Internal Report INAF/IASF Bologna 528/2008

WCAM prototype using Particle Swarm Optimization

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October 30, 2008

Abstract

This technical note reports a new WCAM prototype designed using "Particle Swarm Optimization". The design, a dual profiled corrugated horn (DPCH), is obtained taking into account mechanical constraints and electromagnetic specifications.

1 Introduction

The Particle Swarm Optimization (PSO) is a stochastic evolutionary algorithm used to search for the global optimum of complex problems. It is based on the behavior of insect swarms and exploits the solution space by taking into account the experience of the single insect as well as that the entire swarm. The algorithm (described in [3]) has been used to design complex shape antennas and waveguide impedance transformers. In this work we adapted it to design a dual profiled corrugated horn. This design follows the horn design reported in [4], WCAM-PROT01.

2 Antenna Spcecifications

The antenna requirements and mechanical constraints are specified in the following table:

Band = 80 - 110 GHz	Input waveguide radius = 1.48mm
Return Loss $<$ -30 dB	Step of corrugations = 1mm
Peak χ-polarization level $<$ -30 dB	Width corrugation = 0.7mm

Table 1: *Antenna specifications*

The corrugation step is fixed because WCAM project propose to use stacked alluminum plates of 1mm width. Other parameters as side lobe level and aperture radius exist but they aren't yet fixed because at present they are under investigation. For this work we assume the following mechanical properties:

- number of corrugations = 25;
- aperture radius = 5mm;

The number of corrugations chosen in this design is less that ones used for the WCAM-PROT01 because the goal is to obtain shortest horn with same performance.

3 Geometry

Usually a corrugated feed horn is composed by three parts (fig. 1):

- the smooth-walled input waveguide;
- the mode converter;
- the HE_{11} waveguide.

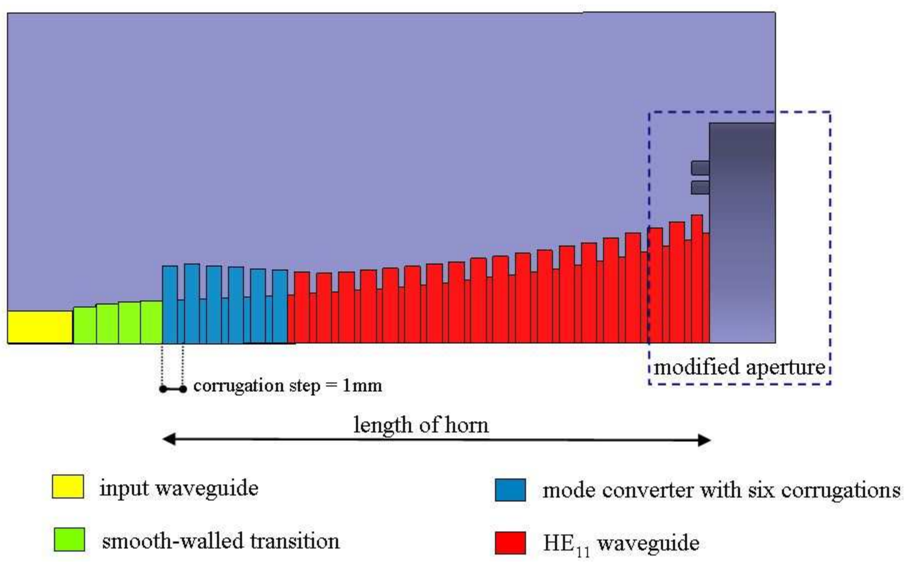

Figure 1: *Four parts of the horn*

The smooth-walled input waveguide permits the connection between the input-waveguide (radius 1.49mm) supporting the TE_{11} mode and the corrugated region of the horn. In this work a transition composed by 4 step (from 1.64mm to 1.94 mm of radius) of 1mm width is used in order to use existing component (fig. 2).

The mode converter is the first corrugated part and is designed to provide a smooth transition from the TE_{11} to the HE_{11} mode.

The HE_{11} waveguide is the second corrugated part. It supports the propagation of the HE_{11} hybrid mode from its generation to its radiation.

We have taken into account a fourth part as well, a plate of 3mm width placed at the aperture with grooves of 0.79mm depth parallel to the axis of the horn (fig. 3). This modified aperture is described in [5] and won't be modified.

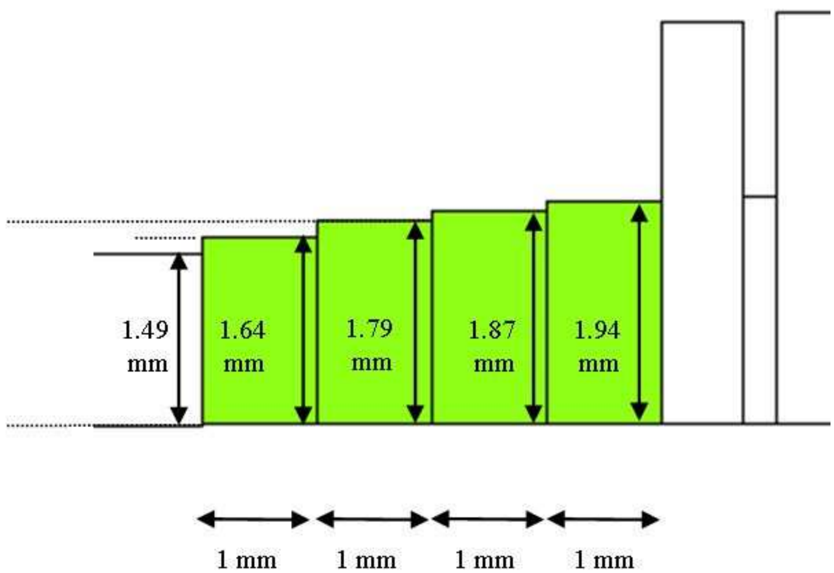

Figure 2: *Stepped smooth-walled transition*

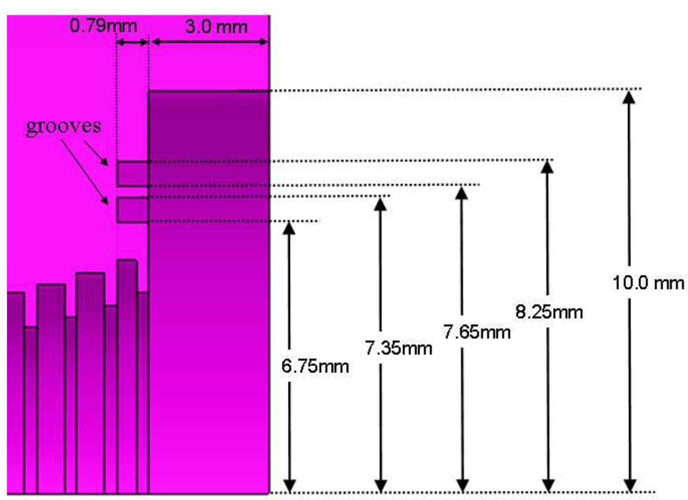

Figure 3: *Aperture region described in [5]*

4 Main design

The first step is to search for a possible candidate, building a design starting from analitical formulas. The profile chosen is tangential/exponential (eq. 1).

$$a_j = a|_{z=j} = \begin{cases} a_{in} + (a_s - a_{in})\left[(1-A)\frac{j}{L_s} + A\tan^{\rho}\left(\frac{\pi j}{4L_s}\right)\right] & j \leq L_s \\ a_s + \exp\left[\ln(1 + a_{out} - a_s)\frac{j-L_s}{L-L_s}\right] - 1 & Ls + 1 \leq j \leq L \end{cases} \tag{1}$$

where a_{in} is the input radius, a_{out} is the aperture radius, a_s is the radius in the transition section between profiles, L is the total length, L_s is the length of first profile, A and ρ represent two parameters that define the tangential profile. A varies in the range $[0;1]$, whereas the parameter ρ is generally equal to two, but taking values such that $0.1 \leq \rho \leq 5$ gives rise to interesting profiles with their own sets of properties.

Every corrugation step consists of a corrugation of 0.7 mm width and a tooth of 0.3 mm width. The j-th corrugation depth (d_j) is obtained by the following rules ([2]):

if $1 \leq j \leq N_{MC} + 1$

$$d_j = \lambda_c \left\{\sigma - \frac{j-1}{N_{MC}}\left(\sigma - \frac{1}{4}\exp\left[\frac{1}{\alpha(k_c a_j)^{\beta}}\right]\right)\right\} \tag{2}$$

else ($N_{MC} + 2 \leq j \leq N$)

$$\begin{aligned} d_j = {} & \frac{\lambda_c}{4}\exp\left[\frac{1}{\alpha(k_c a_j)^{\beta}}\right] \\ & - \left(\frac{j - N_{MC} - 1}{N - N_{MC} - 1}\right)\left\{\frac{\lambda_c}{4}\exp\left[\frac{1}{\alpha(k_c a_{out})^{\beta}}\right]\right. \\ & \left. - \frac{\lambda_{out}}{4}\exp\left[\frac{1}{\alpha(k_{out} a_{out})^{\beta}}\right]\right\} \end{aligned} \tag{3}$$

where N_{MC} is the number of corrugations for the mode converter, N is the total number of corrugations, σ ($0.4 \leq \sigma \leq 0.6$) is a percentage factor for the first corrugation depth of the mode converter, α and β are two parameters, $k_c = 2\pi f_c/c_0$, $k_{out} = 2\pi f_{out}/c_0$, c_0 is the speed of light, f_c and f_{out} are design parameters (the first corrugation is depth $\lambda/2|_{f=f_c}$ whereas the last corrugation is depth $\lambda/4|_{f=f_{out}}$). In this work $f_c = f_{out}$.

In [2] authors approximate α as 2.114 and β as 1.134 approximating the solution for the surface reactance equation. In this work this parameters are modified to optimize the antenna.

Figure 4 shows the geometry of the DPCH.

5 Optimization Parameter Choice

The physical and electromagnetic characteristics of the horn can be controlled by a combination of several parameters. In the table 2 a choice of which paramenters will be modified and which ones will be fixed is showed.

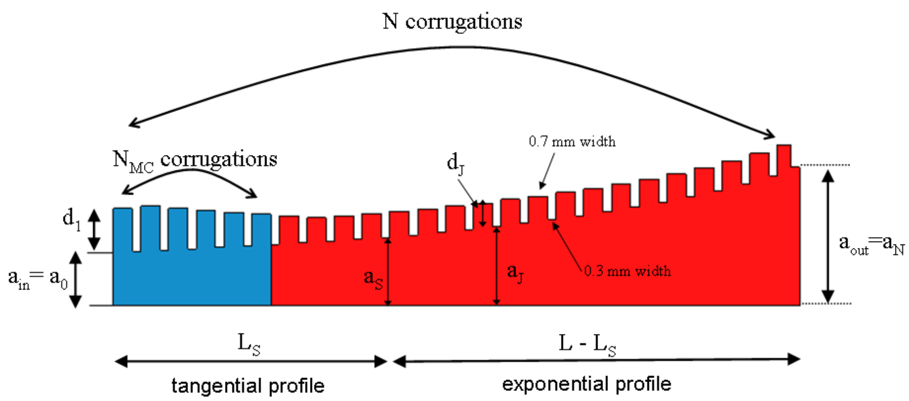

Figure 4: *Geometrical parameters of a DPCH*

Parameter	To optimize	Fixed	Range/Value
Number of corrugations		x	25
Corrugation step		x	1mm
Corrugation width		x	0.7mm
Input Radius		x	1.94 mm
Output Radius		x	5 mm
A	x		$0.1 \div 1$
ρ	x		$0.1 \div 5.0$
L_s	x		$3.0 \div 25.0$ mm
a_s	x		$2.0 \div 4.5$ mm
f_c	x		$80 \div 110$ GHz
f_{out}		x	f_c
σ		x	0.5
N_{MC}		x	6
α	x		$2.0 \div 3.0$
β	x		$1.0 \div 2.0$

Table 2: *Design parameters*

6 Objective function

A objective function (f_{obj}) quantifies the goodness of a solution in a optimization algorithm. It takes the values of each parameters and returns a single number representing how good the solution is. For this work the design parameters are fed into a horn simulation program that creates a horn cross section and simulates the electromagnetic performance. Definition of the objective function is not straightforward in many cases and often is performed iteratively if the fittest solutions produced by PSO are not what is desired. The following function has been used for the optimization:

$$
\begin{aligned}
f_{obj} &= \omega_{RL} \cdot \sum_{i=1}^{N_f} f_{RL}^i + \omega_\chi \cdot \sum_{i=1}^{N_f} f_\chi^i \\
f_{RL}^i &= \begin{cases} S_{11}^i(dB) - S_{11}^{th}(dB), & \text{if } S_{11}^i > S_{11}^{th} \\ 0, & \text{etherwise} \end{cases} \\
f_\chi^i &= \begin{cases} \chi_{pol}^i(dB) - \chi_{pol}^{th}(dB), & \text{if } \chi_{pol}^i > \chi_{pol}^{th} \\ 0, & \text{etherwise} \end{cases}
\end{aligned}
\tag{4}
$$

S_{11}^{th} and χ_{pol}^{th} (threshold values) represent the maximum desidered levels of return loss and peak cross-polarization, S_{11}^i and χ_{pol}^i represent the return loss and peak cross-polarization evaluated at i-th frequency, N_f is the number of frequencies used to compute the performances, ω_{RL} and ω_χ are two weight factor. The choice of these parameters is the following:

- S_{11}^{th}=-32 dB
- χ_{pol}^{th}=-32 dB
- ω_{RL}=0.7
- ω_χ=0.3

The threshold values are less than specifications to force the optimizer to find out a better design.

N_f is a very important parameter because it indicates which frequencies are controlled by optimizer. High values indicate that optimizer works well in the entire band but it is more time-consuming. Low values permit to have a fast solution but don't permit to know the correct behavior in the work band. We have selected the following set of values: $\bar{f}_{GHz} = \{80, 85, 90, 97, 100, 105, 110\}$. In fig. 5 an example of single dimension function $Y(X)$ is showed, where the red-stripes regions indicate where function is penalized (Y^{TH} is a threshold value).

7 Simulation Results

Simulation has been performed on AMD Athlon Dual Core Processing 4400+ (2200 MHz) using a 32bit commercial electromagnetic simulator (SRSR-4d, France Telecom, [1]). The total time has been of about 48h.

In the fig. 6 the trend of the fitness function is depicted. It shows that the PSO is able to find the optimum design for this problem.

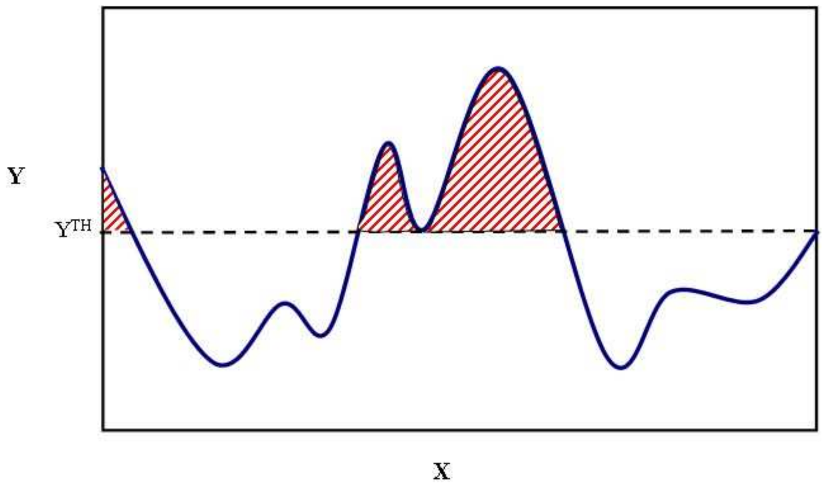

Figure 5: *An example of single dimension function. Y^{TH} is a threshold value and the red-stripes regions indicate where function is penalized*

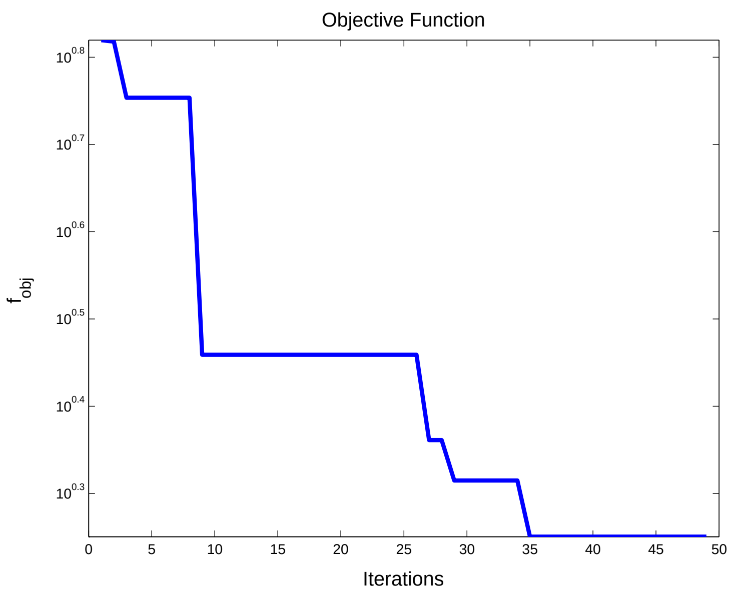

Figure 6: *The fitness function evaluated for every iteration*

Parameter	A	ρ	L_s	a_s	f_c	α	β
Value	0.28	1.86	15.43	3.75	103.1	2.78	1.74

Table 3: *Design parameters*

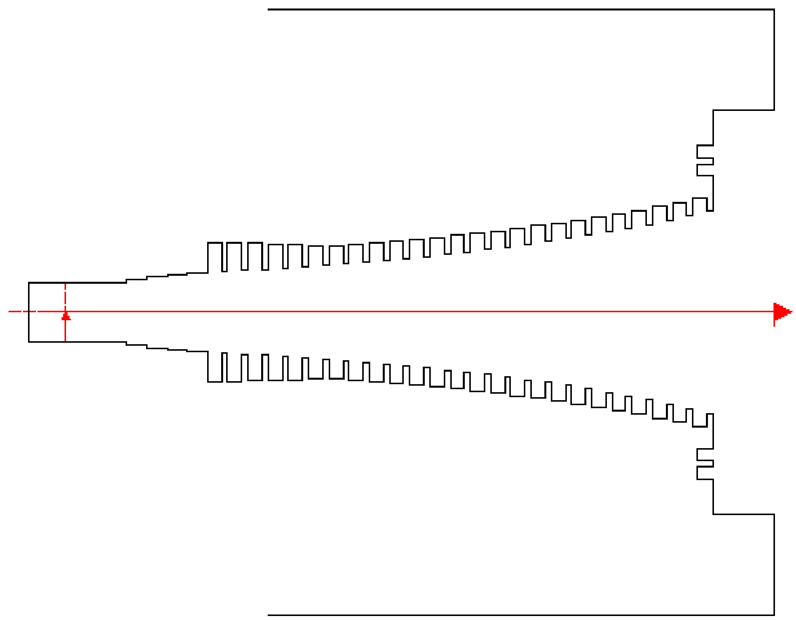

Figure 7: *Best profile found by optimizer*

In the table 3 the ouput parameter of the optimizer is showed.

The performance analysis has been performed from 80 GHz to 110 GHz with a step of 0.25 GHz. In the following figures the impedance and radiation performance are reported.

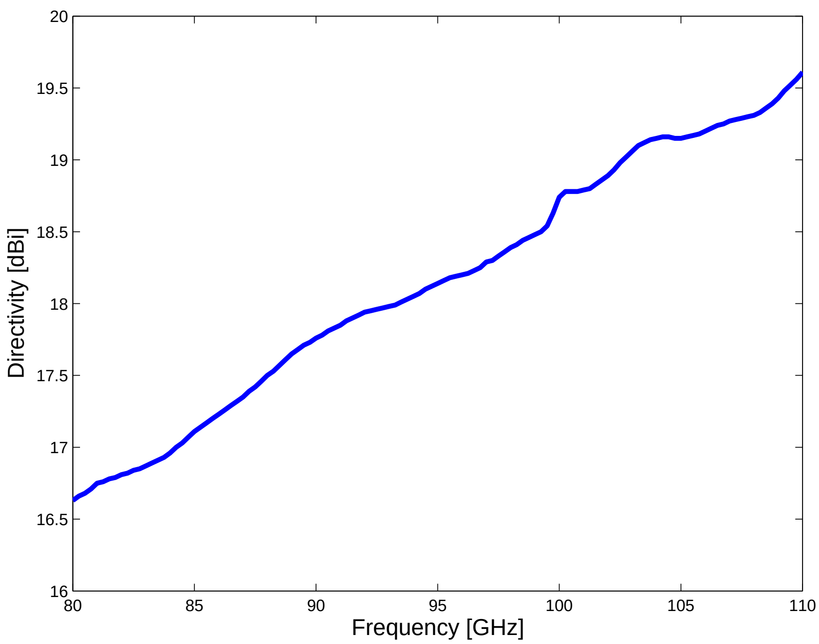

Figure 8: *Directivity as function of frequency*

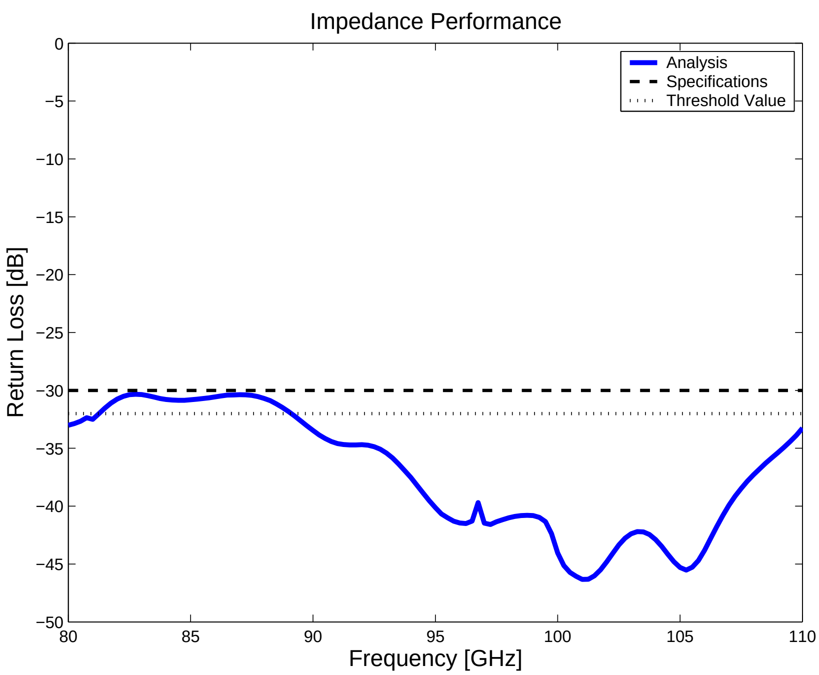

Figure 9: *Return loss as function of frequency*

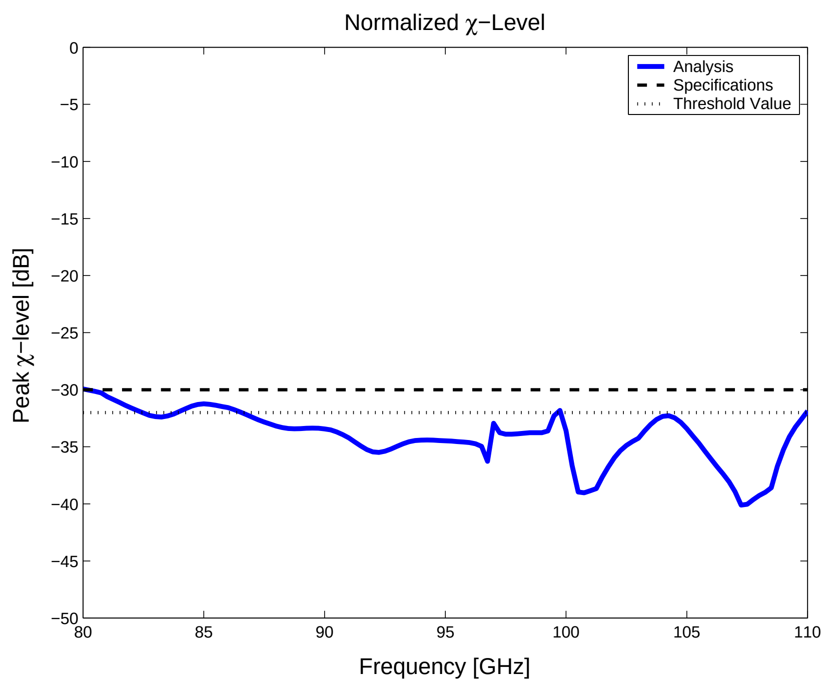

Figure 10: *Peak χ-polarization level respect to maximum radiation as function of frequency*

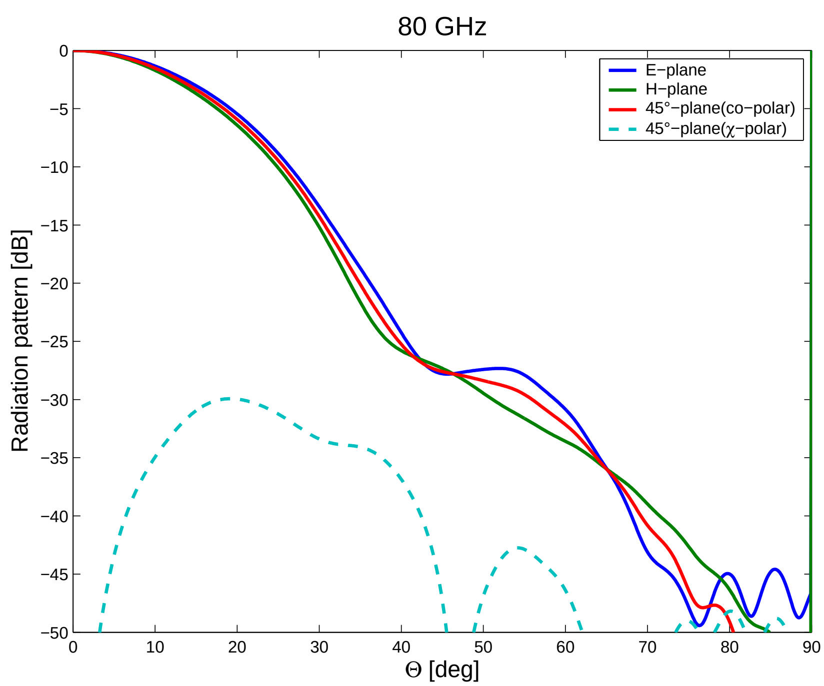

Figure 11: *Radiation Patterns @ 80 GHz*

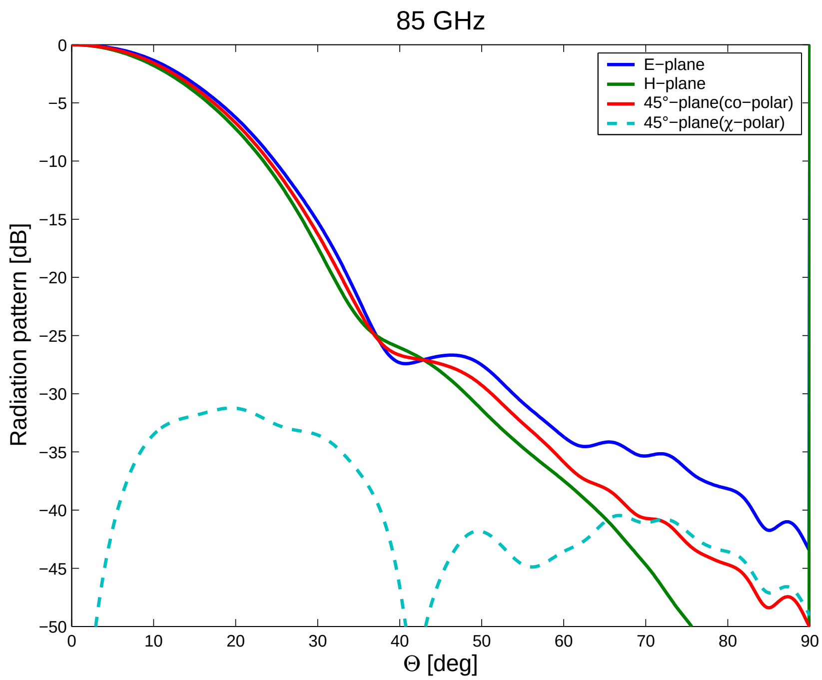

Figure 12: *Radiation Patterns @ 85 GHz*

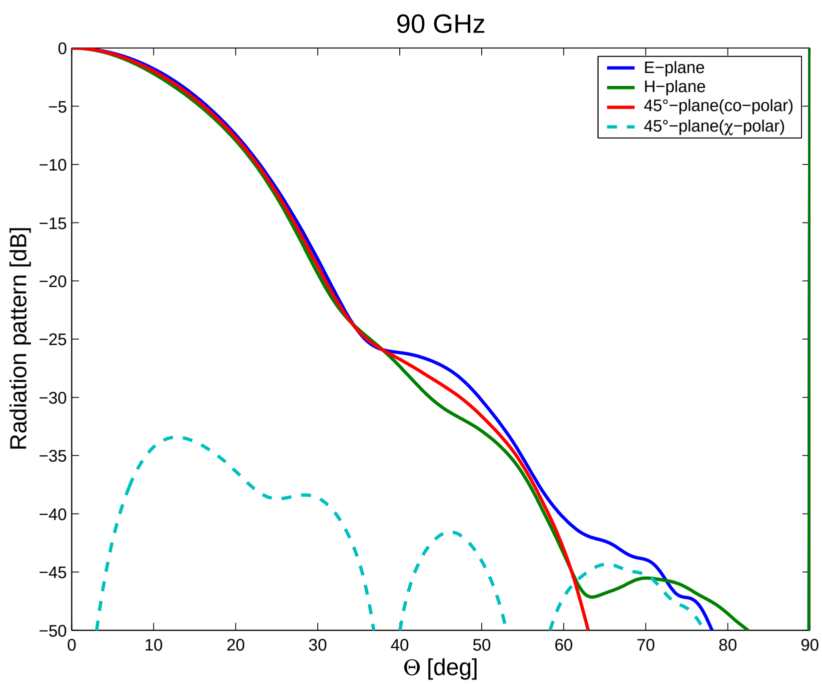

Figure 13: *Radiation Patterns @ 90 GHz*

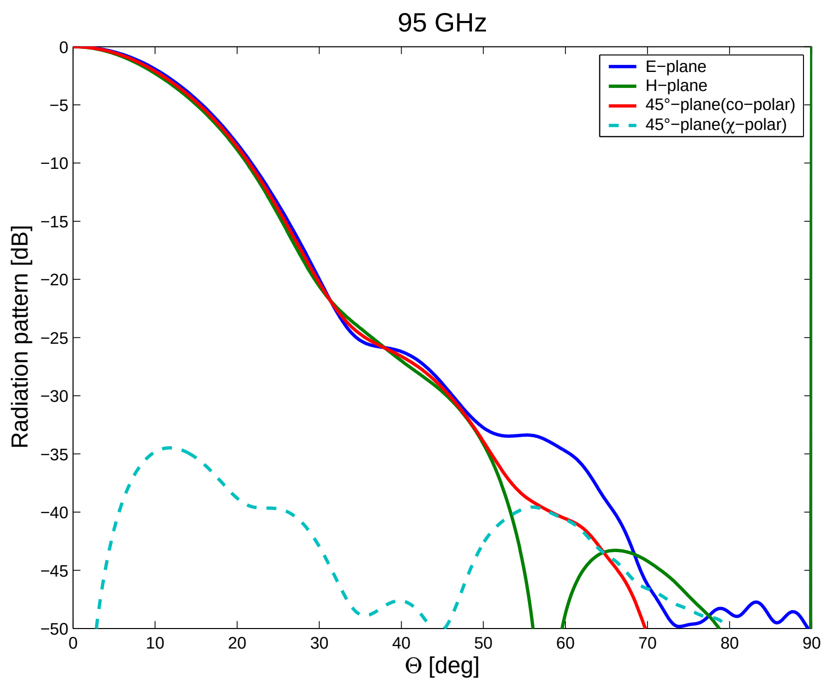

Figure 14: *Radiation Patterns @ 95 GHz*

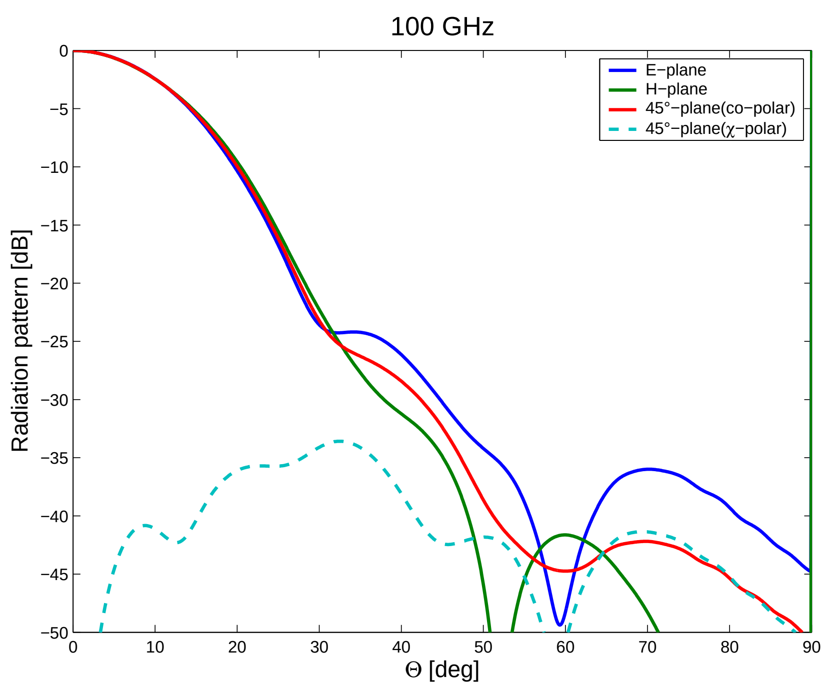

Figure 15: *Radiation Patterns @ 100 GHz*

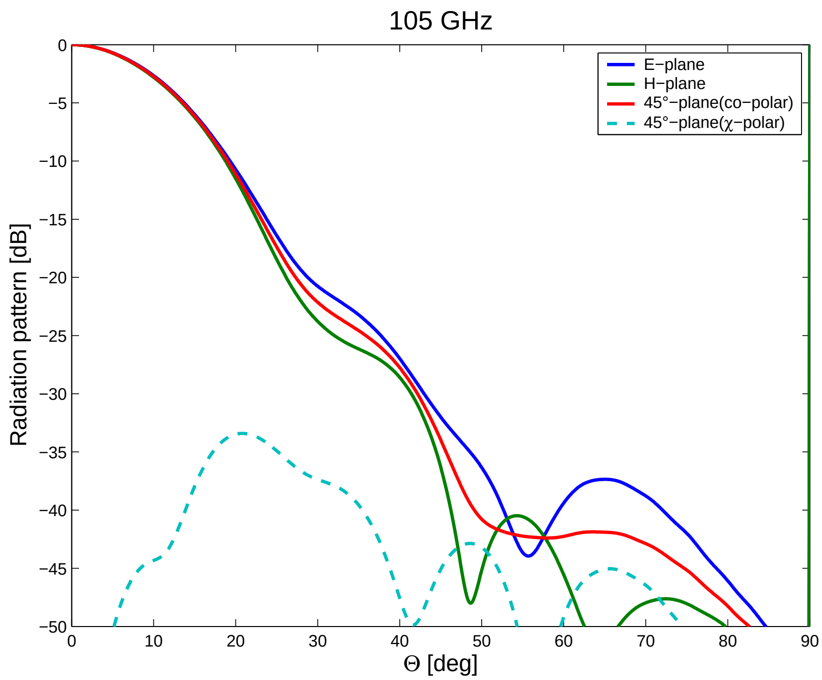

Figure 16: *Radiation Patterns @ 105 GHz*

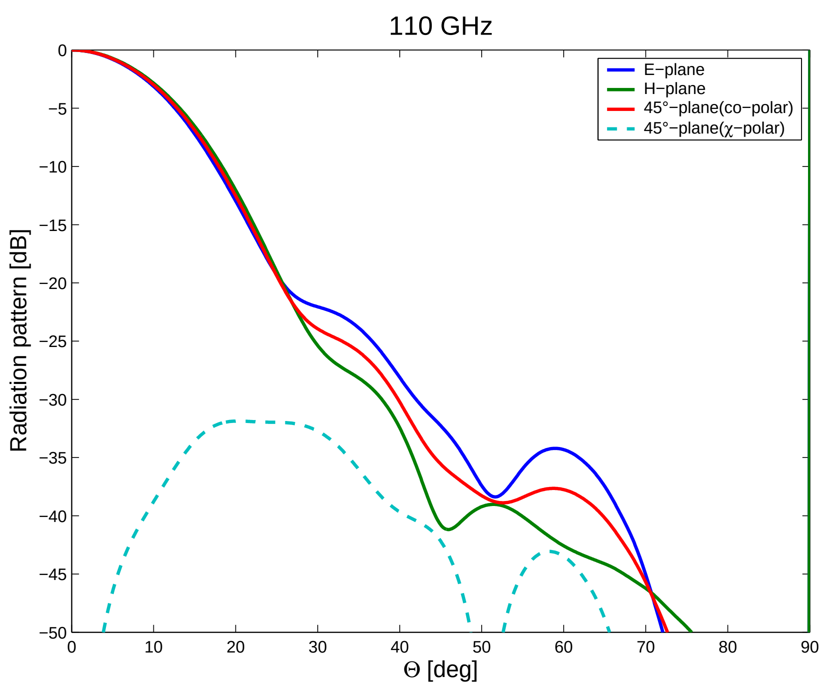

Figure 17: *Radiation Patterns @ 110 GHz*

8 Numerical data

8.1 Geometry

N	L [mm]	R [mm]	N	L [mm]	R [mm]	N	L [mm]	R [mm]
1	3.0	1.49	20	0.7	3.36	39	0.3	3.49
2	1.0	1.64	21	0.3	2.48	40	0.7	4.41
3	1.0	1.79	22	0.7	3.43	41	0.3	3.64
4	1.0	1.87	23	0.3	2.57	42	0.7	4.56
5	1.0	1.94	24	0.7	3.52	43	0.3	3.80
6	0.7	3.47	25	0.3	2.66	44	0.7	4.71
7	0.3	2.02	26	0.7	3.60	45	0.3	3.97
8	0.7	3.45	27	0.3	2.76	46	0.7	4.88
9	0.3	2.07	28	0.7	3.70	47	0.3	4.15
10	0.7	3.41	29	0.3	2.86	48	0.7	5.06
11	0.3	2.12	30	0.7	3.80	49	0.3	4.35
12	0.7	3.37	31	0.3	2.97	50	0.7	5.25
13	0.3	2.18	32	0.7	3.91	51	0.3	4.55
14	0.7	3.34	33	0.3	3.09	52	0.7	5.45
15	0.3	2.25	34	0.7	4.02	53	0.3	4.77
16	0.7	3.31	35	0.3	3.21	54	0.7	5.66
17	0.3	2.32	36	0.7	4.14	55	0.3	5.00
18	0.7	3.28	37	0.3	3.35			
19	0.3	2.40	38	0.7	4.27			

Table 4: *Geometry of the horn described as a chain of sections.* ***N*** *is the number of section,* ***L*** *is the length and* ***R*** *is the radius of every section.*

8.2 Electromagnetic performances

F [GHz]	Directivity [dBi]	Return Loss [dB]	Peak χ-level Polarization [dB]
80	16.6277	-33.0113	-29.929
80.25	16.6572	-32.865	-30.0396
80.5	16.6849	-32.6562	-30.1417
80.75	16.7096	-32.3599	-30.2664
81	16.7506	-32.4998	-30.6051
81.25	16.7646	-32.0076	-30.8491
81.5	16.7788	-31.5172	-31.1047
81.75	16.7935	-31.0931	-31.3597
82	16.8072	-30.7463	-31.5968
82.25	16.8218	-30.5086	-31.8272
82.5	16.8363	-30.3694	-32.0369
82.75	16.8535	-30.3311	-32.2493
83	16.8701	-30.3611	-32.3628
83.25	16.8893	-30.4491	-32.3918
83.5	16.9093	-30.5748	-32.2979
83.75	16.9343	-30.6962	-32.1297
84	16.9619	-30.7886	-31.8993
84.25	16.9953	-30.8283	-31.6553
84.5	17.0296	-30.8473	-31.4441
84.75	17.0671	-30.8511	-31.2914
85	17.1051	-30.8113	-31.2261
85.25	17.1398	-30.7604	-31.2787
85.5	17.1705	-30.7034	-31.3613
85.75	17.1986	-30.6383	-31.469
86	17.2268	-30.5623	-31.5737
86.25	17.256	-30.481	-31.7405
86.5	17.2861	-30.404	-31.9421
86.75	17.3196	-30.3935	-32.1717
87	17.3531	-30.3671	-32.4095
87.25	17.3872	-30.3759	-32.6259
87.5	17.4225	-30.4298	-32.8271
87.75	17.4586	-30.5372	-33.0135
88	17.4961	-30.6852	-33.1777
88.25	17.5349	-30.8776	-33.3235
88.5	17.5733	-31.1554	-33.4038
88.75	17.6109	-31.4675	-33.4225
89	17.6459	-31.8247	-33.4061
89.25	17.678	-32.2232	-33.3709
89.5	17.7071	-32.6339	-33.3602
89.75	17.734	-33.0546	-33.3751
90	17.7591	-33.4634	-33.426

Table 5: *Electromagnetic Performances in terms of directivity, return loss and χ-polarization from 80 to 90GHz.*

F [GHz]	Directivity [dBi]	Return Loss [dB]	Peak χ-level Polarization [dB]
90.25	17.7828	-33.8473	-33.5248
90.5	17.8069	-34.1599	-33.6966
90.75	17.8302	-34.4164	-33.9262
91	17.854	-34.5873	-34.2228
91.25	17.8778	-34.6793	-34.5693
91.5	17.9009	-34.7087	-34.9272
91.75	17.9222	-34.7066	-35.2368
92	17.9406	-34.6922	-35.4356
92.25	17.9543	-34.7427	-35.4865
92.5	17.9642	-34.8643	-35.3919
92.75	17.9719	-35.0829	-35.1965
93	17.9801	-35.4069	-34.9598
93.25	17.9917	-35.8377	-34.7299
93.5	18.007	-36.3482	-34.5563
93.75	18.0262	-36.9331	-34.452
94	18.0485	-37.5333	-34.4103
94.25	18.0733	-38.193	-34.4047
94.5	18.0983	-38.8629	-34.4213
94.75	18.1216	-39.5166	-34.4526
95	18.1423	-40.1313	-34.4779
95.25	18.1596	-40.6714	-34.503
95.5	18.1751	-41.003	-34.5381
95.75	18.188	-41.2992	-34.5753
96	18.2008	-41.4467	-34.633
96.25	18.2143	-41.5015	-34.7378
96.5	18.2306	-41.2875	-34.963
96.75	18.2477	-39.6864	-36.2658
97	18.2895	-41.4608	-32.9421
97.25	18.3025	-41.5794	-33.7747
97.5	18.3298	-41.3549	-33.8907
97.75	18.3582	-41.1736	-33.8934
98	18.3861	-41.0132	-33.8585
98.25	18.4126	-40.8911	-33.8093
98.5	18.4372	-40.8107	-33.77
98.75	18.4602	-40.7905	-33.7566
99	18.4814	-40.8244	-33.7615
99.25	18.5038	-40.9655	-33.6145
99.5	18.5416	-41.3436	-32.2921
99.75	18.6322	-42.3765	-31.8125
100	18.7427	-44.0539	-33.5851

Table 6: *Electromagnetic Performances in terms of directivity, return loss and χ-polarization from 90.25 to 100GHz.*

F [GHz]	**Directivity [dBi]**	**Return Loss [dB]**	**Peak χ-level Polarization [dB]**
100.25	18.7802	-45.1338	-36.6367
100.5	18.7829	-45.7213	-38.9608
100.75	18.7825	-46.0487	-39.032
101	18.7893	-46.3293	-38.847
101.25	18.8035	-46.313	-38.6621
101.5	18.8255	-46.0212	-37.6596
101.75	18.8565	-45.501	-36.7568
102	18.893	-44.808	-35.9547
102.25	18.9343	-44.0825	-35.3354
102.5	18.9779	-43.3454	-34.8828
102.75	19.0205	-42.7727	-34.5335
103	19.0604	-42.3929	-34.2525
103.25	19.095	-42.1957	-33.6102
103.5	19.1228	-42.2248	-33.0447
103.75	19.1427	-42.4524	-32.5967
104	19.1535	-42.8856	-32.325
104.25	19.1571	-43.481	-32.2727
104.5	19.1556	-44.1501	-32.4615
104.75	19.1531	-44.8	-32.8534
105	19.1531	-45.3018	-33.4092
105.25	19.1581	-45.5223	-34.0628
105.5	19.1704	-45.2807	-34.6818
105.75	19.1839	-44.6928	-35.3797
106	19.2002	-43.8088	-36.074
106.25	19.2185	-42.7869	-36.7272
106.5	19.237	-41.7565	-37.3663
106.75	19.2538	-40.7907	-38.0679
107	19.268	-39.9151	-38.9372
107.25	19.2799	-39.1395	-40.1113
107.5	19.2902	-38.4579	-40.0328
107.75	19.301	-37.8488	-39.627
108	19.3149	-37.2933	-39.2723
108.25	19.3342	-36.7774	-38.9804
108.5	19.3602	-36.2879	-38.5878
108.75	19.3938	-35.8157	-36.7075
109	19.4332	-35.3659	-35.2501
109.25	19.4762	-34.9113	-34.1247
109.5	19.5208	-34.4248	-33.2556
109.75	19.5649	-33.8774	-32.5658
110	19.6074	-33.2569	-31.8638

Table 7: *Electromagnetic Performances in terms of directivity, return loss and χ-polarization from 100 to 110GHz*

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