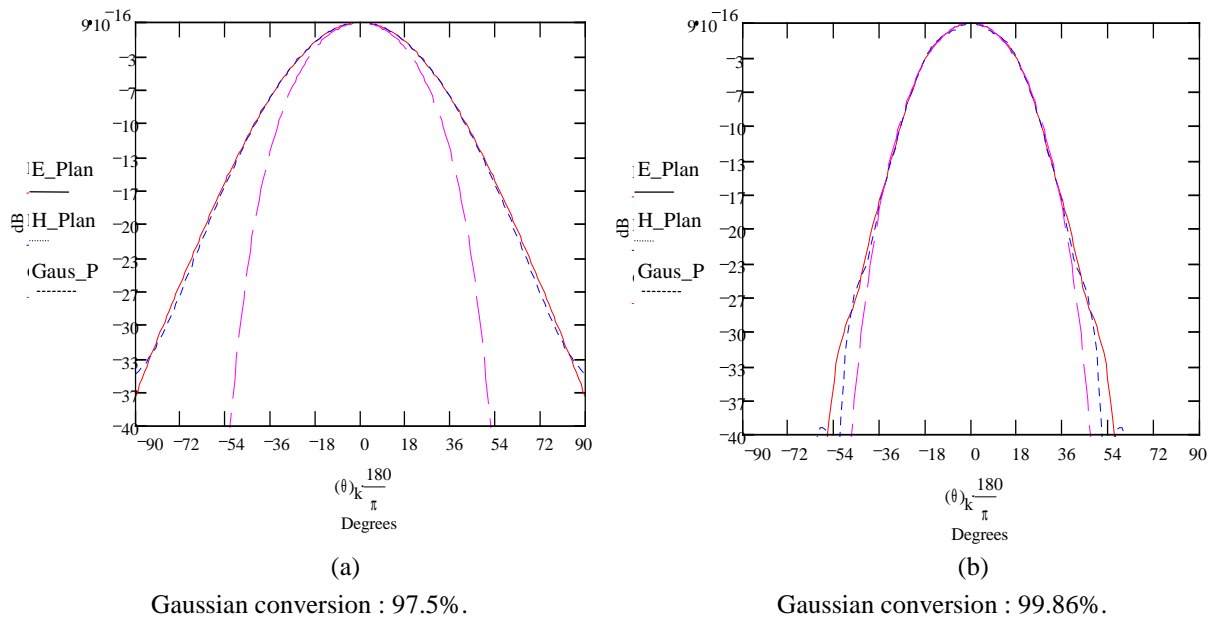

(a)

Gaussian conversion : 97.5%.

(b)

Gaussian conversion : 99.86%.

Figure 7 : Far field radiation pattern (a) of the TE_{11}-HE_{11} mode antenna converter together the fundamental gaussian beam and (b) HE_{11}-fundamental gaussian beam antenna together the real fundamental gaussian beam.

We can see the conversion efficiency to the fundamental gaussian beam improvement of the output mixture. In (a) is only 97.5% (we can see in the figure 7(a) the difference between the E and H planes and the fundamental gaussian beam) and the gain 13dB, if we join the second component the efficiency is increased until 99.86% (see figure 7 (b) high similitude between the horn antenna output mixture and the fundamental gaussian beam) and the gain until 22dB. So we have obtained a highly gaussian structure at the output mixture, very useful for stringent applications.

Also, as results we present two graphics where the bandwidth can be determined. As in the above section, in figure 8 (a), we see the relation between the frequency and the gaussian conversion efficiency, and in 8 (b) the relation with the reflected power. This figure has been obtained using a horn antenna working at 30 GHz, with 19.75mm of input radius and with α value of 0.58 over a length of 100mm.
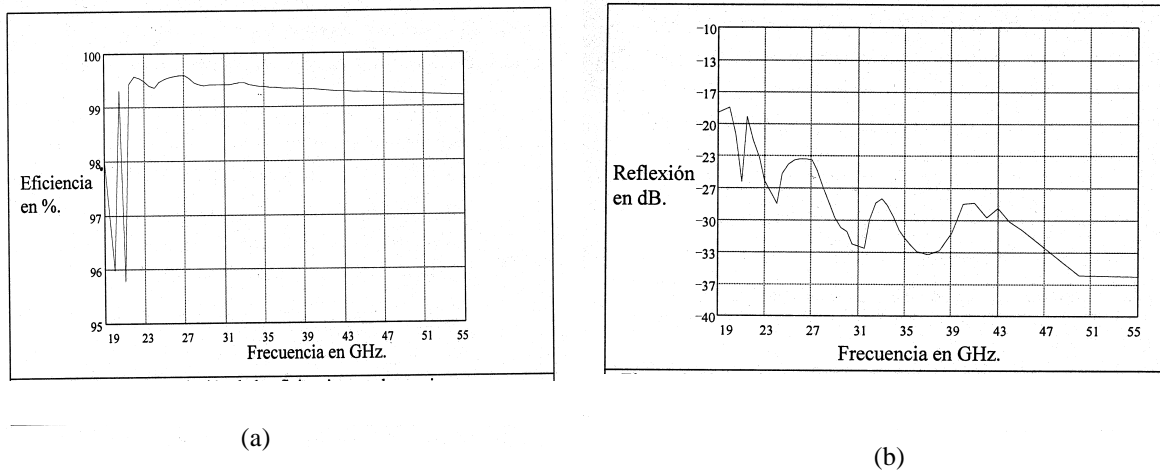

(a)

(b)

Figure 8 : Bandwidth in function of (a) conversion efficiency to a fundamental gaussian beam and (b) reflected power .

As conclusions of figure 8, we can say the component is more limited on low frequencies than on high frequencies obtaining a wide bandwidth (50% around central frequency).

Summarising, with this type of horn antenna we have improved the gaussian conversion efficiency, the symmetry is very high and the bandwidth is excellent (bigger than 50%), so this one can be used in very hard and stringent applications.

Future Working Lines

Nowadays, we are working with a new type of corrugated horn antenna, this one is the result of joining the two ideas presented above, and consists on generating the fundamental gaussian beam directly from the TE_{11} mode.

The equation that defines the profile is the same that in the above section (the gaussian propagation, see equation 2) but now the difference is in the α value. In this case, it has to be bigger, in this way, the horn antenna aperture velocity is slower, so we can control the mode conversion between the TE_{11} and the HE_{11}mode. Of course, we also have to use the impedance adapter.

With this type of horn antenna we will obtain shorter devices than in the case of joining the two previous single components, but the total gaussian conversion efficiency will decrease a little bit.

Firstly results we show the far field radiation pattern (see figure 9) and bandwidth studies varying the corrugation period (see figure 8). This variation is done inside the impedance adapter, changing the corrugation duty cycle between 7p/8 and p/2 (p is the corrugation period) on the adapter length (L_1).

Analysing the radiation pattern, in figure 9, we can see the gaussian beam versus the horn antenna output mixture pattern, the conversion efficiency is 98.3% (obtaining a fundamental gaussian beam with a beam waist of ω_o =0.53Rout placed 15mm inside of antenna throat). The reflected power is -50 dB, and the crosspolarization is under -40dB. These values change in function of the case under study. For example working at 8 GHz and using an α value of 0.8 we have obtained a conversion efficiency of 99.3%, crosspolarization under -42dB and directivity about 14.8 dB.

Far fiel radiation pattern

E_Plane$_k$

H_Plane$_k$

Cross_Plane$_k$

Gauss_Plane$_k$

dB

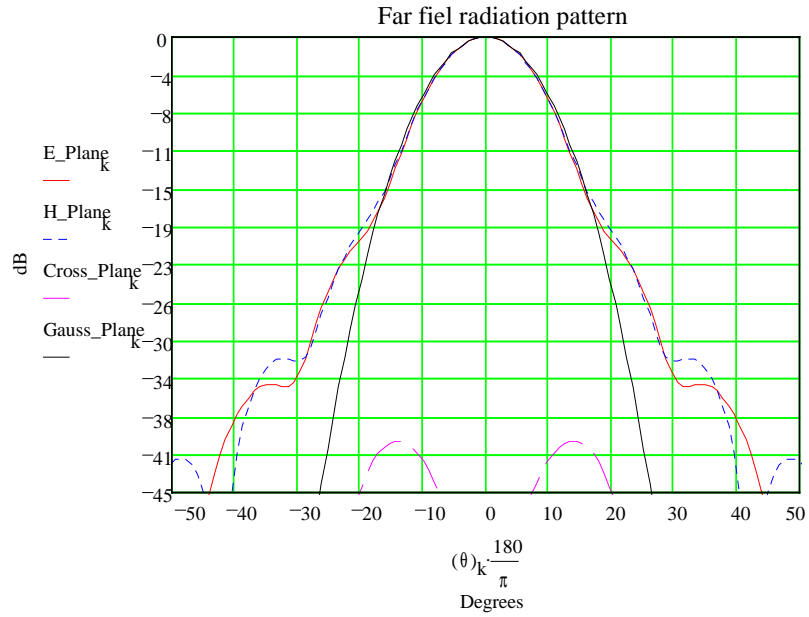$(\theta)_k \cdot \dfrac{180}{\pi}$

Degrees

Figure 9 : Far field pattern obtained with an α value of 1.8, working frequency 90 GHz, an output radius of 9.2 mm and a length of 43mm.

Now, in figure 10, a comparison between changing or not the corrugation period is presented. We analyse a case with duty cycle constant and equal to p/2 and another case in which varies between 7p/8 and p/2 during a length L_1 maintaining the last value on the rest of component. We will call them case 1 and case 2 respectively.

Case 1 :
(1) Reflected
    Power
(2) CrossPol.

Case 2 :
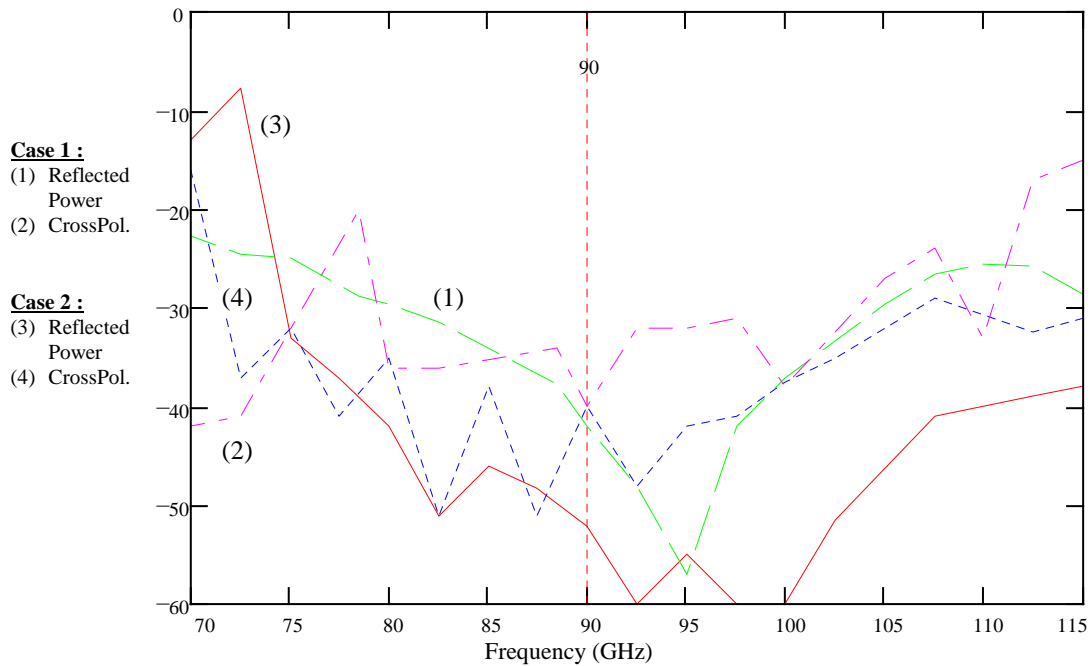(3) Reflected
    Power
(4) CrossPol.

Frequency (GHz)

Figure 10 : Reflected power and crosspolarization on two different cases of impedance adapter inside horn antenna. Case 1 : fixed period, and case 2 variable period.

As results, we can say that, in general, the variable period works better than the fixed one to get a wide bandwidth.

Conclusion

We have shown two different components to generate a HE_{11} and a fundamental gaussian beam mode respectively in a very efficient way. These components are valid to any frequency obtaining a very good results with short length such in radiation features like in bandwidth.

Also, we have presented our new developments about corrugated horn antennas, to get directly a fundamental gaussian beam from monomode circular waveguide TE_{11}. With the first results, we can say the component works in a efficient way, and it is an alternative election in function of necessities in our applications.

Finally, all these components have been successfully simulated using the mode matching and scattering matrix techniques and the Moment Method.

Acknowledgement

References

[1]   Garin, P., Rebuffi, L. et al., "Circular Waveguide: Reference Formulas for Propagation and Radiation". XIV International Conference on Infrared and Millimetre Waves. Würzburg 1989.

[2]   Olver, A. D., Clarricoats, P.J.B., Kishk, A.A. and Shafai, L. "Microwave Horns and Feeds" Chap. 8 and 9, IEE electromagnetics waves series 39. 1994.

[3]   Olver, A. D. "Corrugated Horns", Electronics and Communications Engineering Journal. pp 4-10. February 1992.

[4]   Rudge, A.W., Milne, K., Olver, A.D. and Knight, P. "The handbook of Antenna Design", IEE Electromagnetic Waves Series, Volumes 1 and 2, 1986: Peter Peregrinus Ltd.

[5]   Wencker, G. "Rekursionsformeln und Entwicklungen der Strukturfunktionen Gaußscher Strahlen". A.E.U. Band 23, 1969, pp 521-523.

[6]   Del Río, C., Gonzalo, R. and Sorolla, M., "High Purity Gaussian Beam Excitation by Optimal Horn Antenna". Proceedings of ISAP'96, pp. 1133-1136, CHIBA, JAPAN.

[7]   Sorolla, M., Del Río, C. and Gonzalo, R. "Optimized antenna system for low power testing of the quasioptical transmision line at TJ-II experiment". Digest Int. Conf. on Infrared and Millimeter Waves, Berlin, Germany, July 1996.

[8]   Gonzalo, R., Del Río, C., Teniente, J. and Sorolla, M. "Optimal horn antenna design to excite high purity gaussian beam using overmoded waveguides". Digest Int. Conf. On Infrared and Millimeter Waves, Berlin, Germany, July 1996.