

MODERN CORRUGATED HORN ANTENNA DESIGN FOR EXTREMELY LOW SIDELOBE LEVEL

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Abstract

The present paper deals with the design of modern corrugated horn antennas for extremely low sidelobe level with the use of the well known corrugated Gaussian Profiled Horn Antenna aperture (corrugated GPHA's) to improve the radiation pattern and reduce the antenna size.

Some design rules will be given so that an initial nice profile can be used quickly as input profile of modern optimization codes to improve the size. This initial profile can reduce the computing time of an optimization program quite a lot, so it is usually the method we use to design the final corrugated horns in our own optimization code.

Introduction

The design of circular horn antennas has been based, for a long time, in the control of the guide mode mixture to excite an HE_{11} circular corrugated waveguide mode because of the nice radiation properties of this hybrid mode, (see fig. 1). It is well known that this hybrid mode can be made up of approximately a combination of 85% TE_{11} and 15% TM_{11} smooth circular waveguide modes with an appropriate relative phasing between them. The starting field distribution is usually the TE_{11} mode of the circular waveguide under monomode operation, and by means of a proper step or taper in the horn radius, the right amount of TM_{11} (amplitude and phase) is excited (Potter type horns) [1,2,3].

This technique, firstly used in non-oversized horns, was later extended to oversized ones, using long and smooth conical tapers after the step. To get nice radiating features, two main parameters had to be considered: the output diameter and the horn length. Since the coupling coefficient between waveguide modes is directly related to the waveguide slope change, for a given output radius that fixes the desired beamwidth, the change in horn length allows the designer to select the appropriate phasing in the 85% of TE_{11} and 15% of TM_{11} mode mixture obtaining the appropriate sidelobe and crosspolarization minimum levels. Therefore, the only parameter to adjust is the taper length. This type of horn antennas were extensively used in the past decades and were known as Potter type horns, [1]. Its drawback was the reduced bandwidth and their advantages were the reduced weight, reduced size and simplicity.

Another technique is based on circular corrugated waveguides and takes profit of the fact that 85% TE_{11} and 15% TM_{11} mode mixture corresponds to the fundamental mode of a circular corrugated waveguide, the HE_{11} mode. This technique reported in [2,3,4,5] involves a gradual matching of the smooth monomode circular waveguide to another corrugated one wherein the corrugation depth is smoothly tapered from $\lambda/2$ to $\lambda/4$, (see fig. 2).

These two outlined techniques are combined in the so-called conical corrugated horn antennas with a matching device at their input port. Corrugated horn antennas present a wider frequency response than Potter type horns. Their design parameters are basically: corrugation parameters (period, duty cycle, depth, shape, etc...); length and profile of the $\lambda/2$ -to- $\lambda/4$ impedance matching device; and the horn geometry in order to optimise the global performance of the horn.

Directivity, gain, sidelobe and crosspolarization levels are important design parameters for many applications involving horn antennas. Additional design parameters, relevant to satellite applications are length and weight, which need to be minimized [6,7].

During the last 20 years, many of the applications involving high performance horn antennas (satellites, radio-telescopes) have been equipped with conical corrugated horn antennas.

Conical corrugated horn antennas are one of the best possibilities to accomplish stringent radiation pattern requirements; but during the last decade another shorter and better profiles for corrugated horn antennas have aroused. Nevertheless, a brief review of the way of designing conical corrugated horn antennas has been summarized in the following paragraphs. This simple design method will help in the understanding of modern corrugated horn antenna design for the rest of this paper.

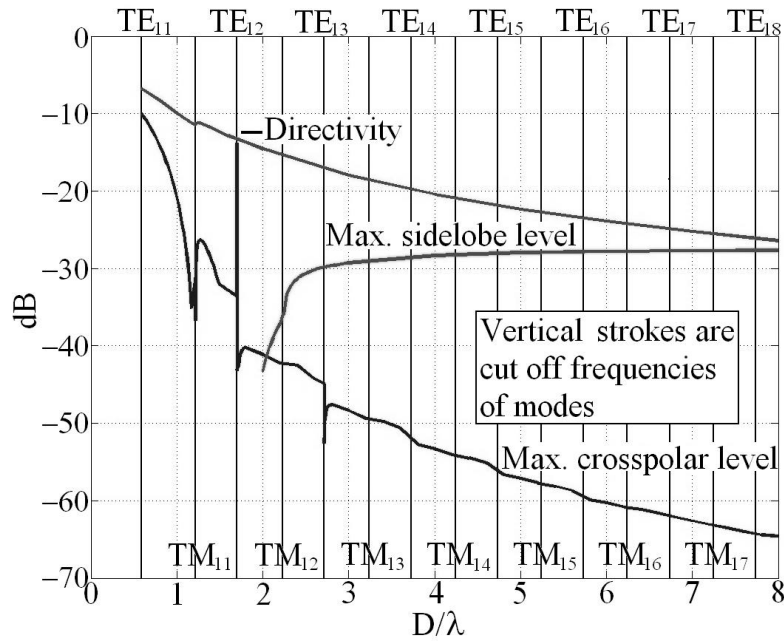


Fig. 1. Radiation properties of the HE₁₁ hybrid mode against antenna aperture diameter (D_{output})

Conical corrugated horn antenna design

The HE₁₁ mode is an excellent mode for radiation features, because it is a fundamental gaussian beam with a purity of 98.1% and has a very low crosspolarized component. In a conical corrugated horn antenna, a quite pure HE₁₁ mode is generated after the impedance transformer between the throat and the flare angle regions. If the angle of the antenna is not very high, (below 20 degrees), this mode is smoothly tapered to a larger diameter.

As smoother is the tapering of the HE₁₁ mode to the aperture (lower profile angle) of the antenna as more pure will be its power at the output against other spurious modes like HE_{1n} or EH_{1n}. For high performance antennas the flare angle must be reduced, so the length will then increase.

Among the specifications detailed for the design of a conical corrugated horn antenna, there is an specially important parameter, the directivity needed for the design, or more specifically, the edge taper of the radiation pattern at a certain angle (copolar beamwidth).

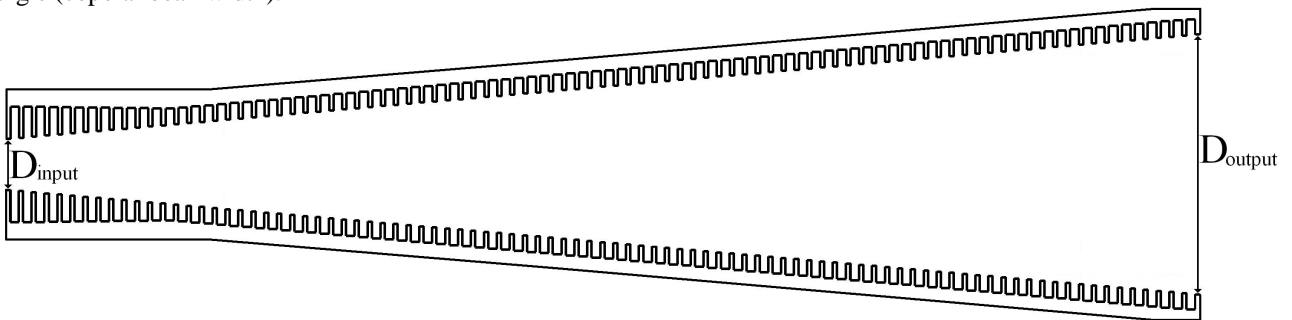


Fig. 2. Conical corrugated horn antenna

So, once we have defined the directivity of the design and assumed at the aperture an HE₁₁ mode, the output diameter of the conical corrugated horn antenna is nearly fixed from a physical point of view.

For normal conical corrugated horn antenna design, there are several diagrams for -3 dB and -10 dB half beamwidth that define the copolar pattern in terms of the profile angle and the aperture diameter [3]. If we consider sidelobes/shoulders below -20 dB (which is usually required for this type of antennas), directivity design curves can be easily converted to the -3 dB and -10 dB or any other half beamwidth pattern decay. In figure 3a we can select the appropriate aperture diameter of the conical corrugated horn antenna for a given directivity design value.

Usually, for moderate to high directivities (>18 dB) and high performance, the profile angle will be below 20 degrees. As we decrease this angle, the antenna becomes longer for a given directivity, but its radiation pattern decay is quicker approximating to the radiation pattern decay of a fundamental gaussian beam. The profile angle is usually defined by the maximum sidelobe level and beam purity allowed for the design, (see fig. 3b).

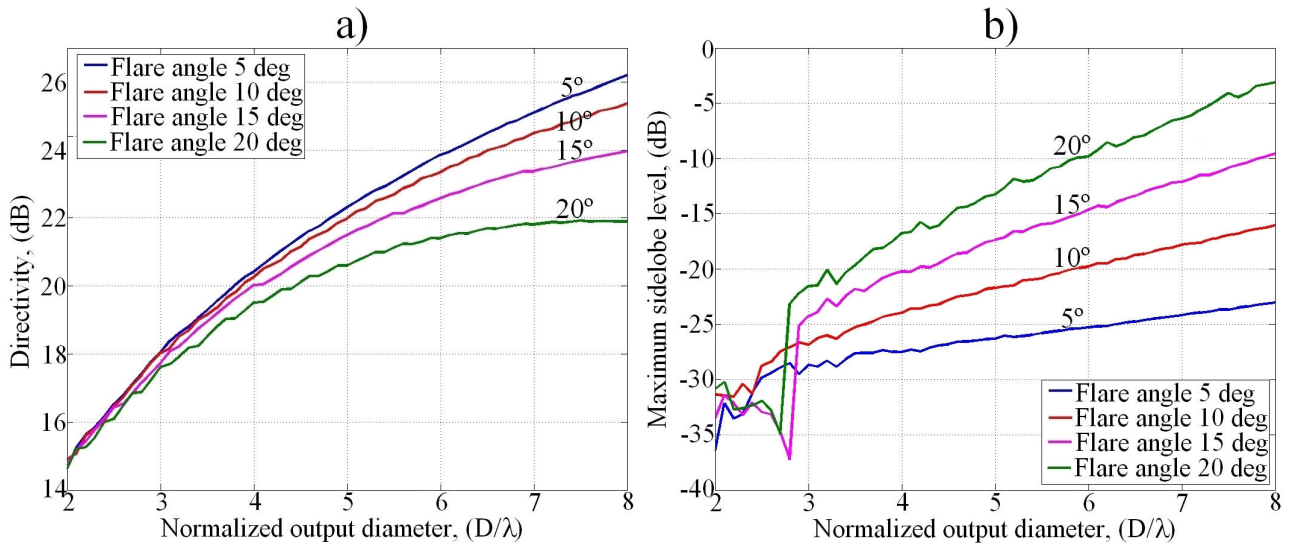


Fig. 3. a) Directivity design curves for conical corrugated horns antennas
 b) Maximum sidelobe level design curves for conical corrugated horns (shoulders are included as sidelobes)

But, the efficiency of the HE_{11} mode to the fundamental free space mode (fundamental gaussian) is not very high for a conical corrugated horn antenna. Then, the sidelobe level for a conical corrugated horn antenna with moderate directivities (above 18 dB) cannot be lowered below -30 dB, (see figure 3b and figure 1).

Big flare angle conical corrugated horn antennas (15 and 20 deg) present shoulders that broaden the radiation pattern and increase quite a lot the spillover radiation towards unwanted directions whereas small flare angle ones present a quite pure radiation pattern till the first sidelobe. So, the conical corrugated horn antenna with lower profile angle will present a higher performance with a smaller aperture diameter, although it will be translated into a longer profile.

Gaussian corrugated horn antenna design

Gaussian Profiled Horn Antennas (GPHA's) were firstly proposed in the year 1995 during the research developed in [8,9]. Those GPHA's were smooth waveguide horns that optimized the conversion between the smooth circular waveguide mode TE_{01} (at the input of the antenna) to the gaussian mode Ψ_{01} (at the aperture of the antenna) with a really nice conversion efficiency (above 99%). As gaussian modes are the solution of the paraxial wave equation for free space, every radiation (which complies the paraxial condition) propagated in free space can be decomposed in terms of gaussian modes.

By using these horn antennas, the matching between the waveguide and the free space is almost perfect, being the most "natural" way to match the two media. From a waveguide mode or mode mixture, what a GPHA does is to excite a very similar transversal field distribution with Gaussian propagating features.

Most of the applications in telecommunication, telecontrol and telemetric systems deal with the fundamental gaussian mode Ψ_{00} as the main free space mode of a modern radiation pattern. To obtain a high purity Ψ_{00} mode at the aperture of a horn antenna, the corrugated version of the GPHA developed in [10,11,12] aroused. The introduction of the corrugated GPHA becomes very useful to address the most stringent requirements in directivity, gain, sidelobe and crosspolarization levels as well as reducing the total length and weight of the resultant profile.

The design procedure for a corrugated GPHA starts like in a conical corrugated horn with a detailed list of specifications; directivity, maximum allowable crosspolar level, sidelobe level, return loss... But unlike for conical corrugated horn antenna design, corrugated GPHA design follows a completely different path, as it will be seen in the following paragraphs.

It has been shown in other papers about corrugated GPHA's that with these profiles we can improve important far field radiation pattern features of any existing conical horn, like sidelobe levels, while keeping its other far field characteristics, by adding some part of a corrugated GPHA at its end.

Corrugated GPHA's aroused to implement a perfect match between waveguide modes (mostly HE_{11} mode or similar mode mixtures) and the fundamental free space modes (fundamental gaussian mode, Ψ_{00}). If we have the possibility of obtaining at the aperture of a horn antenna a field that is nearly the transversal field distribution of a fundamental gaussian mode, its radiation pattern would be also nearly a fundamental gaussian beam propagation.

Because of the definition of the gaussian beam modes, the Ψ_{00} mode doesn't have sidelobes and crosspolarization, so it is a much better mode for radiation purposes than the HE_{11} mode.

The Gaussian beam modes are a solution of the paraxial wave equation in the free space. Any paraxial radiation from a waveguide can be understood as an infinite summation of Gaussian beam modes, since they are orthogonal and therefore can generate a basis in free space. The conceptual idea involves the generation of any kind of transversal field distribution having Gaussian radiation features. Feeding a GPHA with several appropriate field distributions (i.e., TE_{0m} , HE_{11} circular waveguide modes), we can excite very efficiently a pure Gaussian beam mode.

The profile of a GPHA is defined basically by the expansion formula of the gaussian beam modes. So, the Gaussian beam broadening (decay of fields to 1/e of the central value) is given by:

$$\varpi(z) = \varpi_0 \cdot \sqrt{1 + \left(\frac{2 \cdot z}{k \cdot \varpi_0^2} \right)^2} \quad (1)$$

where ϖ_0 is the beamwaist at $z=0$ and $k=2\pi/\lambda$ is the wavenumber in free space. The corresponding waveguide profile which follows the curve for Gaussian equi-amplitude relative surfaces is given by,

$$R(z) = r_0 \cdot \sqrt{1 + \left(\frac{2 \cdot z}{k \cdot \varpi_0^2} \right)^2} \quad (2)$$

where $r_0=D_0/2$ is the input radius of the corrugated profile and $\varpi_0=\alpha \cdot r_0=\alpha \cdot D_0/2$ is the beamwaist value at $z=0$ related with the D_0 through the parameter α . The α parameter controls the aperture angle of the horn for a given frequency and waveguide radius. D_0 is the input diameter. Figure 4 shows the relationship between the horn profile (2) and the beamwaist propagation imposed by (1).

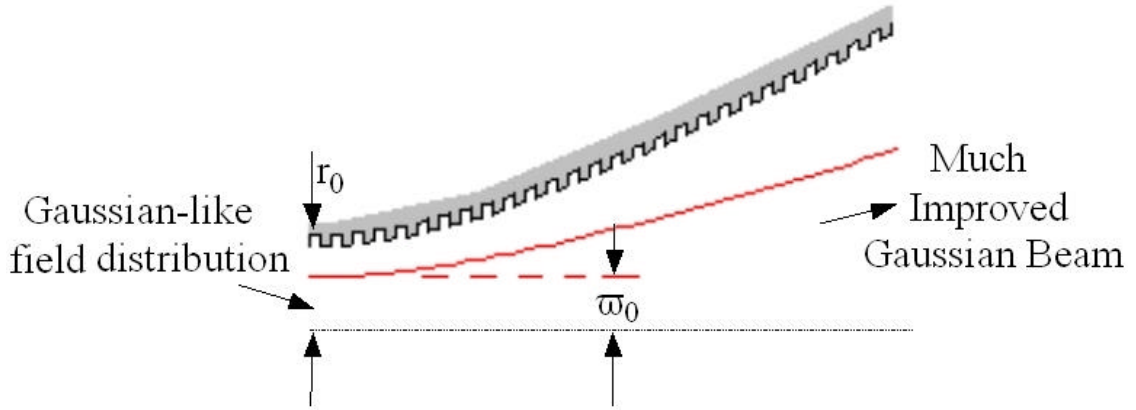


Fig. 4. Corrugated Gaussian Profiled Horn Antenna, (corrugated GPHA)

The input field distribution to a corrugated GPHA could be anyone with a controlled diffraction. In principle, any waveguide mode or mixture of waveguide modes with low amplitude near the metallic walls is suitable to feed a corrugated GPHA, but if we want to obtain a high purity fundamental gaussian beam an HE_{11} mode is one of the best input fields. The forward scattered fields will have the same transversal amplitude distribution as the original ones but with gaussian broadening properties.

The α parameter can vary between 0.5 and 0.8 but usually the optimum value is around 0.65. The last parameter we must define to completely design the corrugated GPHA is the profile length, L . To define the length of a GPHA we have developed an empirical formula with a parameter called factor of length, f , see (3).

$$L = \lambda \cdot \overline{D_0} \cdot \sqrt{f \cdot \left[1 + \left(\overline{D_0} \right)^2 \right]} \quad (3)$$

where $\overline{D_0} = D_0/\lambda$ is the normalized input diameter of the GPHA.

The factor of length, f , can be any number between 0.01 and 0.3. The larger this number, the longer the antenna will be. If the antenna is very long we can say that we are over-guiding the gaussian beam and the addition of more antenna length is not really improving the beam, so the efficiency can be the same than with a shorter antenna. The best value for very nice gaussian beam efficiency and not excessive length (which means low sidelobes) is $f = 0.1$ but values of f between 0.05 and 0.1 are usually enough and are the most currently used giving a short profile with not a big output diameter, see figure 5.

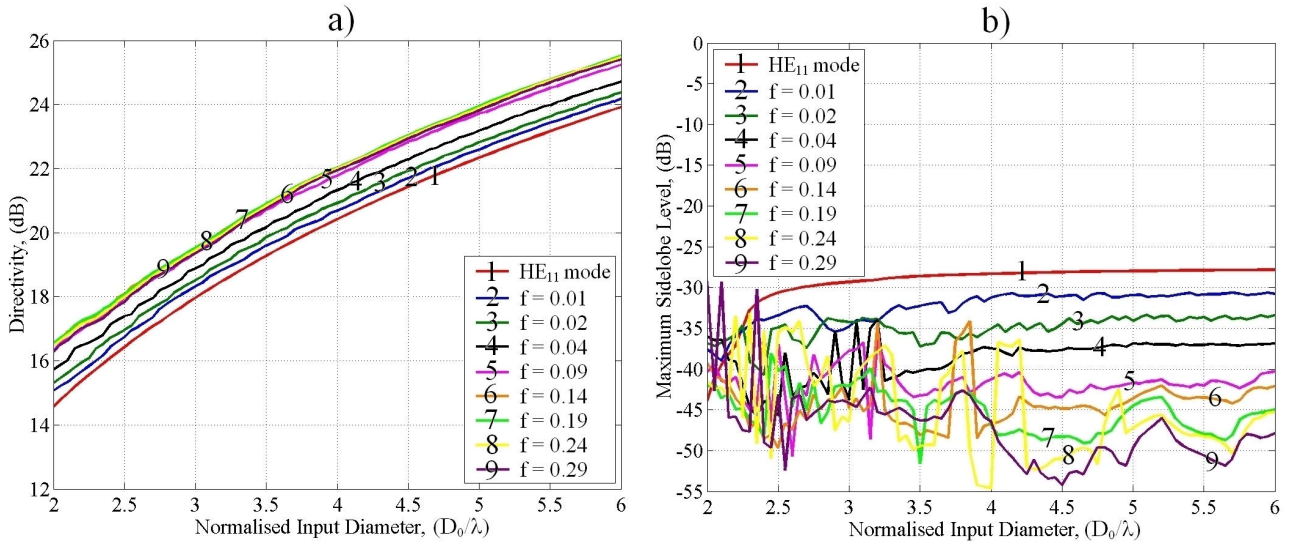


Fig. 5. a) Corrugated GPHA directivity in terms of L , $\alpha=0.59$
b) Corrugated GPHA maximum sidelobe level in terms of L , $\alpha = 0.59$

From figure 5b and directivities above 20 dB we can see that a small piece of corrugated GPHA of a ridiculous length with $f = 0.01$, can improve quite a lot the radiation pattern of a conical corrugated horn antenna lowering the sidelobe below -30 dB. Increasing the length to $f = 0.03$, the sidelobe level would be below -35 dB.

The main difference between the design of a corrugated GPHA versus a conical corrugated horn antenna is the diameter that defines the radiation pattern. While corrugated GPHA control directivity by their input diameter, (D_0), conical corrugated horns control directivity by means of their output diameter, (D_{output}).

TE₁₁ to HE₁₁ mode converters available

As it has been said, corrugated GPHA's need at the throat a quite pure HE₁₁ mode to produce nice radiation patterns. Then, once corrugated GPHA design has been completely defined we should select which type of TE₁₁ to HE₁₁ mode converter to use to feed that corrugated GPHA. This mode converter usually starts from a smooth circular monomode waveguide propagating the TE₁₁ mode and ends at the required aperture diameter to feed the corrugated GPHA model.

In the literature one could find several types of TE₁₁ to HE₁₁ mode converters. One of them is the horn type proposed by Potter, [1], its disadvantage is a poor bandwidth. Another type of TE₁₁ to HE₁₁ mode converter could be just a conical corrugated horn antenna, its disadvantage is its size. A corrugated GPHA with large α values (above 1.5 usually) can be another possibility of TE₁₁ to HE₁₁ converter with the same disadvantage of a conical corrugated one but with slightly better bandwidth characteristics. But there are other shorter possibilities with enough bandwidth characteristics, a symmetrical corrugated GPHA converter [13], a reduction of the conical horn profile by means of a serpentine-shaped taper [14] or a spline profile defined as input of a corrugated GPHA in [15].

In fact, a hard effort has been made during the last years to improve the length of this mode converter. Optimisation programs for each of the groups working on this subject have aroused. These programs usually reduce the size of this part of the complete profile but leave the output GPHA profile complete. A great reduction can be made in this component, this reduction can be more important if the bandwidth requirement for the given antenna design is also reduced. But usually these optimisation programs are attached to the design of this type of converter by means of normal corrugated horn techniques, but there are other really nice possibilities in fact.

One of the best TE₁₁ to HE₁₁ converters available for this type of horn apertures is the prime focus feed more commonly known as a choked feed [16]. Its main advantage is its size (really compact) and on the opposite, the main disadvantage is a slightly reduced bandwidth in comparison to a normal corrugated converter.

Several of these techniques are going to be covered in the next paragraphs to design an example of a modern corrugated horn antenna, their size, performance and bandwidth will be covered as well so a designer can decide which type of profile best meets the requirements and use it as input of an optimization code.

Complete design of a 22 dB directivity corrugated GPHA

For comparison purposes, a conical corrugated horn antenna with 22 dB directivity and -25 dB sidelobe level is going to be developed against several corrugated GPHA's with different kinds of TE₁₁ to HE₁₁ mode converter inputs. The

rest of the designs will be for 22 dB directivity and -35 dB sidelobe level, except the last one that will be for -40 dB sidelobe level.

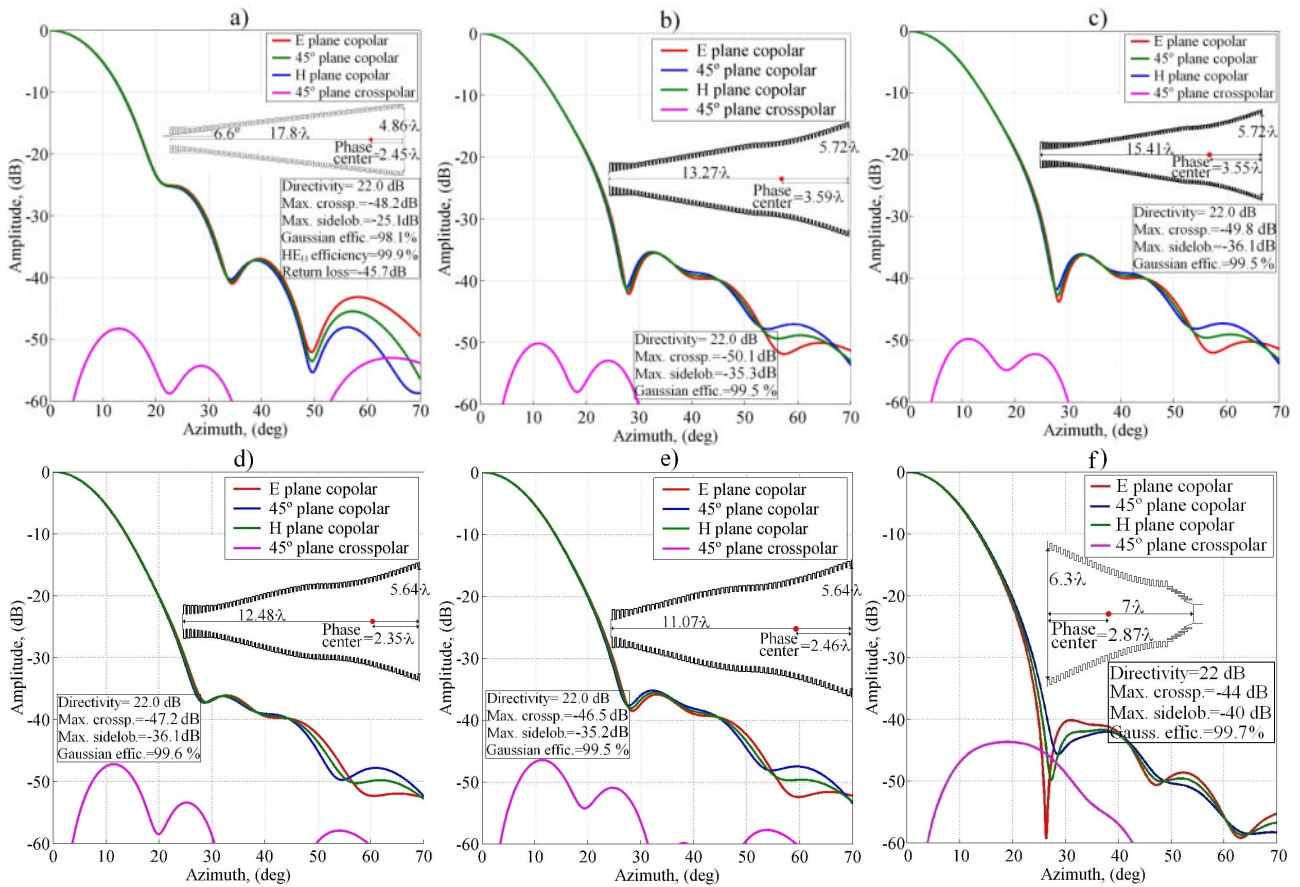


Fig. 6. Corrugated horn designs for 22 dB directivity

- a) Conical corrugated Horn
- b) Conical corrugated + GPHA output
- c) Normal GPHA + GPHA output
- d) Symmetrical GPHA + GPHA output
- e) [15] input converter + GPHA output
- f) Choked waveguide horn input converter + GPHA output

The choked profile GPHA is incredibly short and its wider output diameter is determined by the -40 dB sidelobe level obtained for it, (see figure 6f).

In figure 7 the bandwidth performance of the previous designs is shown in terms of return loss, crosspolar level, directivity, phase center position and sidelobe level. From that figure we can conclude the following:

- The return loss bandwidth is very nice for the choked + GPHA, (always below -30 dB). For the rest of horn antennas is similar but slightly better for the GPHA+GPHA and the symmetrical GPHA+GPHA. The reason for this is the smoother throat section in these antennas.
- Regarding to crosspolar level (with $\lambda/4$ corrugation depth), the bandwidth is similar in all the designs, except for the choked+GPHA that presents a poorer bandwidth (around 10% bandwidth for -40 dB crosspolar level). A slightly wider crosspolar level bandwidth for the GPHA+GPHA, the symmetrical GPHA+GPHA and the [15] input profile+GPHA can be observed.
- Figures 7c and 7d can be explained altogether because they are strongly related. In figure 7c we can see the directivity bandwidth curve for each design. It can be appreciated three different slopes.
 - The lowest slope is found for the conical+GPHA and GPHA+GPHA. Both of them provide a high efficiency HE_{11} at the inner diameter. The phase centre of both (figure 7d) presents also a certain slope, this means that as higher the frequency is as more inside the phase centre of the horn antenna is placed. In fact, a phase centre variation going inside the antenna provides a narrower diameter where the antenna effectively radiates. This effect compensates a lot the slope of the directivity, but the phase centre moves quite a lot also.
 - Symmetrical GPHA+GPHA and [15] input profile+GPHA present a steeper slope in directivity. The reason for this behaviour depends strongly on the lower purity of the HE_{11} mode at the inner diameter. However, if we check the bandwidth curve of the phase centre we see that both are flatter than the others. This means that in fact this both

designs are radiating from a single point phase centre in most of the frequency band. The diameter of the horn at phase centre remains the same, then the radiation pattern controlled by this effective diameter changes the directivity quicker with frequency.

-The choked+GPHA presents the steepest change in directivity as well as the flattest phase centre position but in the narrowest bandwidth.

- Maximum sidelobe level bandwidth always follows a slope that provides lower sidelobe level for lower frequencies and higher sidelobe level for higher frequencies in the band. This must be taken into account if we need to maintain the sidelobe level, for example, below -35 dB along all the usable bandwidth of the antenna. The choked GPHA has also a poorer sidelobe level bandwidth although lower than for any other design in this paper.

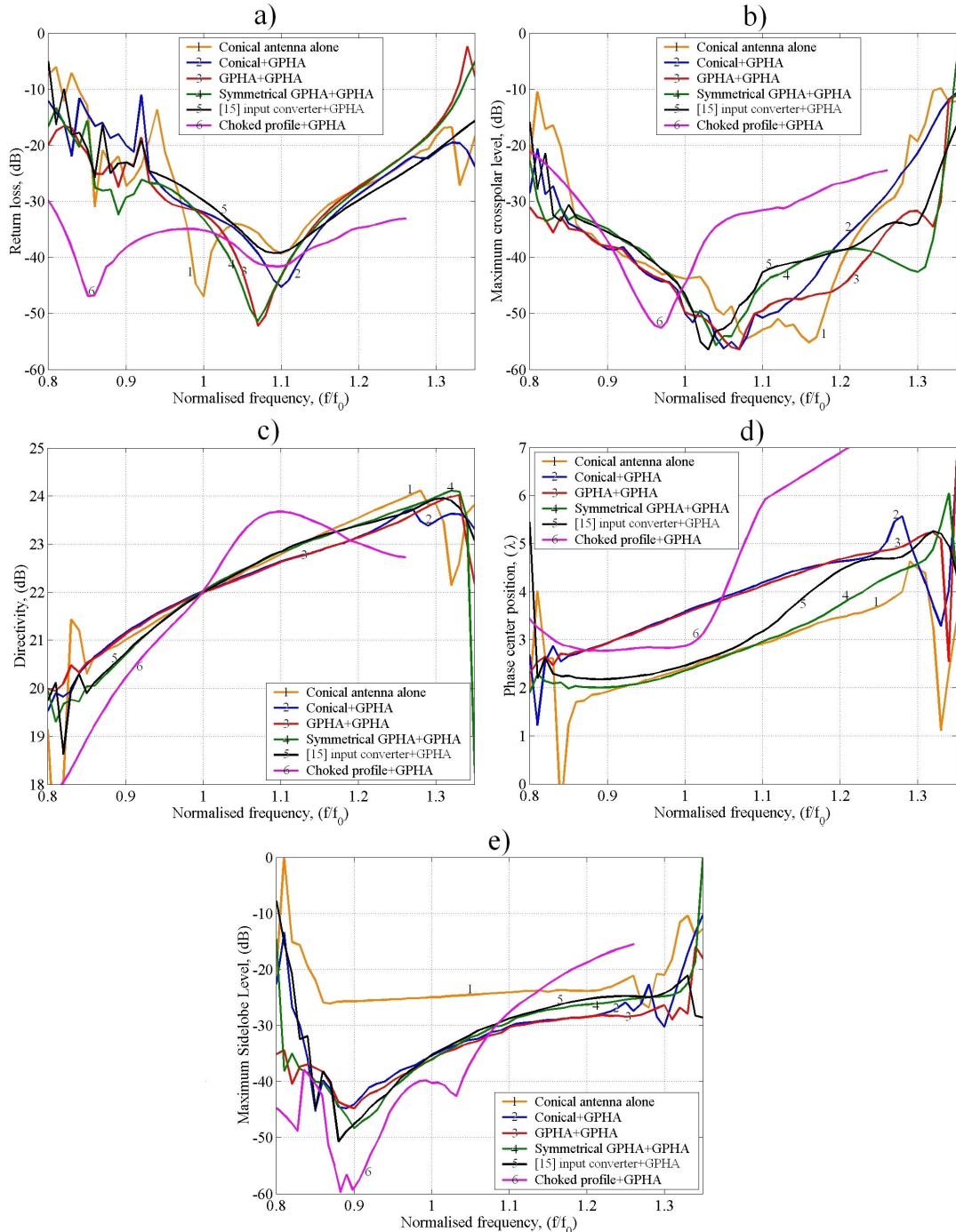


Fig. 7. Bandwidth comparison between the different designs
a) Return loss b) Maximum crosspolar level c) Directivity
d) Normalised phase center position e) Maximum sidelobe level

Conclusions

This paper presents an study on the state of the art of corrugated GPHA's as modern corrugated horn antennas. Their advantages and disadvantages versus conical corrugated horns have been developed.

On summary it is possible to say that the return loss bandwidth for corrugated GPHA's can be one of the most important problems to achieve bandwidths above 30%. This is clearly not the case of the choked+GPHA profile, because it doesn't present return loss problems in a huge bandwidth despite it has poorer bandwidths in the rest of the radiation pattern parameters. A research on this type of GPHA's is being carried at present to improve this results.

A compromise must be reached between maximum allowable change in directivity along the usable bandwidth and maximum allowable movement of the phase centre. Both can be adjusted as customer requires for any corrugated GPHA design.

Maximum sidelobe level must be chosen for a given profile taking into account its bandwidth. The worst case sidelobe level will always be the highest frequency in the band.

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