Design and measurement of a waveguide WR10 to microstrip transition for W band cryogenic amplifiers.

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1. Introduction

W band cryogenic amplifiers are designed with WR-10 waveguide input and output ports because of their lower loss and relaxed mechanical requirements with respect to coaxial connectors. The amplifier will be built in microstrip or coplanar technology so a transition from waveguide to microstrip is needed.

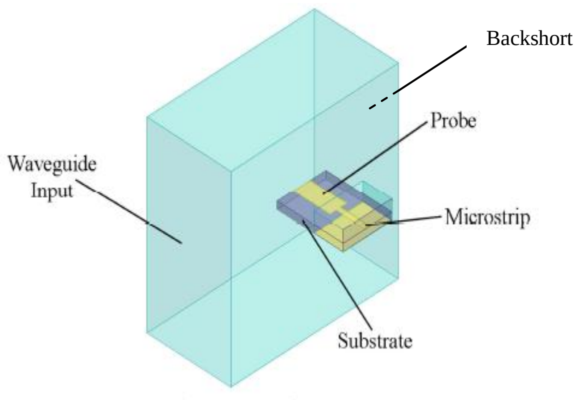
It is possible to classify the transitions from rectangular waveguide to microstrip in three groups:

1. Transitions via apertures in the ground plane of the microstrip which couple energy trough cuts in the broad-wall or end-wall of the waveguide[1].
2. Transitions located along the propagation direction of the waveguide[2].
3. Transitions using probes perpendicular to the propagation direction of the waveguide.

A transition of the third type (referred as “probe” from now on) was selected for this design because of its easy implementation and the absence of tight tolerance mechanical joints. Probe transitions are particularly suitable for millimeter wave use and are the type more frequently used for W band.

The microstrip probe can be implemented with the plane of the substrate a) aligned or b) perpendicular to the waveguide propagation direction. In both cases, the microstrip should enter in the rectangular waveguide through a window in the center of the broad wall, minimizing the perturbation to the current lines. Both types appear to have similar electrical performance so the choice of the aligned type (Figure 1) was made based upon the easiness of integration and the adequate orientation of the waveguide in the amplifier chassis.

The probe is a rectangular patch of dimensions WP (width) x D (length), at a distance L of the back-side short. A matching network, used to achieve broadband matching of the probe impedance to the microstrip line (WD width), consists of a high impedance microstrip line (WI, LI) and a quarter-wave impedance transformer (WT, LT).



[1] Amjad A. Omar, Nihad I. Dib, *“Analysis of slot-coupled transitions from microstrip-to-microstrip and microstrip-to-waveguides”*, IEEE Trans. Microwave Theory Tech., vol. MTT-45, pp. 1127-1132, Jul.1997.
[2] J.H.C. van Heuven, *“A new integrated waveguide-microstrip transition”*, IEEE Trans.Microwave Theory Tech., vol. MTT-24, pp. 144-147, March 1976.

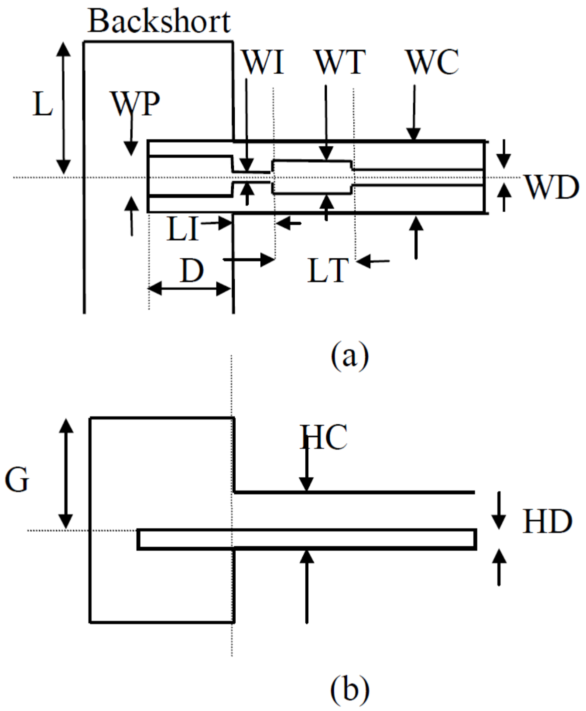


Figure 1. Configuration of an E-plane probe. a) View from waveguide narrow wall. b) View in direction of propagation towards back-short.

2. Design of the probe.

The first step in the design process is to select the substrate. The dimensions of the probe depend on the dielectric constant. We decided to design a probe for three different substrates (Table 1):

Probe substrate	ε_r	*height (µm)*
Duroid[3]	2.94	127
Cuflon[4]	2.05	127
Quartz	3.80	50

Table 1. Characteristics of the substrates used for the probes.

The cut-off frequency of the window opening at the broad-wall of the waveguide also depends on the dielectric constant and the height of the substrate of the probe. The second step in the design process is to select the width and height of this window, taking into account:

- The waveguide modes should be in cut-off in the cavity of the microstrip line.
- The disturbance to the mode in the main waveguide should be minimized.

The disturbance of the waveguide can be reduced by minimizing the area of the window. Based on probe dimensions for different substrates designed in [*1*], the height of the window, *HC*, was fixed at 259 µm. The width *A* of the window must be smaller than 1.02 mm (with a Duroid substrate) for

[3] Rogers 6002

[4] PN: CF-A-5-3.5-14, 5 mills Cuflon, 1 oz Cu/ 0.25 oz Cu, made by Polyflon (a Crane Company), thermal expansion: 129 ppm/ºC (x,y,z)

a f_c > 120 GHz following the formula of Donadio [2] for estimating the cut-off frequency, f_c, of the lowest waveguide mode supported by a channelized microstrip. The value of f_c is given by:

$$fc := \frac{c}{2 \cdot A \cdot \sqrt{\dfrac{1}{1 - \dfrac{h}{HC} \cdot \left(1 - \dfrac{1}{\varepsilon r}\right)}}}$$

being *HC* the total height of the cavity, ε_r the dielectric constant and *h* the height of the substrate. The fundamental design parameters of the probe are the distance to the back-short *L*, the width of the probe *WP* and its length *D*. By changing these parameters, the impedance of the probe changes and the matching with the rectangular waveguide can be achieved.

The design of a broadband transition looks for a combination of these three parameters where the probe input impedance varies very little over frequency, i.e. the rate of change of both the real part and imaginary part of impedance with frequency is small.

There are two additional elements after the probe that could be use to match it to a 50 Ω system:

- A high impedance inductive line (*WI*, *LI*), in series with the probe, to resonate out the capacitive reactance of the probe.
- A quarter-wave impedance transformer (*WT*, *LT*), after the inductive line, to match the real part of the probe impedance to 50 Ω.

Three different probes have been designed and fabricated in Yebes, one for each substrate of the Table 1. The simulation software used in the optimization process was HFSS v.13. Some practical issues of the waveguide milling process were accounted for:

- The diameter of the milling cutter used to machine the rectangular waveguide. The radius of the corner of the waveguide is 0.25 mm (marked as (a) in Figure 2).
- The tolerances of fabrication of the width of the milling channel for the transition in the box, *Wcc*: The width will be 40 µm wider than the substrate (i.e. *Wcc* = *WC* + 40 µm) in all designs (marked as (b) in Figure 2).

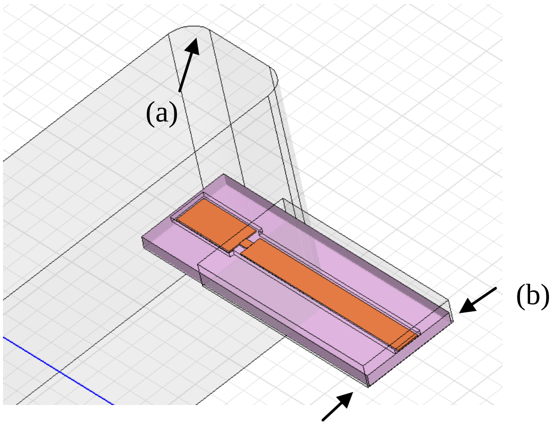


Figure 2. Example of a probe simulated in HFSS.

The optimized probe dimensions obtained are listed in Table 2.

Probe	D	WP	L	WI	LI	WD	WC	HC	HD	G
Duroid	625	344	838	80	100	240	880	259	127	1270
Cuflon	665	324	848	80	100	234	973	259	127	1270
Quartz	660	230	860	50	190	100	600	259	50	1270

Table 2. Dimensions of the probes obtained for the three different substrates. All dimensions are in μm (see Figure 1).

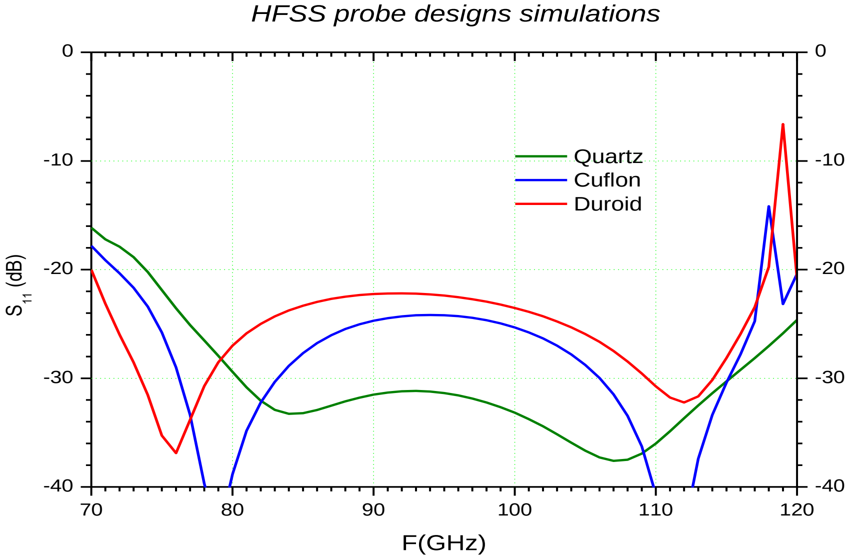


Figure 3. HFSS simulations of the three different probes.

3. Manufacturing the probe.

In order to check the performance of the probes, back to back transitions with Duroid and Cuflon probes were manufactured. The drawing for the Duroid substrate is presented in Figure 4. The substrate was milled on both sides using the fiducial mark alignment facility of the LPKF[5]. Cuflon was particularly difficult to process with the laser machine due to the infrared transparency of this substrate.

Figure 4. Back to back transition of Duroid.

[5] LPKF ProtoLaser 200 from LPKF Laser & Electronics.

The box for the transition is similar to the one which will be used for the W-band LNA (see Figure 5). It is split in half of the long side of the WR-10 waveguide. The transition is glued by epoxy[6] in its box channel taken into account that the surface of the top side of the substrate has to be in the same z-plane than the surface of the half box (requirement established in the design).

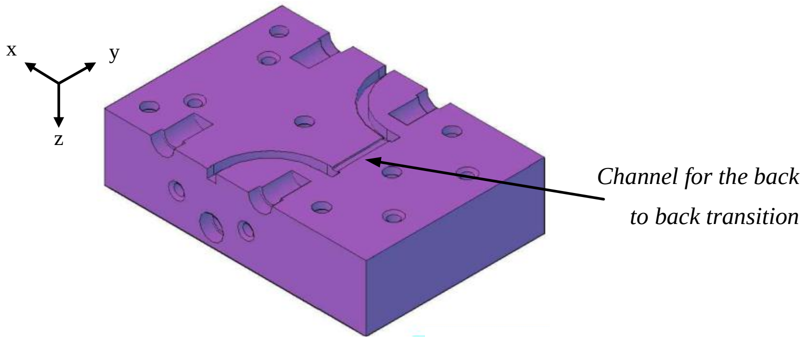


Figure 5. Box for the measurement of the back to back transition.

The results of the measurements of the two back to back transitions are shown in Figure 6:

- Return loss is similar and better than -15 dB in both transitions in almost all band (70-115 GHz).
- Insertion loss is lower than 1.8 dB in the 70-115 GHz band. It is lower in the Cuflon than in the Duroid transition (0.85 vs 1.2 dB at 90 GHz) but the difference between them is too large to be explained only by the difference of the loss tangent of the dielectric materials. The surface roughness of the copper metallization may play a role in this.
    - The theoretical value of the total transmission loss of ideal WR-10 waveguides within the module is 0.1 dB[7] at 90 GHz.
    - Boxes with straight sections of 20 and 40 mm long WR-10 waveguides were manufactured using the same approach used to build the back to back transitions. The measured insertion loss obtained is presented in Table 3. From these measurements the value extrapolated for a 29.8 mm length of WR-10, will be between 0.15-0.26 dB.

WR-10 golden waveguide	VNA[8]	SNA[9]
20 mm long	0.1 (S_{11} < -30 dB)	0.15 (S_{11} < -20 dB)
40 mm long	0.2 (S_{11} < -30 dB)	0.35 (S_{11} < -20 dB)

Table 3. Insertion loss measured in two WR-10 waveguides fabricated in Yebes.

    - The ADS estimated transmission loss for the Cuflon and Duroid microstrip lines is 0.3 and 0.33 dB[10] respectively, at 90 GHz. Note that the real value will always be higher than this.

[6] Epo-tek H20E.
[7] For a WR-10 gold plated waveguide (conductivity $4.1 \cdot 10^7$ S/m) looses are theoretically calculated in 3.2 dB/m at 90 GHz. The length of the input and output curved WR-10 waveguide port (see Annex 1 Duroid box plane) is 14.9 mm, so there is a total of 29.8 mm of WR-10 inside the module.
[8] VNA (vector network analyzer): E8364B PNA from Agilent with the OML microwave head N5260AW10.
[9] SNA (signal network analyzer): HP8757A from Agilent. "Configuration of the Laboratory Setup for Scalar R/T Measurements in the Extended W-Band (70-115 GHz)", IT-CDT 2015-4.

- Taken into account 0.2 dB for insertion loss in the WR-10 waveguides in the box and 0.3 dB for losses in the microstrip, the estimated net transmission loss per transition will be lower than 0.18 dB for Cuflon and 0.35 dB for Duroid waveguide to microstrip transition at 90 GHz. However, this estimation is very inaccurate and should not be used for critical calculations. The only thing that can be deduced from this calculation is that the loss of the transitions is very low and that, in practice, the total loss is probably dominated by the effect of the waveguides and the additional length of microstrip lines.

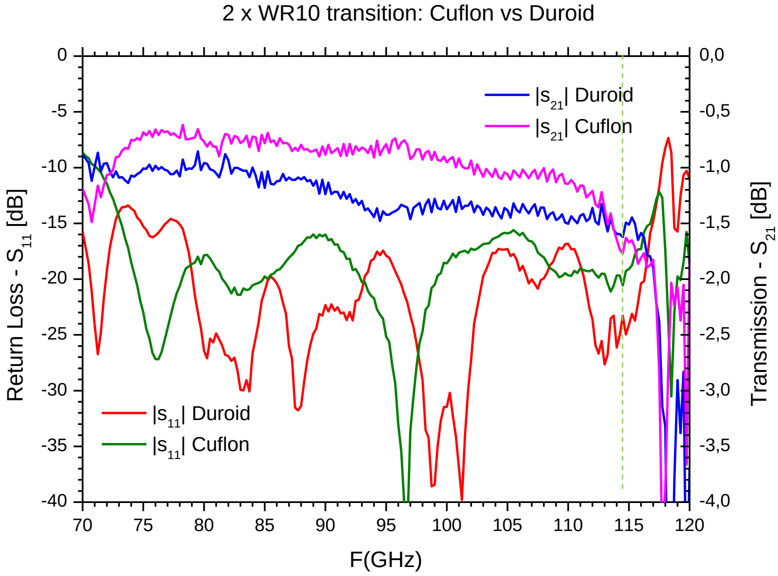


Figure 6. Measurements of the back to back Duroid and Cuflon transitions.

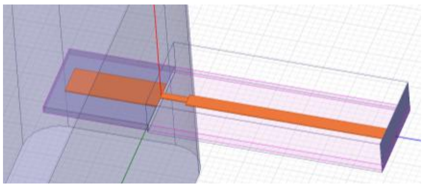
The Quartz transitions were made in fused Quartz using the IAF[11] process. A complete back to back Quartz transition was not available and then it was not possible to check the performance in a similar way as with the Duroid or Cuflon substrates. To partially verify the design, it was decided to connect two Quartz transition with a 50 Ω Duroid line in between connected with bonding wires[12]. The experiment was performed using a box made for the Duroid transitions (instead of building one optimized for Quartz) (see Table 2). Transitions are placed in the box keeping the parameter L (distance to the short, 860 um) because of its main role in the performance, so transitions are displaced from the middle of the channel. In order to estimate how these modifications affect the performance of the Quartz transition, three simulations were compared (see Figure 7a):

[10] The microstrip dimensions are 7.26 mm long, 127 μm substrate thickness, 132 μm cover high, in gold finish (σ=4.1·10^7 S/m). *Cuflon*: 234 μm width, ε_r = 2.05, tanδ = 0.00045, α_d = 3.94 dB/m, α_c = 62.8 dB/m. *Duroid*: 240 μm width, ε_r = 2.94, tanδ = 0.0012, α_d = 12.9 dB/m, α_c = 70 dB/m.

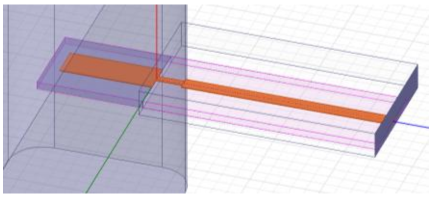
[11] Fraunhofer Institute for Applied solid state physics.

[12] The distance between the input Quartz transition and the 50 Ω Duroid line is 25 μm; they are joined by two bonding wires of 80 μm length with a 20 μm loop. The distance between the 50 Ω line and the output Quartz transition is 70 μm; they are joined by two bonding wires of 120 μm with a 20 μm loop.

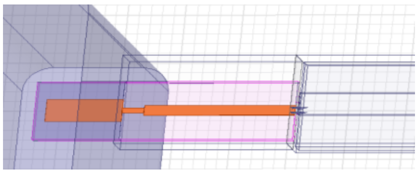
a) "Designed": It is the Quartz transition simulated in an optimized box (see Figure 7).



b) "Duroid Box": It is the previous transition simulated in a box made for the Duroid transition. It takes into account the different width of the channel box and the displacement of the transition from the middle of the channel (see Figure 7).



c) "Two trans+50 Ω line, DB": It is the simulation of the assembly fabricated and measured (two quartz transitions displaced from the middle of the channel, connected to a 50 Ω line with bonding wires similar to the real ones, see Figure 7).



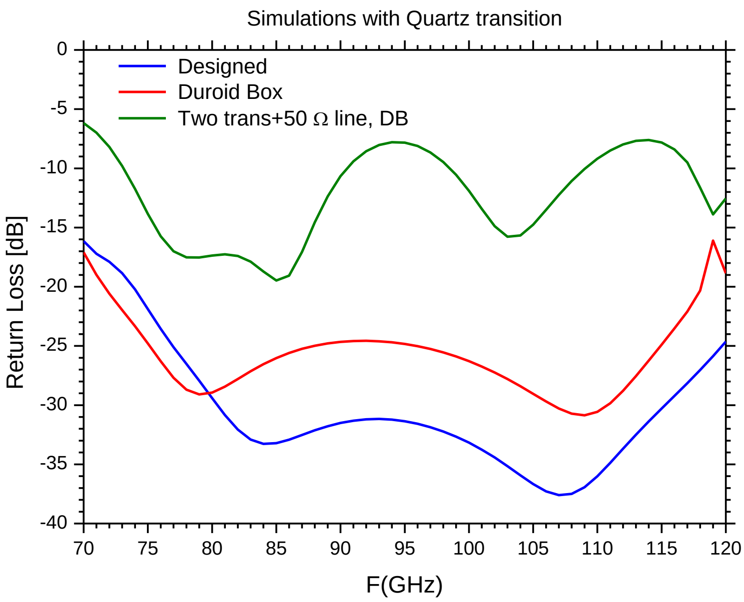


Figure 7. Simulations of Quartz transitions for different assemblies.

Comparing simulations of the cases (a) and (b) of Figure 7, it is possible to conclude that the use of a non-optimum box does not seriously deteriorate the performance of the transition.

However, the result (c) shows that the effect of the bonding wires and the transition to the Duroid line degrades the return loss of the assembly quite strongly, being the dominant effect and hiding the real performance of the transitions.

Figure 8 shows the comparison of the simulation versus the measurement of the assembly (c). The mean value of the estimated and measured return loss is similar. The measured insertion loss is about 1 dB higher than value obtained previously for the back to back Duroid transition (Figure 6).

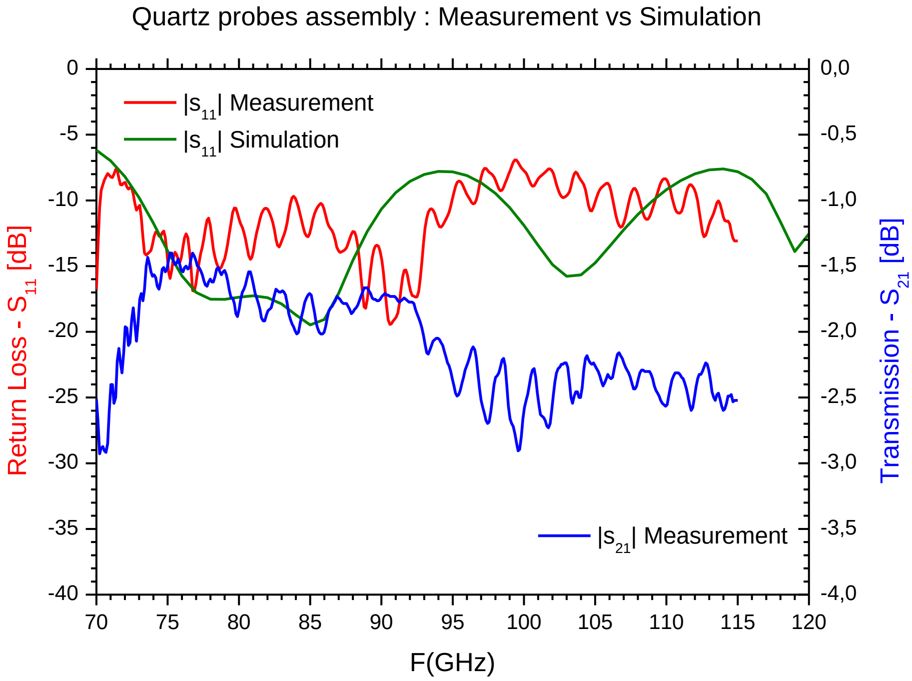


Figure 8. Assembly of two Quartz transition with a 50 Ω line connected with bonding wires, mounted in a box designed for the Duroid transition. Comparison of the measurement with the simulate HFSS S-parameters obtained with HFSS.

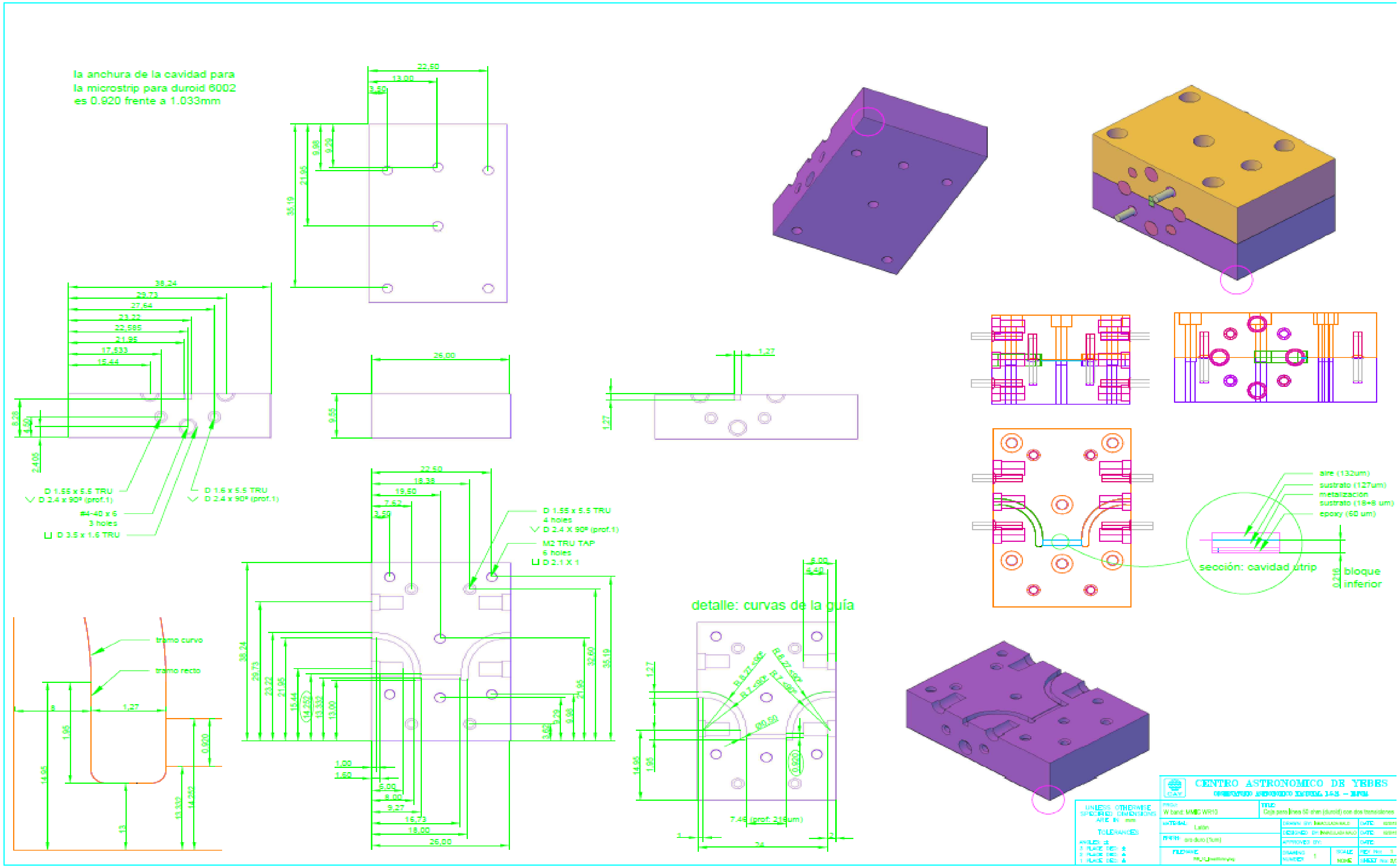
4. Conclusion.

Waveguide to microstrip transitions for the 70-116 GHz band have been designed and fabricated with Duroid, Cuflon and Quartz substrates. The best results in terms of insertion loss were obtained with Cuflon, although due to the difficulties appearing in the laser etching process presently used in Yebes, its practical use in LNAs is not recommended. Very similar performance was obtained with the Duroid substrate and the manufacturing process was much easier. The Quartz transitions were found easy and convenient to handle, since the substrate is transparent, which makes easier the alignment in the box and the inspection once mounted. However, since no back to back Quartz transition were available for experimentation we could not conclude if the design performed as expected from the measurements taken.

5. References.

[1]. Y-C. Leong, S. Weinreb, *"Full band waveguide-to-Microstrip probe transitions"*, Microwave Symposium Digest, 13-19 Jun 1999 IEEE MTT-S International.
[2]. O. Donadio, *"G-band waveguide to microstrip transition for MMIC integration"*, Ph. D. School of Engineering, University of Glasgow, Jan 2012.

Down split box for the back to back Duroid transition.



Up split box for the back-to-back Duroid transition.