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Millimeter Wave Receivers for QUIJOTE CMB polarization experiment

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EPI 2013 Conference

Santander
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QUIJOTE CMB experiment overview

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- Q-U-I JOint TEnerife (Stokes parameters Q, U and I)
- Cosmic Microwave Background (CMB) polarization receivers
- To obtain polarization maps in the frequency range 11- 40 GHz
- Angular resolution: ~1 degree

QUIJOTE experiment consortium

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Instituto de Astrofísica de Canarias (IAC), Tenerife (Spain): Coordinator

Instituto de Física de Cantabria (IFCA), Santander (Spain)

Universidad de Cantabria (UC), Santander (Spain)

University of Cambridge, (UK)

University of Manchester, Jodrell Bank Centre for Astrophysics (UK)

IDOM, Bilbao (Spain)

Observatorio del Teide (Tenerife, Canary Islands)

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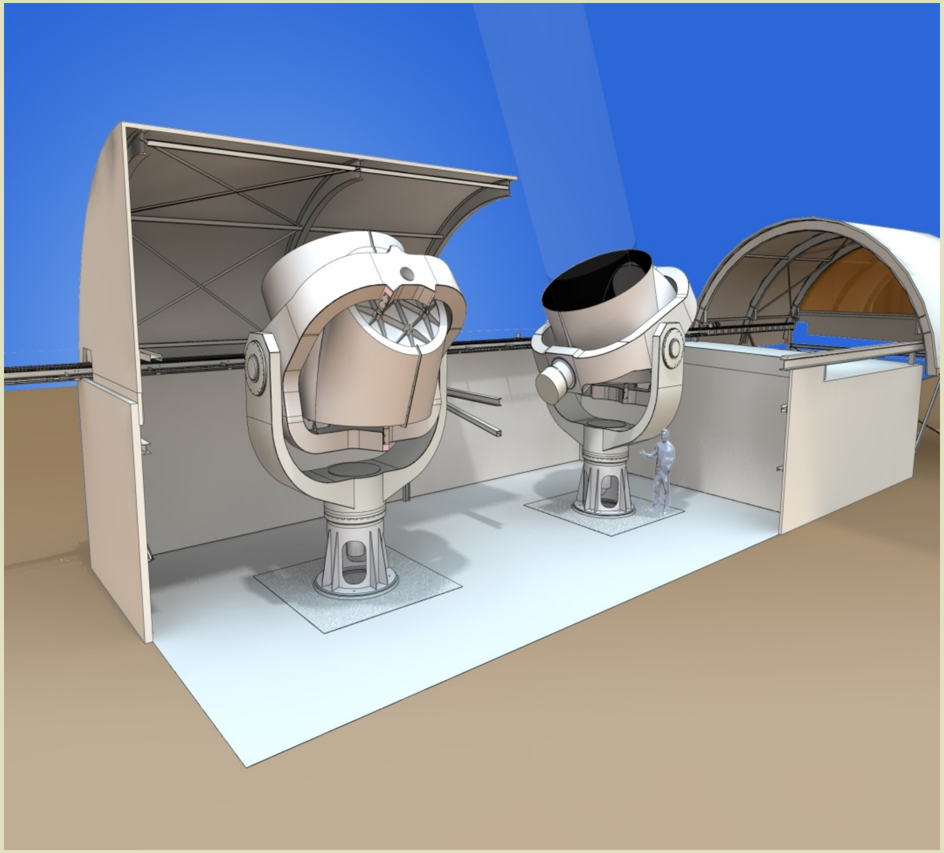
Izaña site, 2.390 m



QUIJOTE Instruments 1 and 2 and enclosure

QUIJOTE experiment. Basic features

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- Polarimeters: polarisation Stokes parameters (Q, U and I) Cosmic Microwave Background (CMB) and other processes of Galactic and extragalactic emission.
- Angular resolution of ~ 1 degree

QUIJOTE-CMB Experiment. Nominal characteristics of the three instruments: MFI, TGI and FGI.

	MFI				TGI	FGI
Nominal Frequency [GHz]	11.0	13.0	17.0	19.0	30.0	40
Bandwidth [GHz]	2	2	2	2	8	10
Number of horns	2	2	2	2	31	40
Channels per horn	4	4	4	4	4	4
Beam FWHM [°]	0.92	0.92	0.60	0.60	0.37	0.28
T_{sys} [K]	25.0	25.0	25.0	25.0	35.0	45.0
NEP [μK $s^{1/2}$]	280.0	280.0	280.0	280.0	45.0	50.0
Sensitivity [Jy $s^{1/2}$]	0.30	0.42	0.31	0.38	0.06	0.06

MFI = Multi-Frequency Instrument (First Instrument: QUIJOTE 1)
TGI = Thirty-GHz Instrument (Second Instrument: QUIJOTE 2)
FGI = Forty-GHz Instrument

Low frequency channels in QUIJOTE MFI

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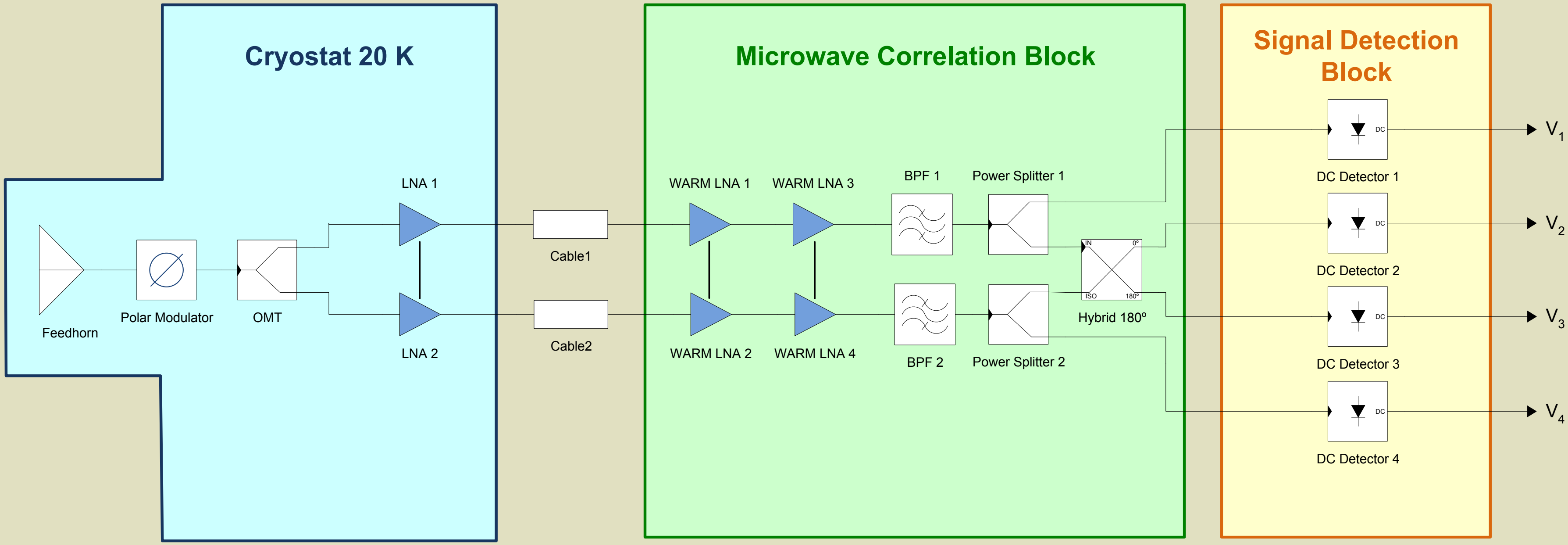

Simultaneous Q and U detection

Output detected voltage in QUIJOTE MFI

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$$V_j = \frac{1}{2} I_j + \frac{1}{2} Q_j \cos(4\varphi + \theta_j) + \frac{1}{2} U_j \sin(4\varphi + \theta_j)$$

$$\theta_1 = 0; \quad \theta_2 = \pi; \quad \theta_3 = +\frac{\pi}{2}; \quad \theta_4 = -\frac{\pi}{2}$$

Q, U and I = Stokes parameters

φ = Position angle of the modulator

These parameters depend on the time and on the channel (*j* = *1, 2, 3, 4*)

Low frequency channels in QUIJOTE MFI

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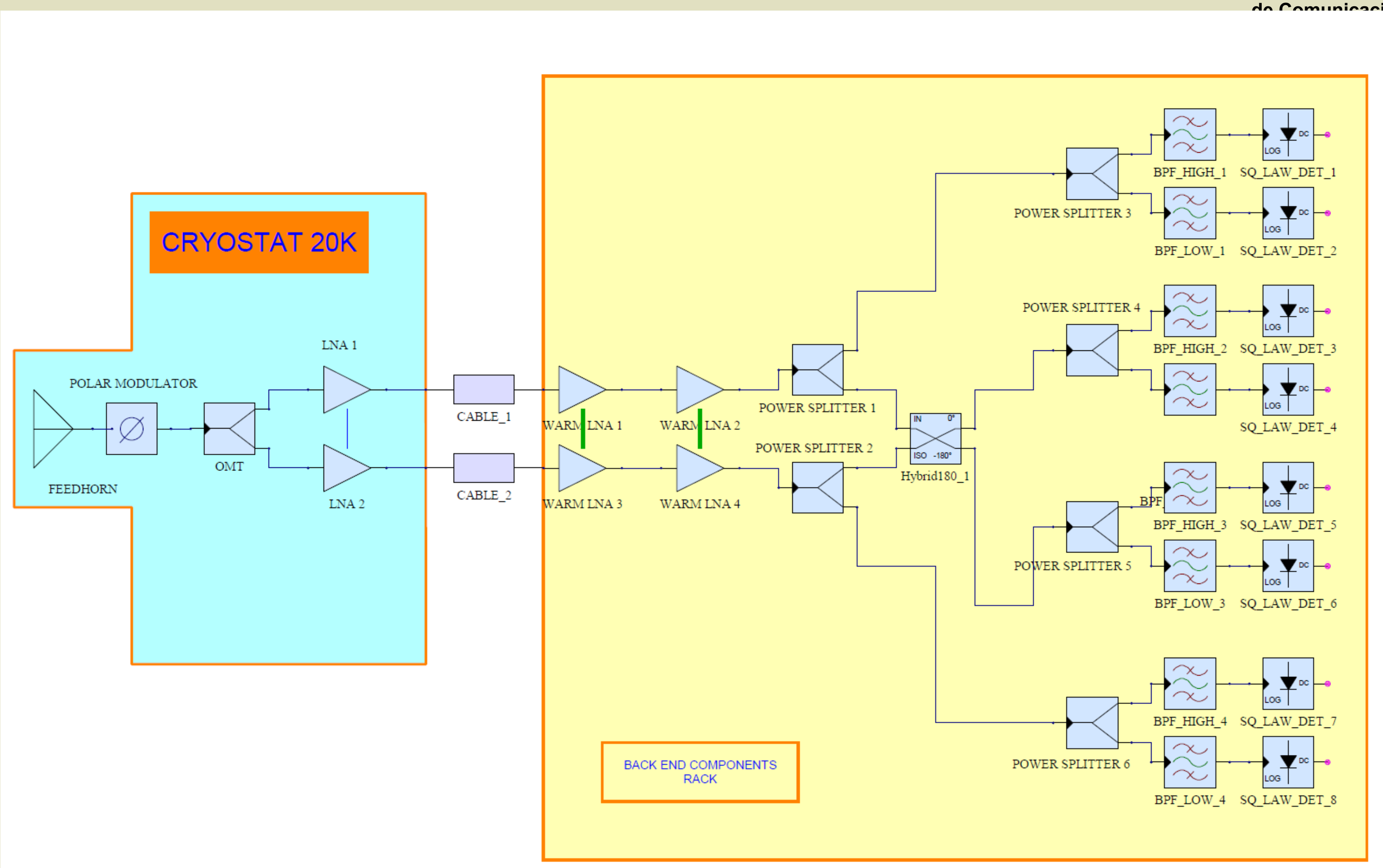

Low frequency channels: 11-13 GHz and 17-19 GHz: eight channels per pixel

30 GHz channel in QUIJOTE MFI

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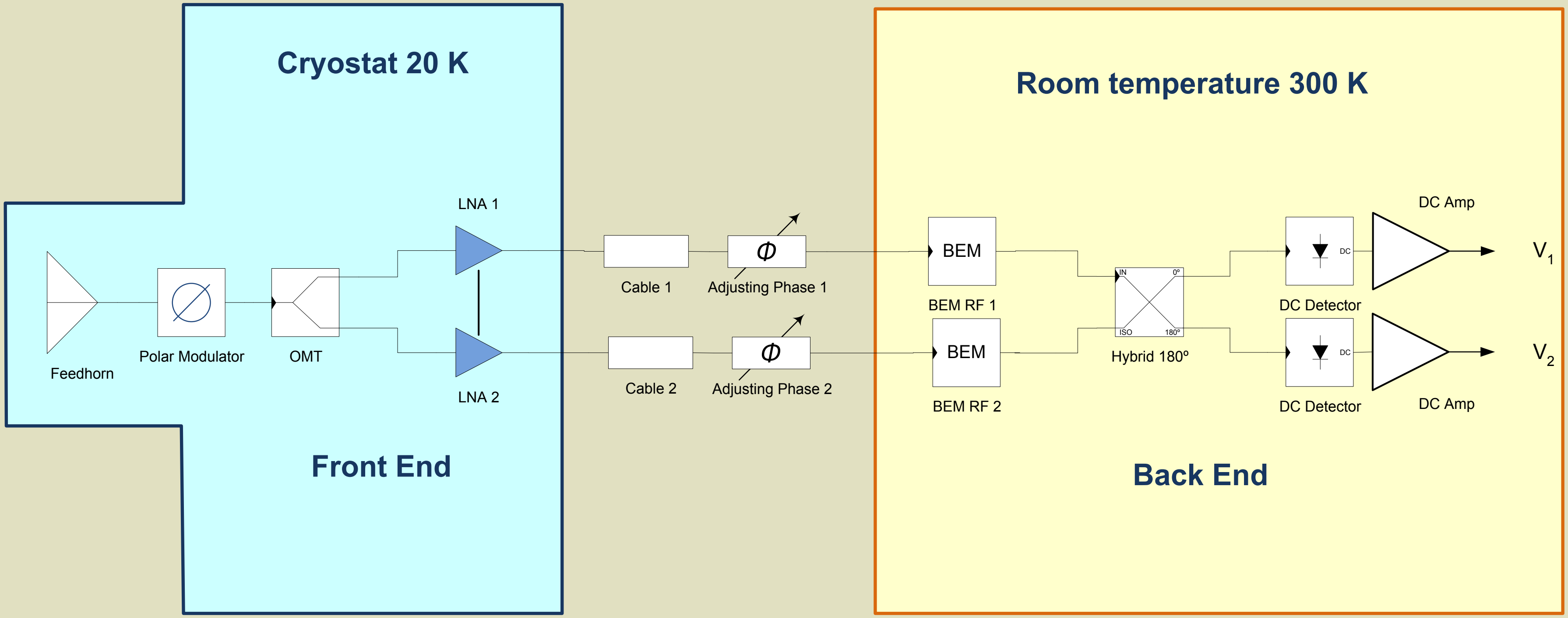

Modulator to stabilize gain drift. Simple design: two channels per pixel.

QUIJOTE MFI: Focal plane distribution

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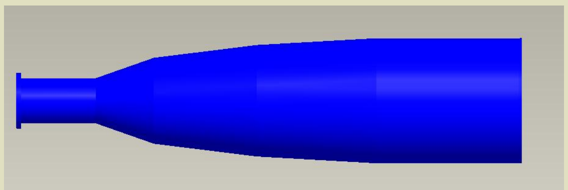
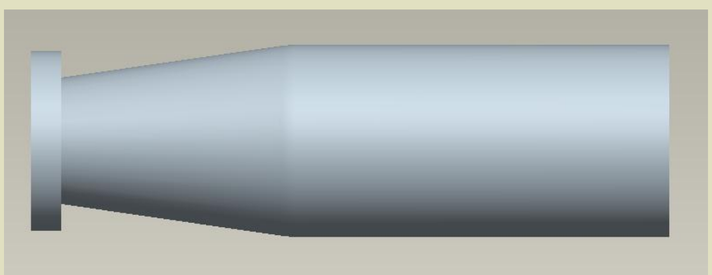
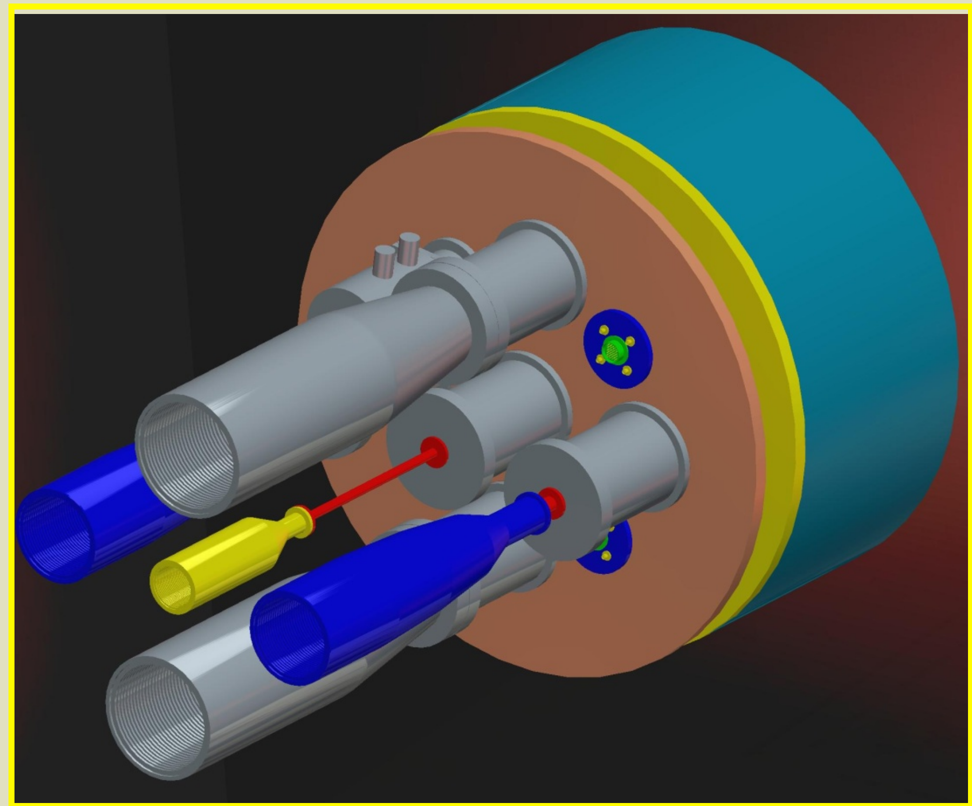
26-36GHz Horn


14-20GHz Horn


10-14GHz Horn



QUIJOTE MFI: Corrugated feed-horns (Sept. 2010)

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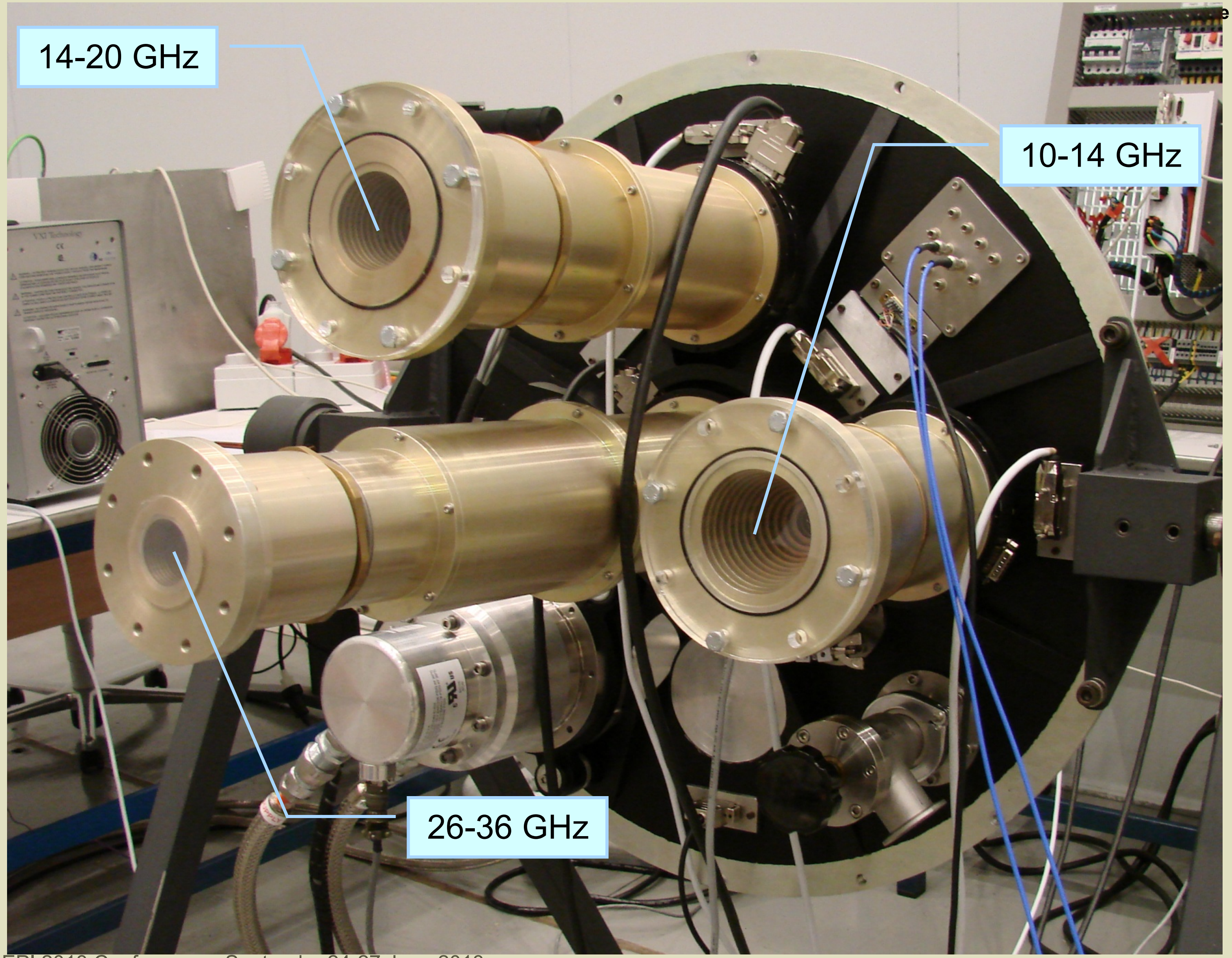

QUIJOTE MFI: Receivers integration

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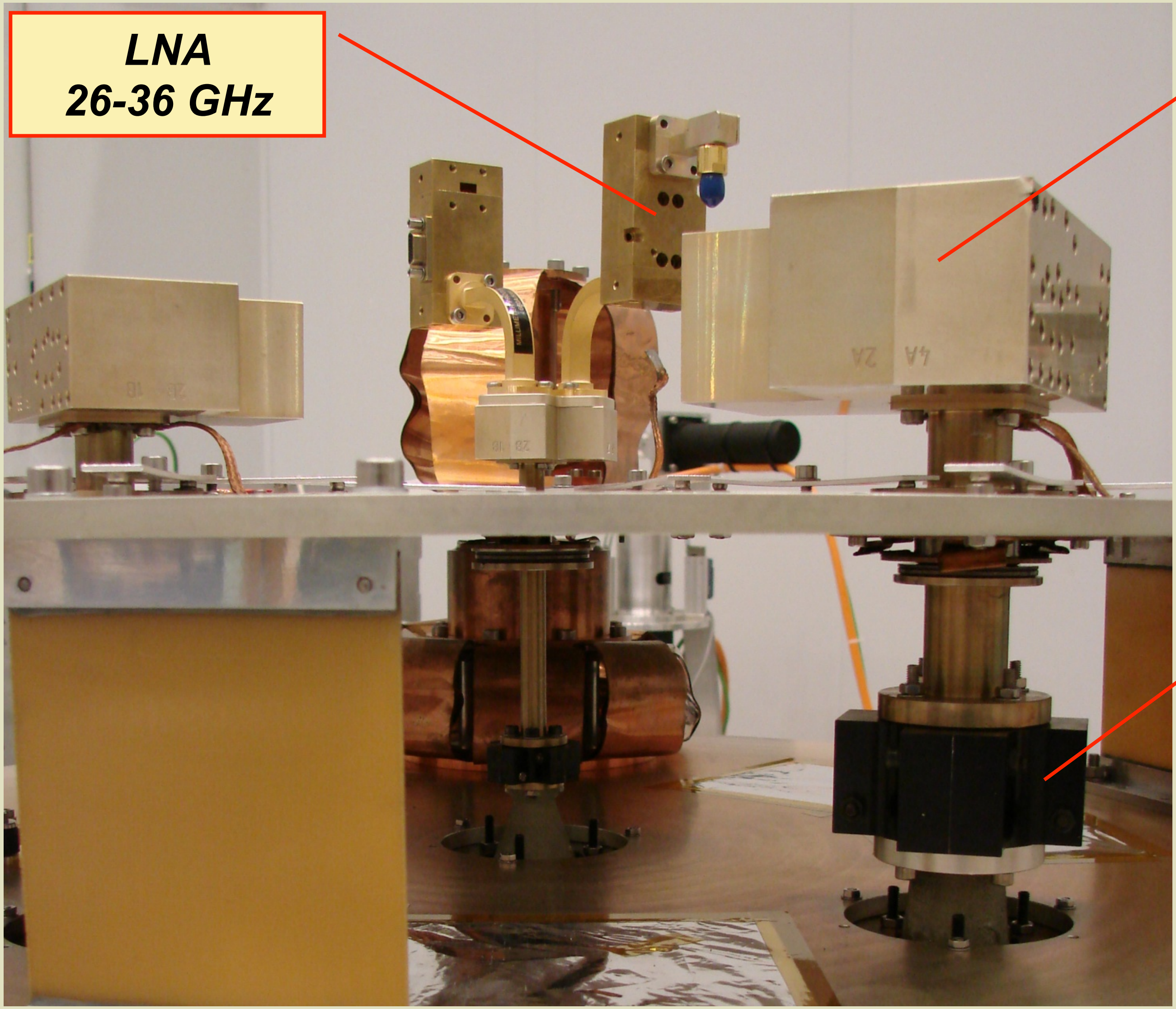
LNA 26-36 GHz

OMT 11-13 GHz



Polar modulator 11-13 GHz

QUIJOTE MFI: Receivers integration

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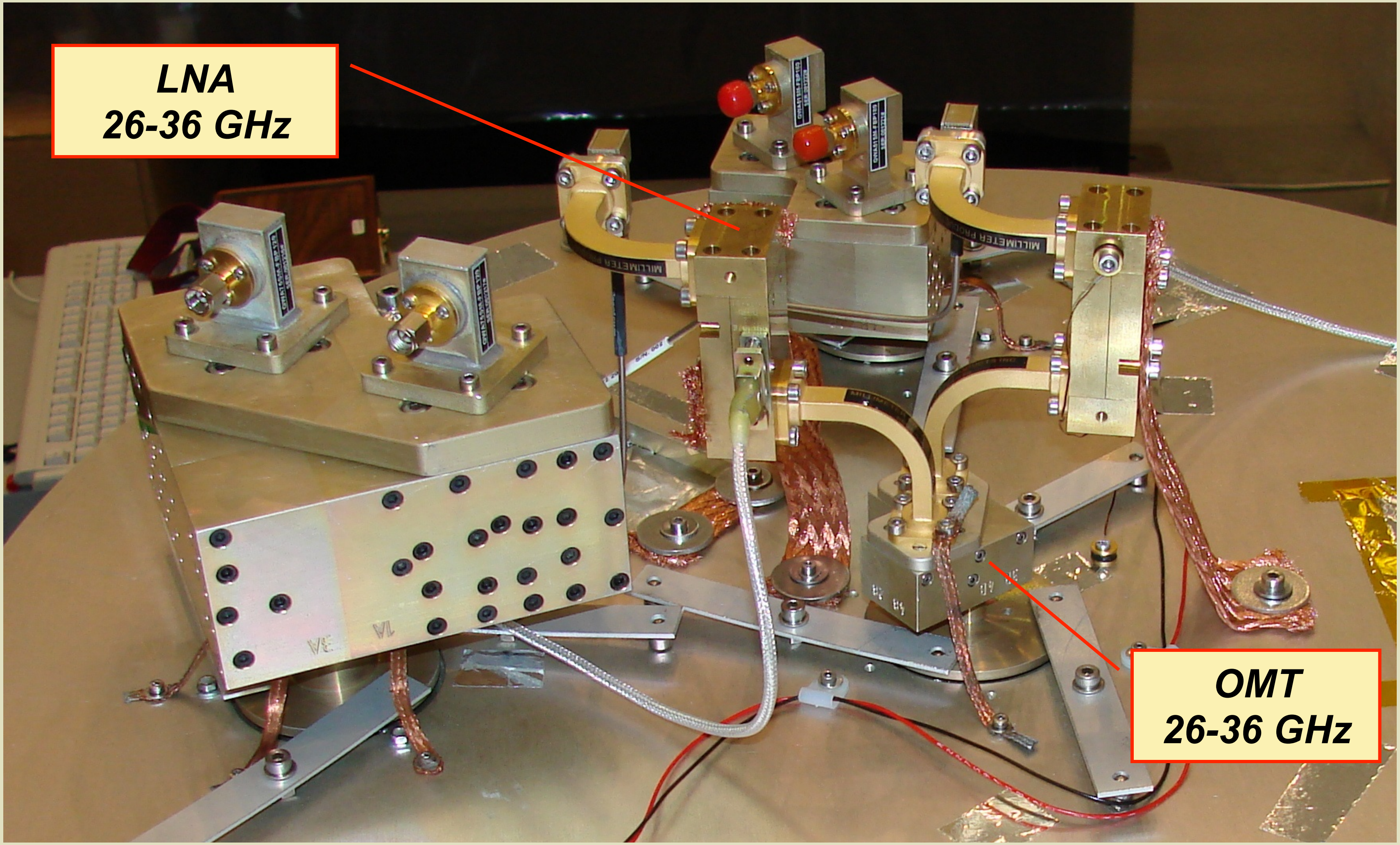

QUIJOTE MFI: Receivers integration

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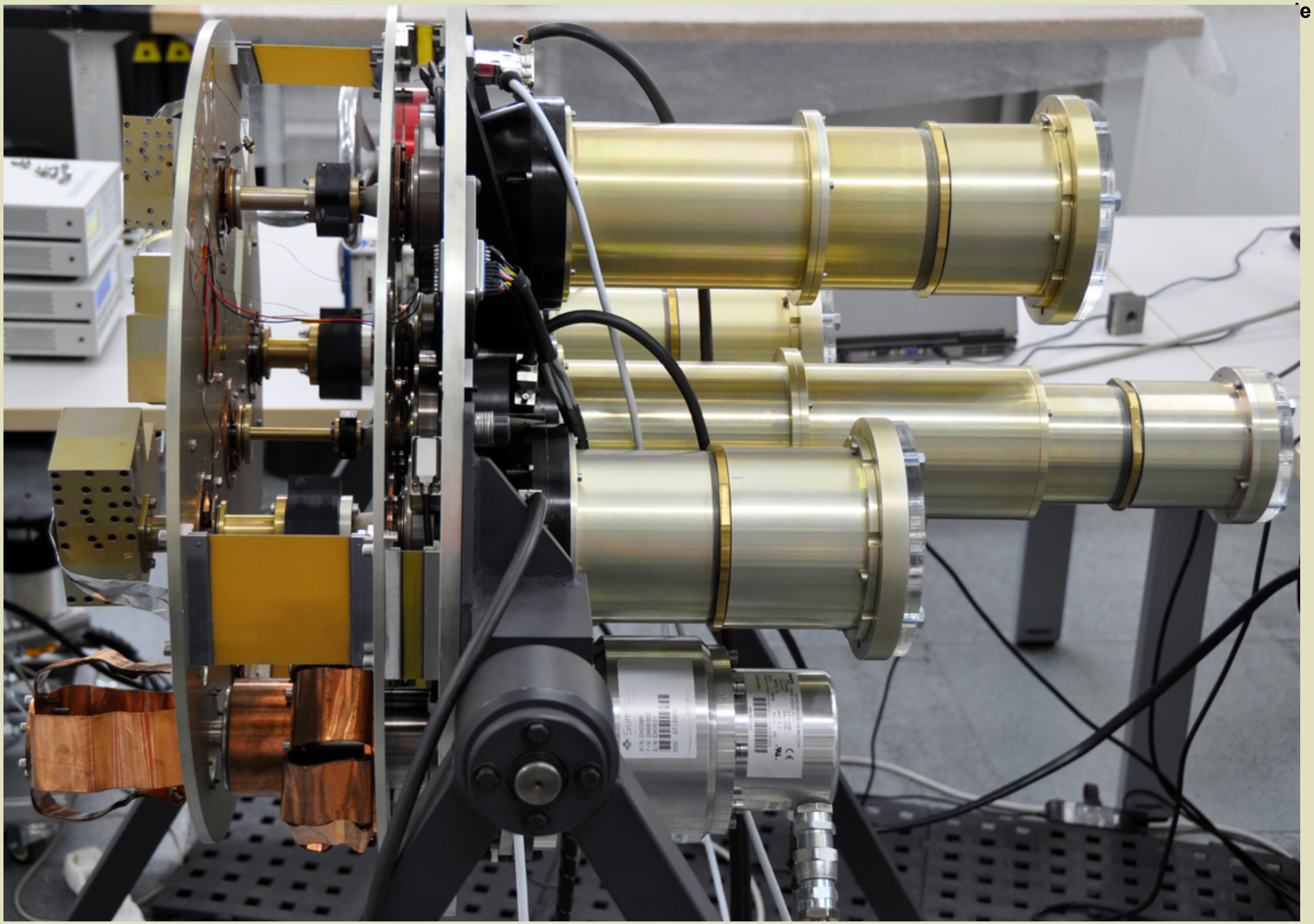

First Instrument: Four receiver chains

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Polar Modulator

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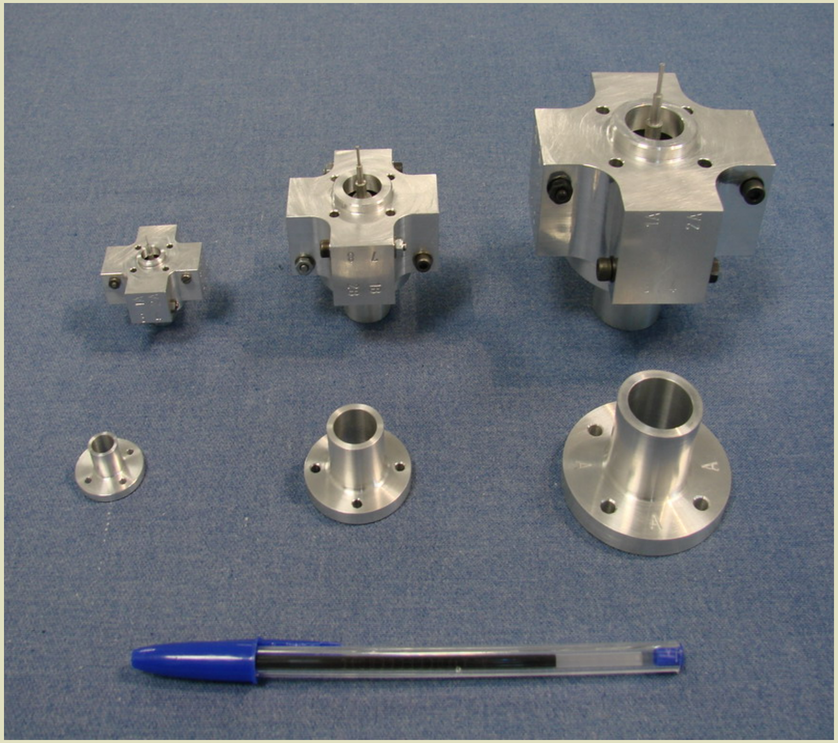
- Key component of the polarimeter
- Rotating polar modulator
- Cryogenically cooled: low losses, low impact on noise
- Waveguide component: turnstile 4-way junction

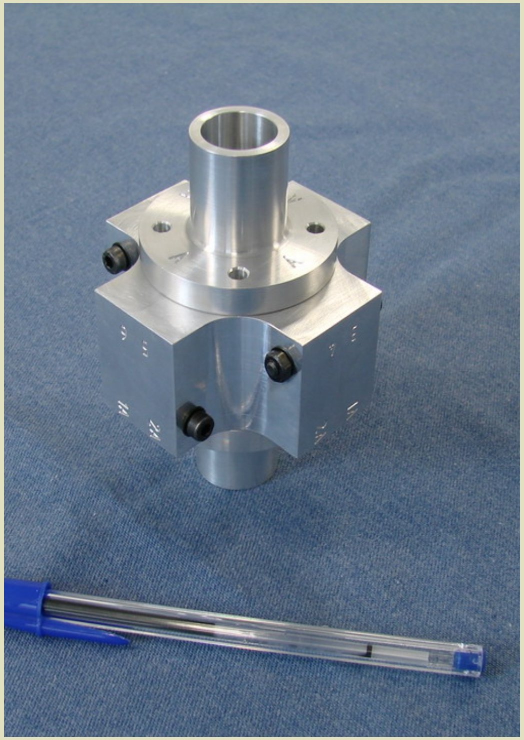


Units:

10-14 GHz

14-20 GHz

26-36 GHz



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Polar Modulator S-parameter tests

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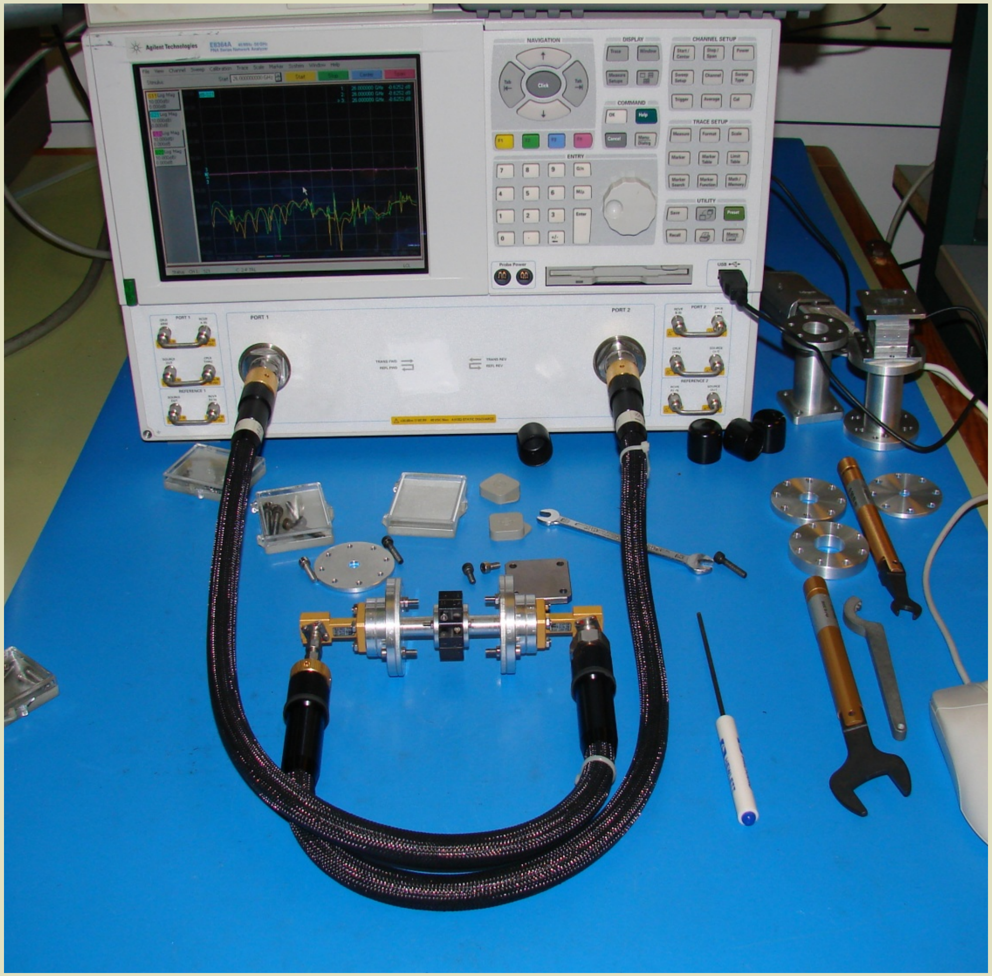

- Low return losses
- Low insertion losses
- High polar isolation
- Tests at 3 polar modulator orientations: 0º, 45º and 90º
- Plots: spikes caused by misalignment of the circular waveguide interfaces
- Tests at Room Temperature

Polar Modulator Return Loss

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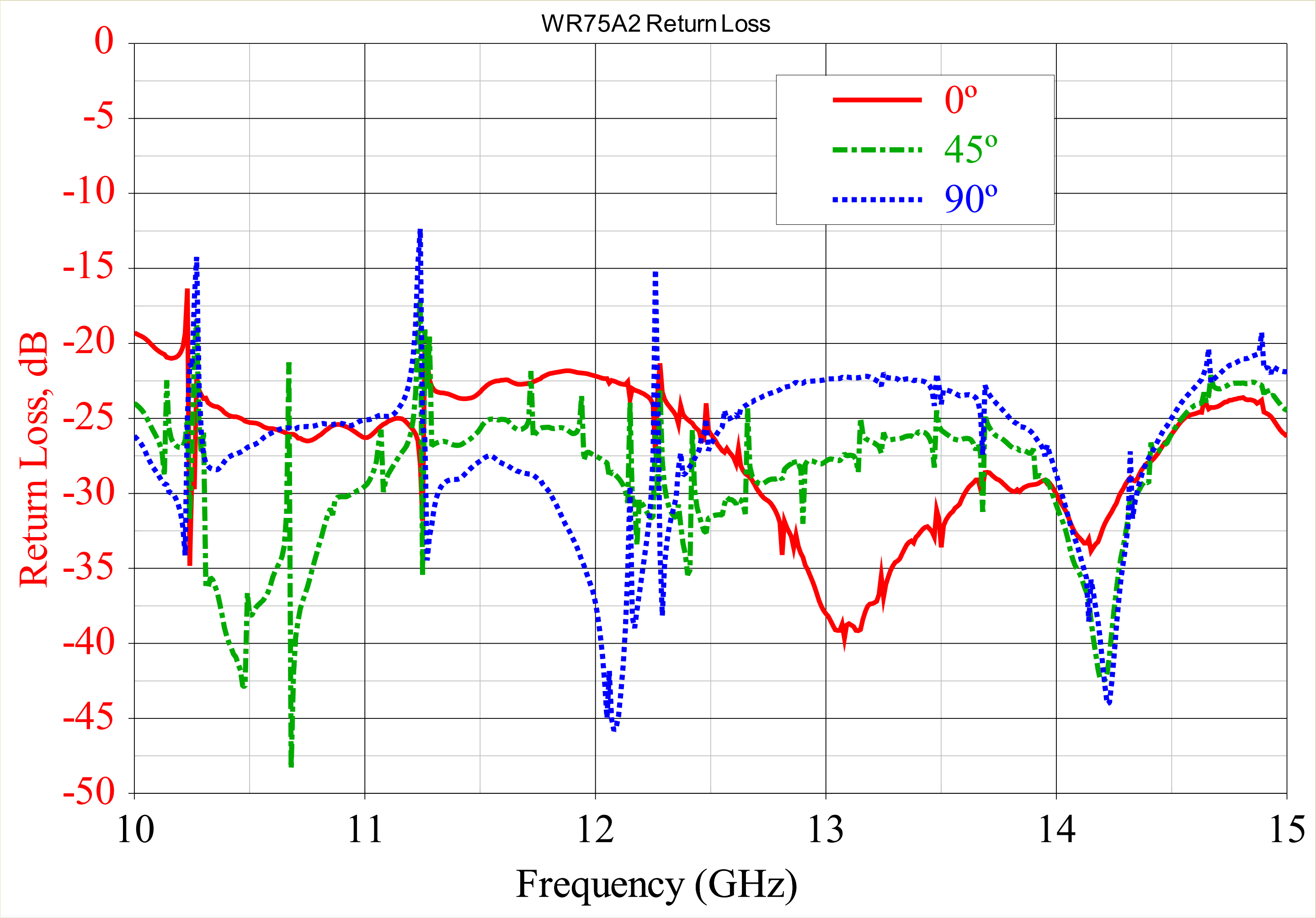

Polar Modulator Insertion Loss

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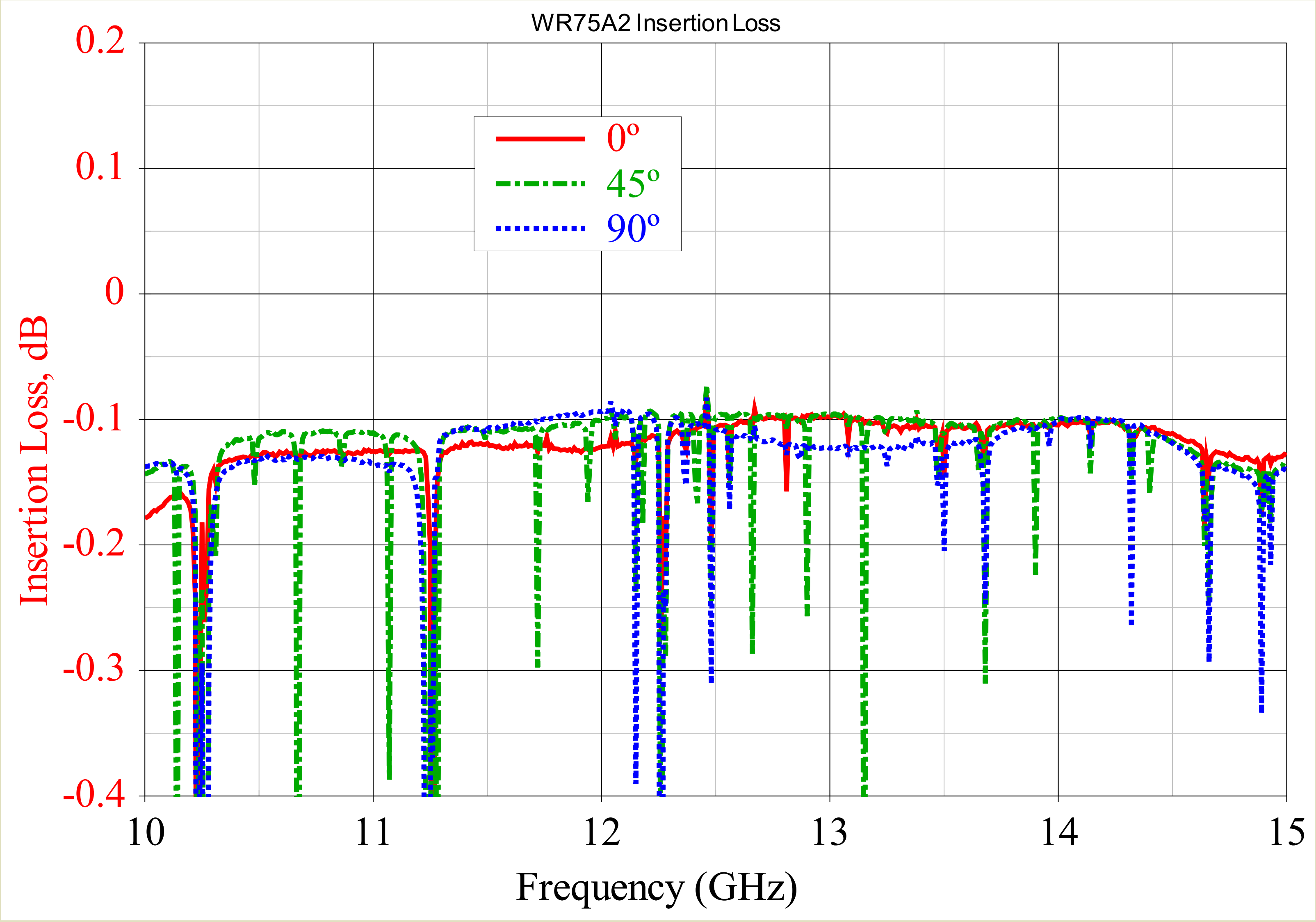

Polar Modulator Isolation

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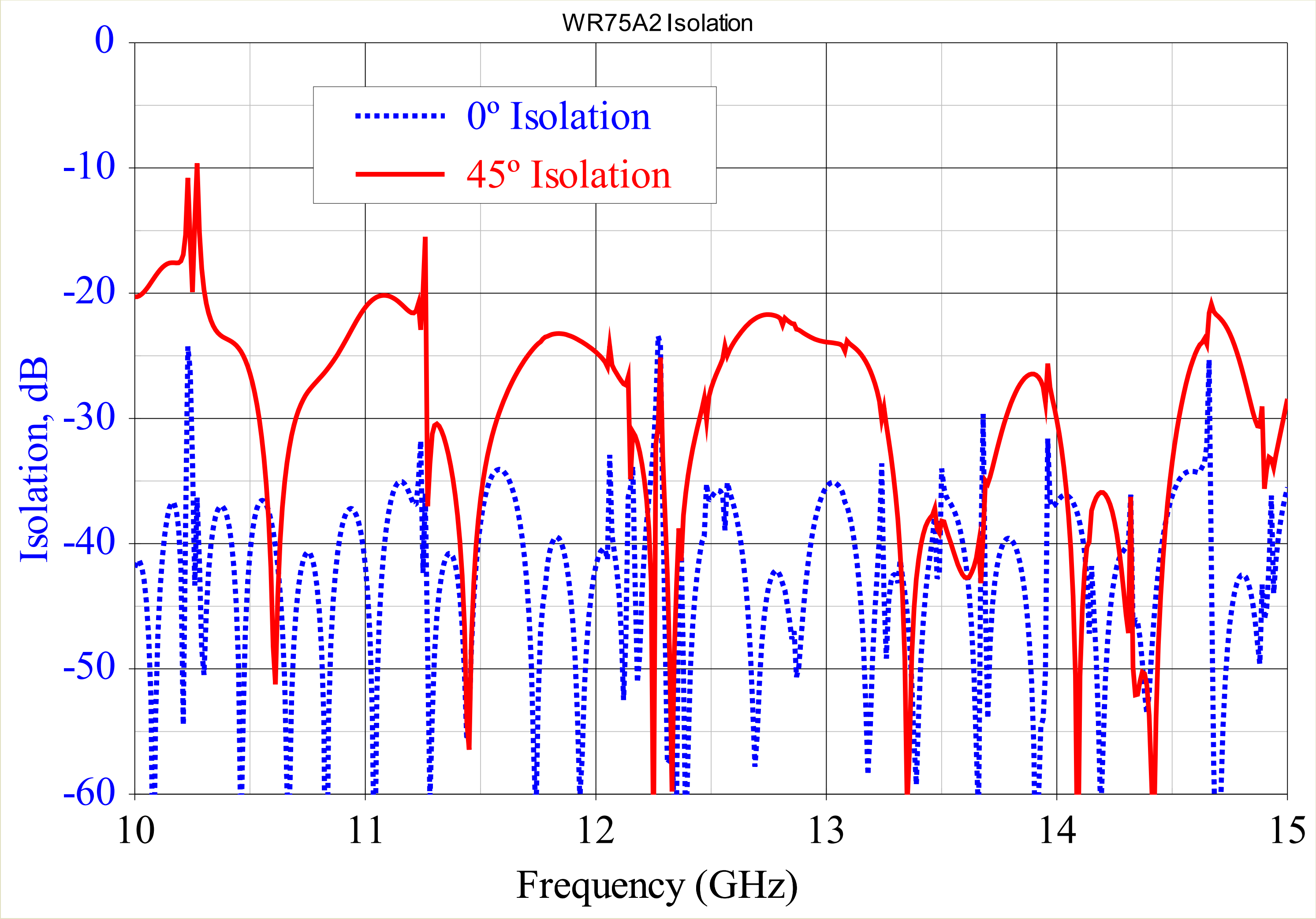

Orthomode Transducer (OMT)

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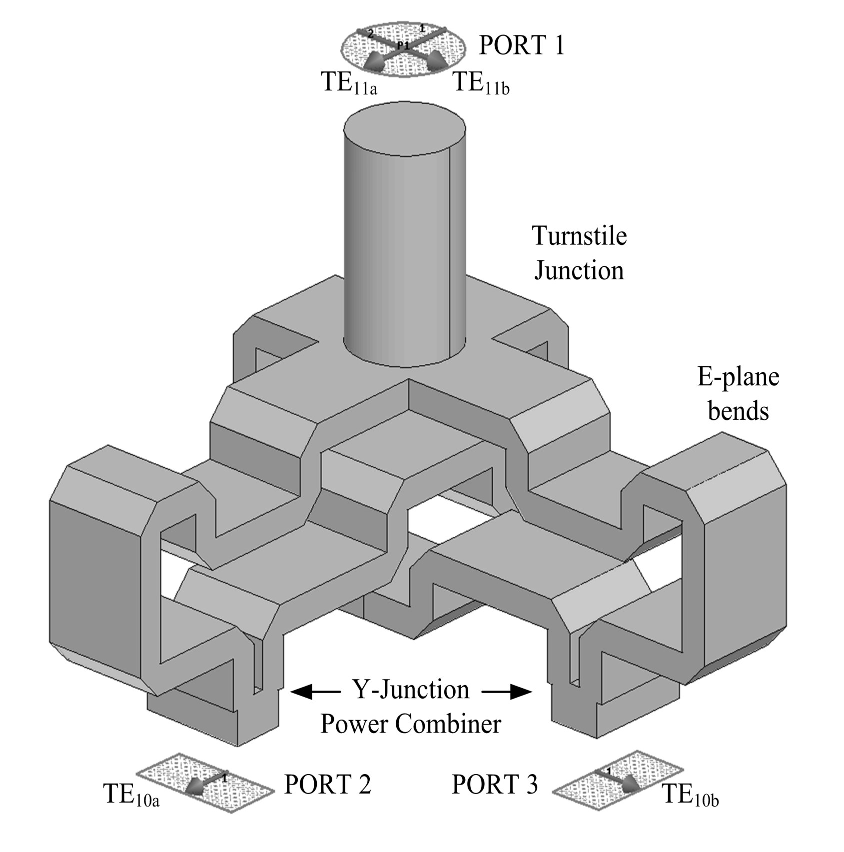
Device with physical 3-ports and electrical 4-ports
- Port 1: TE10 (vertical) rectangular waveguide
- Port 2: TE10 (horizontal) rectangular waveguide
- Port 3: TE11 (vertical) circular waveguide
- Port 4: TE11 (horizontal) circular waveguide



- **Separates linear orthogonal polar components**
- **Sets a limit in the cross-polarization**
- **Based on turnstile junction**
- **Phase balanced outputs**
- **Broadband (> 40 % bandwidth)**

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Orthomode Transducer (OMT)

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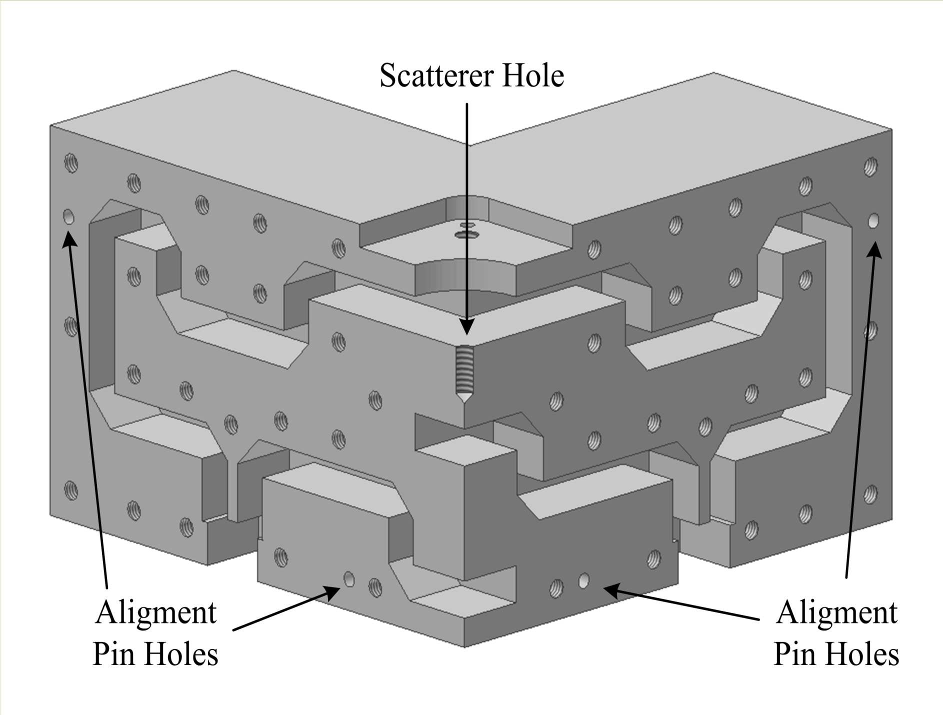
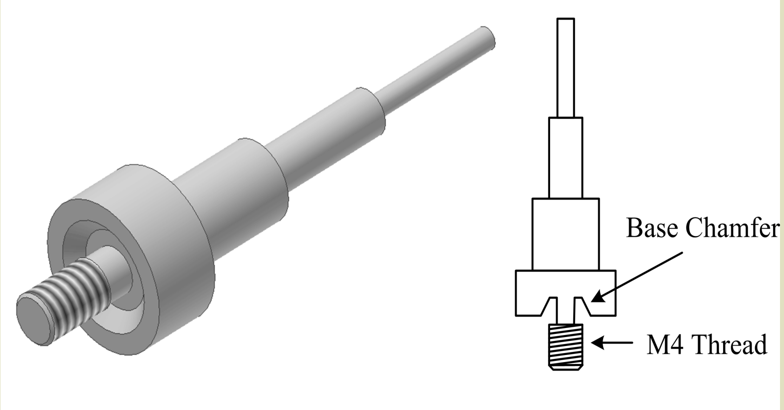
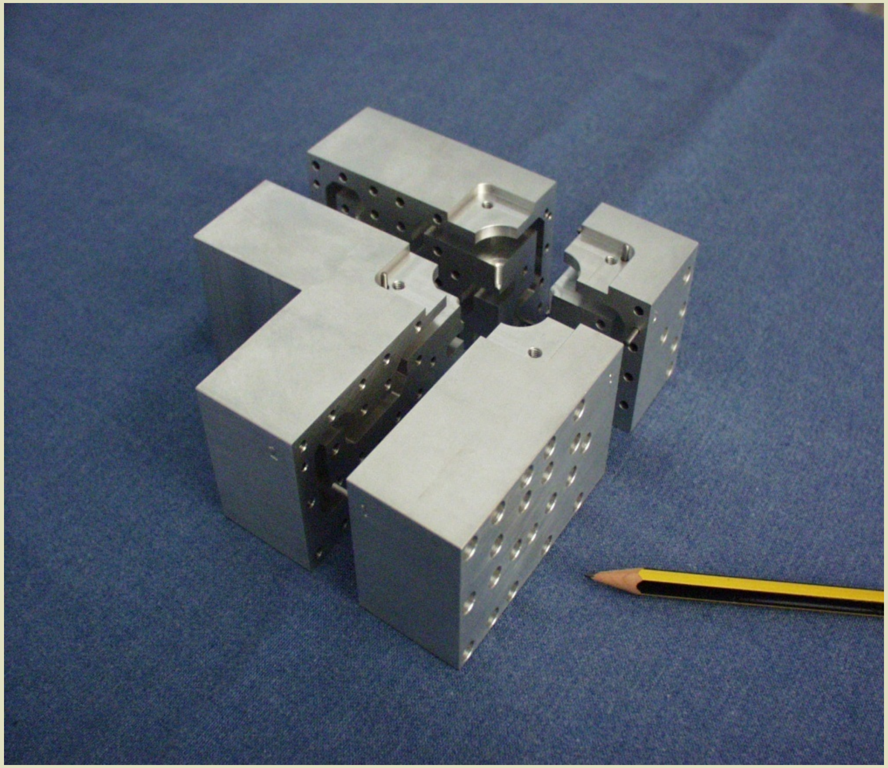
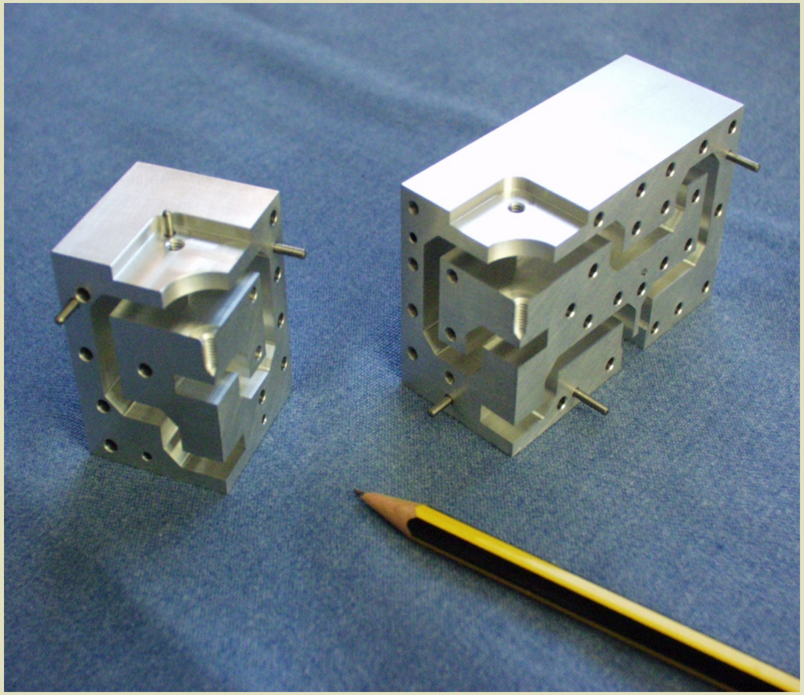




- **Reduced height rectangular waveguide**
- **Optimized E-plane bends**
- **Scatterer: a critical part of turnstile junction**
- **Scalable structure (WR75, WR51, WR28)**

Orthomode Transducer (OMT)





OMT parts (WR75 version, 10-14 GHz)

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Orthomode Transducer (OMT)

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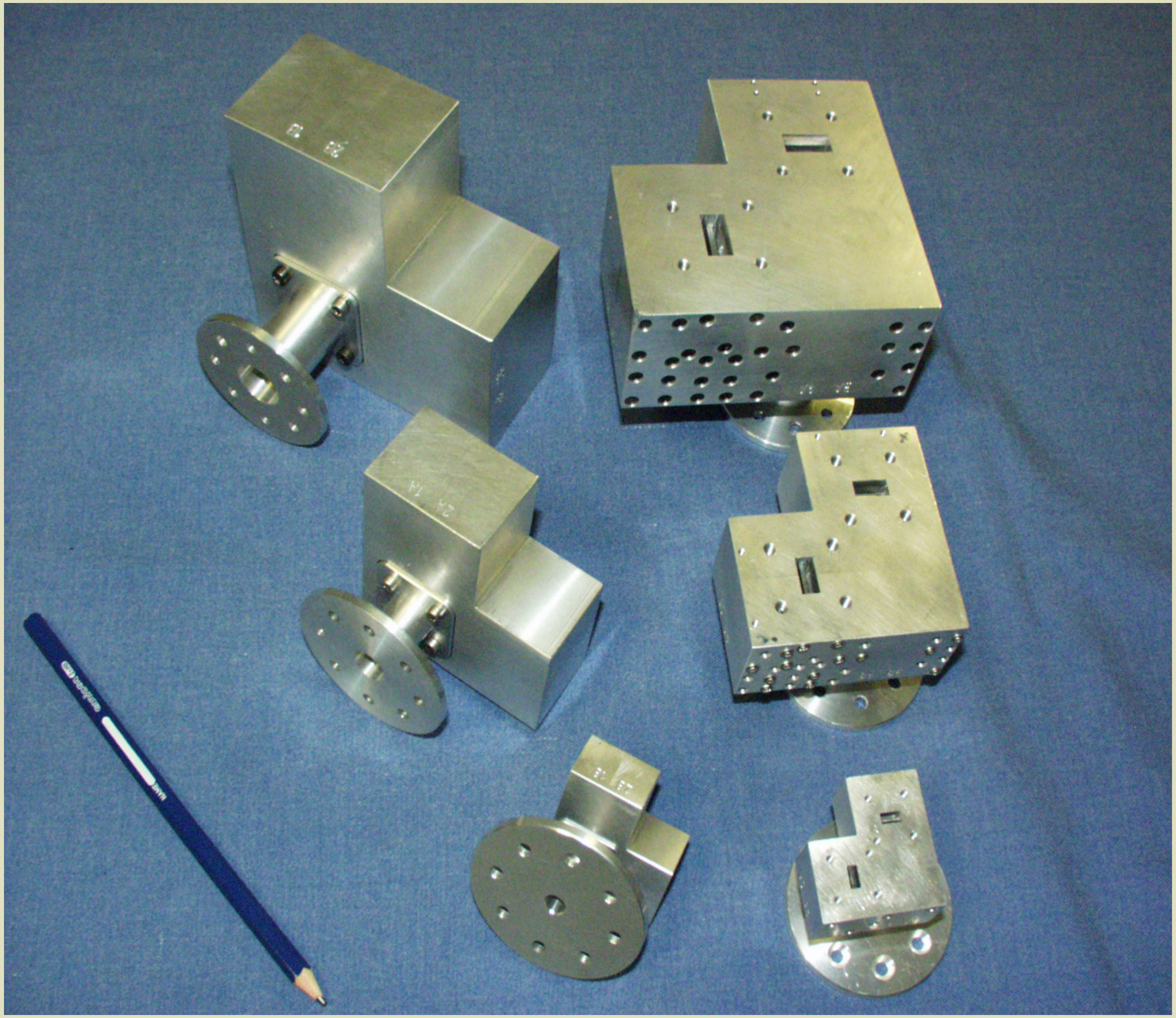

Units:

10-14 GHz

14-22 GHz

26-36 GHz

Ortho Mode Transducer (OMT) S-parameter tests

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- Low return losses
- Low insertion losses
- High isolation
- Excellent phase balance
- Tests at Room Temperature

OMT Insertion Loss

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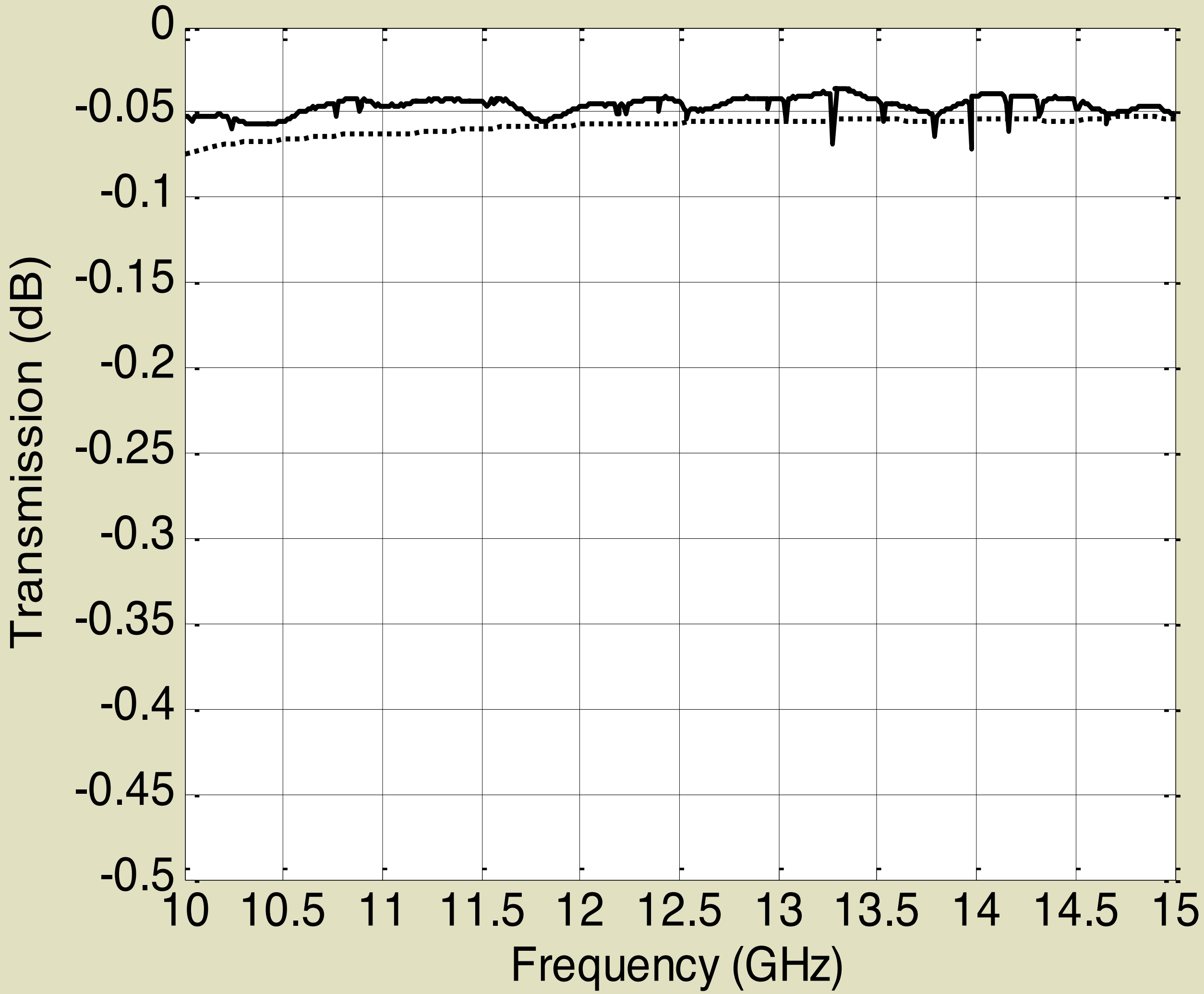

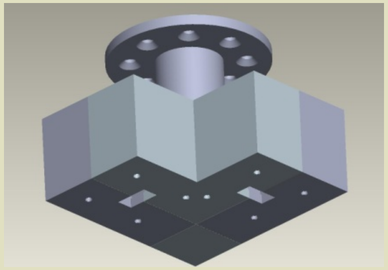

≈ 0.05 dB

solid line: test

dashed line: simulation

OMT Isolation (between rectangular ports)

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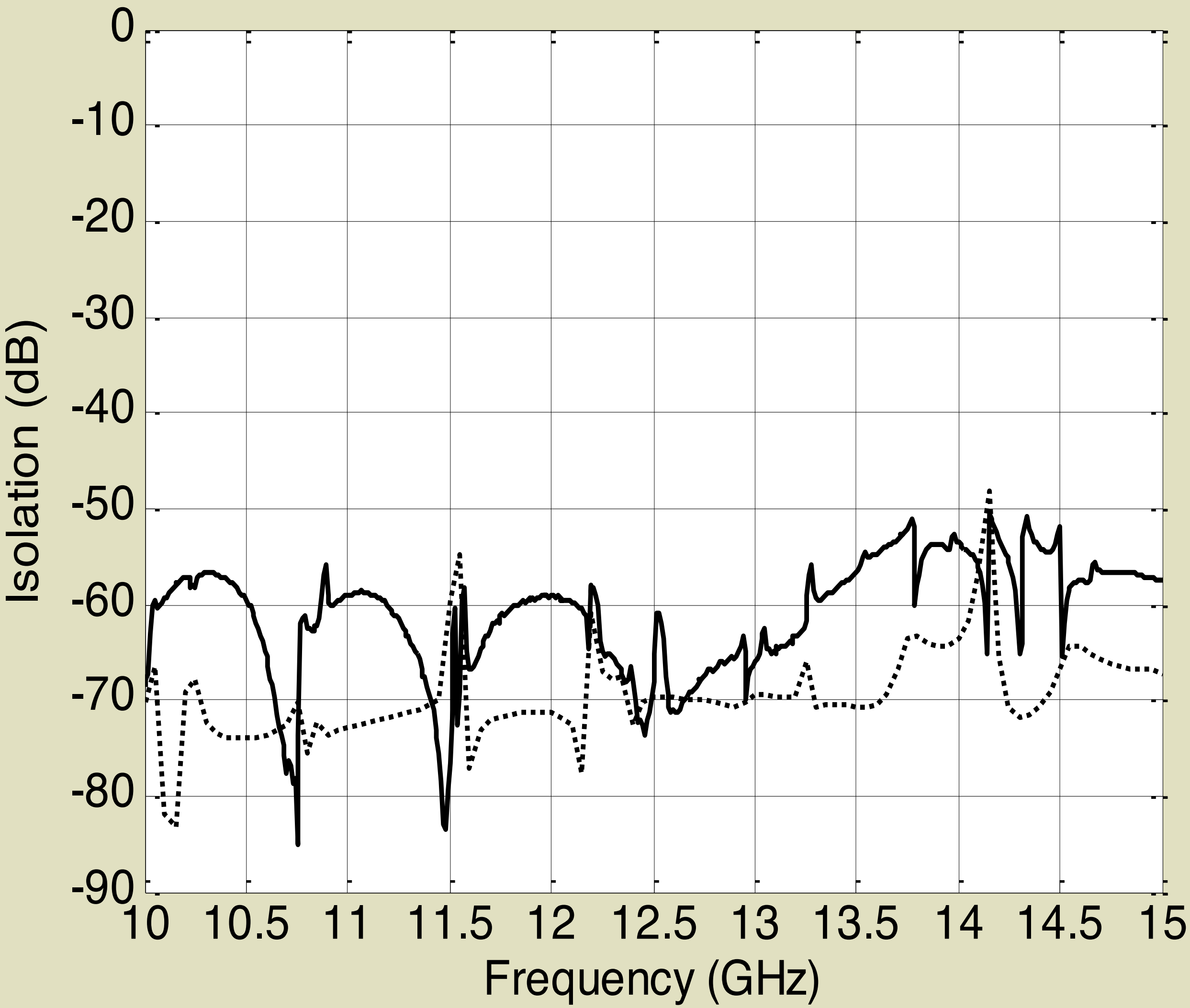

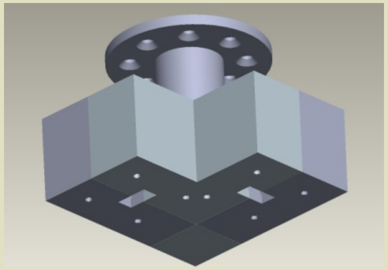

better than 50 dB

OMT Phase balance (between rectangular outputs)

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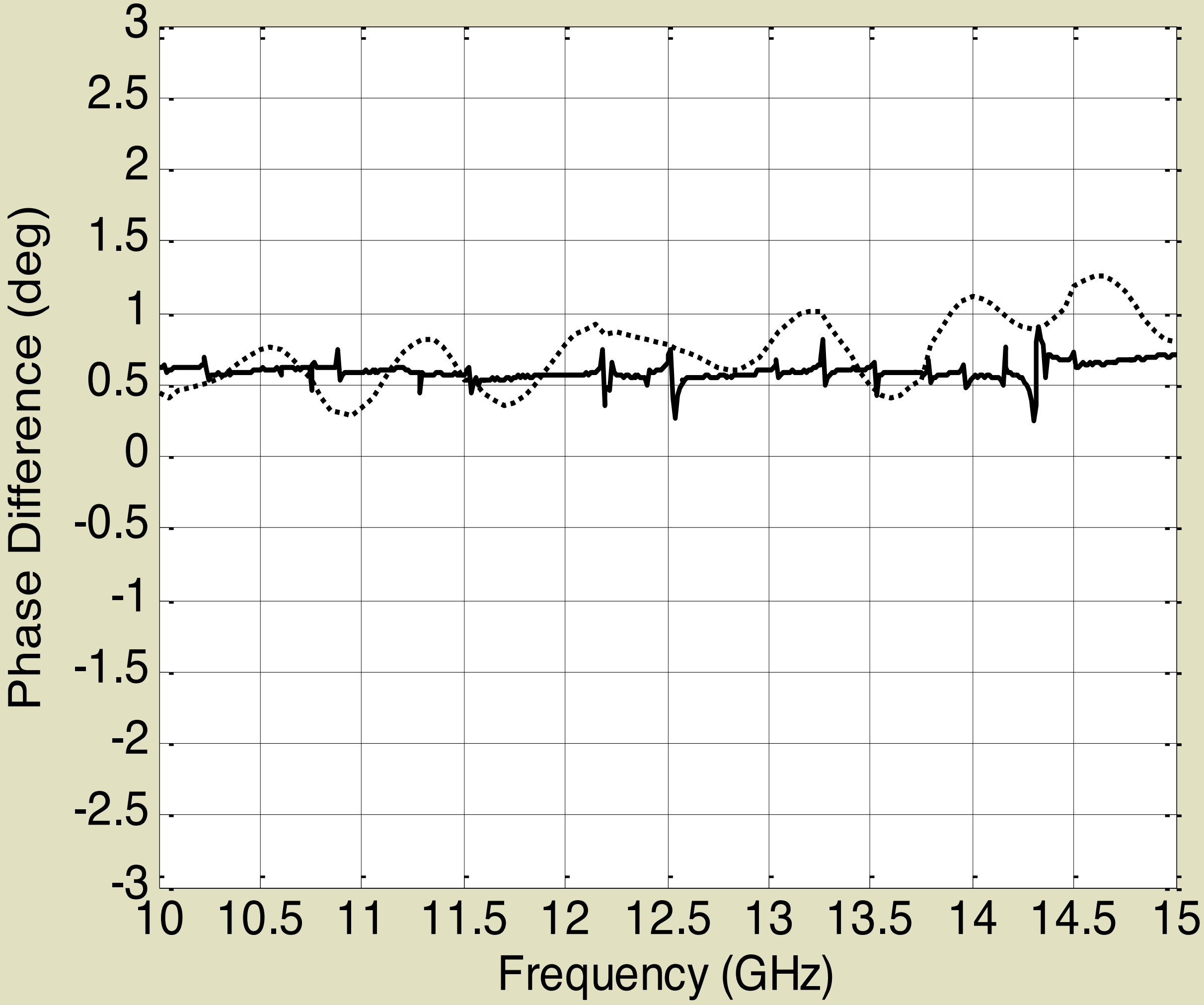

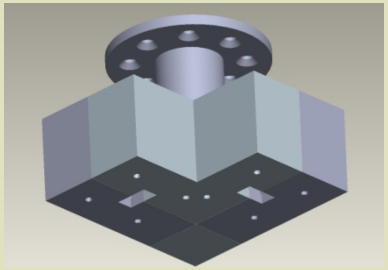

Δphase < 0.7º

Cryo-LNA. Gain and Noise Temperature

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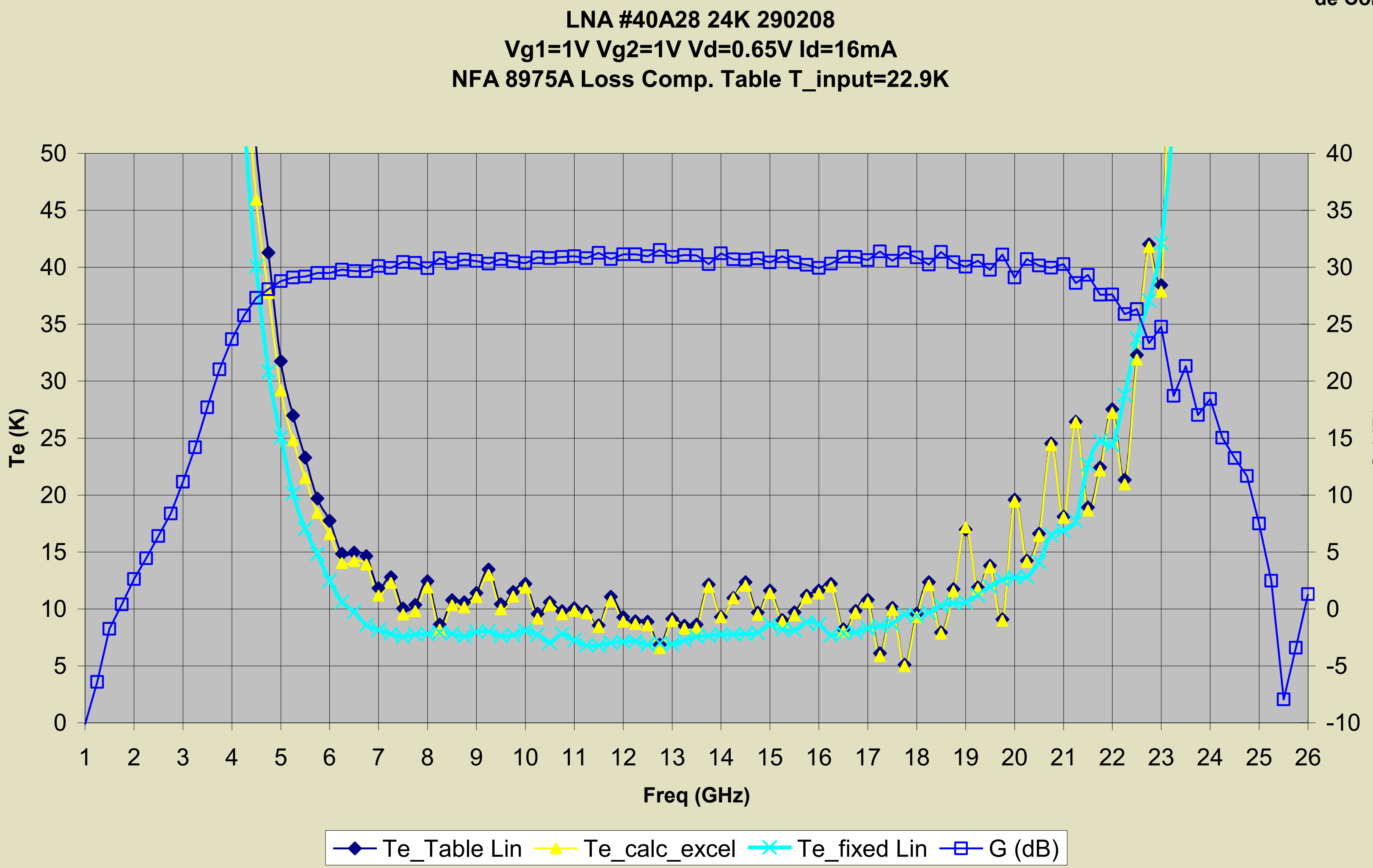

LNA for low frequency channels

10-14 GHz BEM rack RF Gain (QUIJOTE 1)

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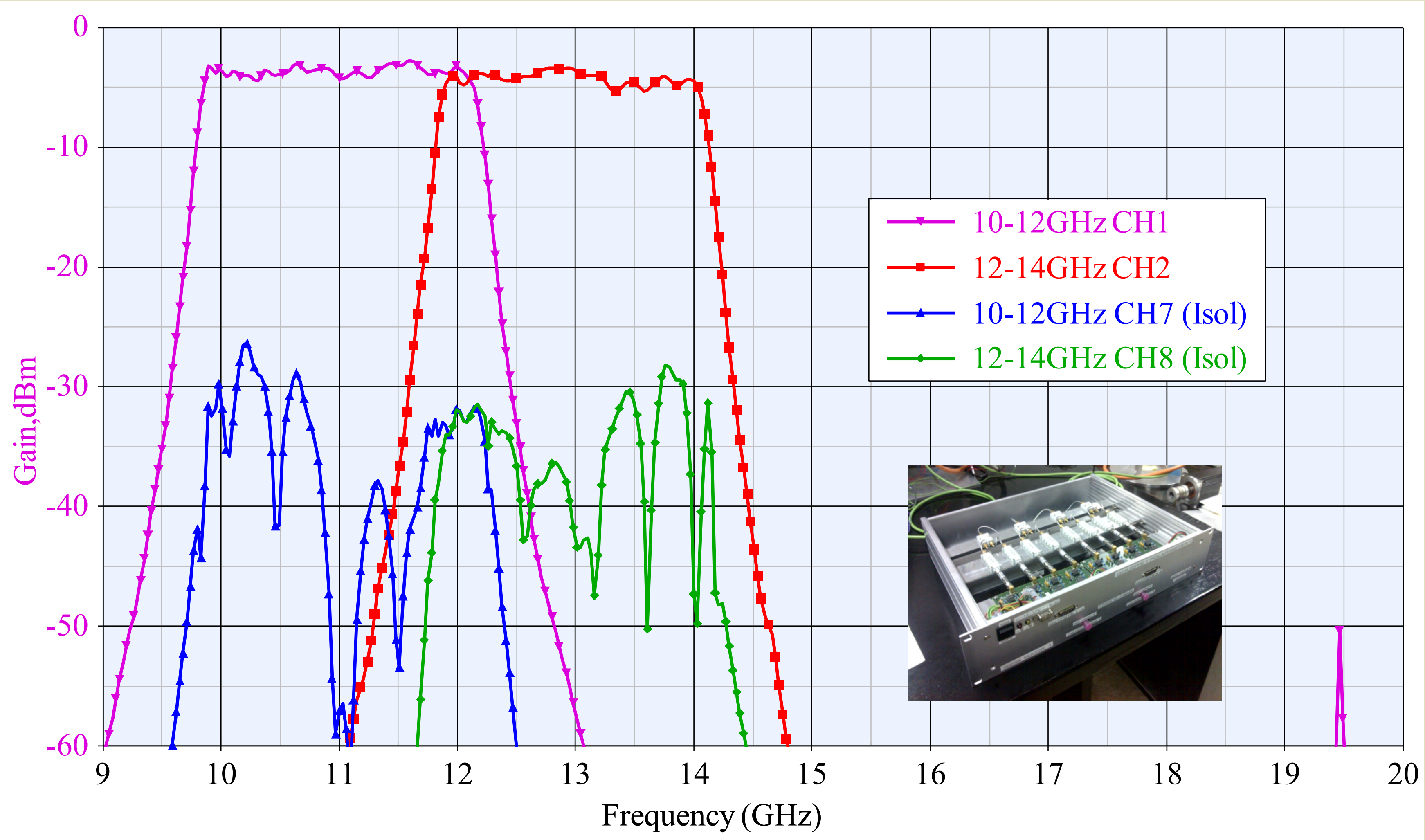
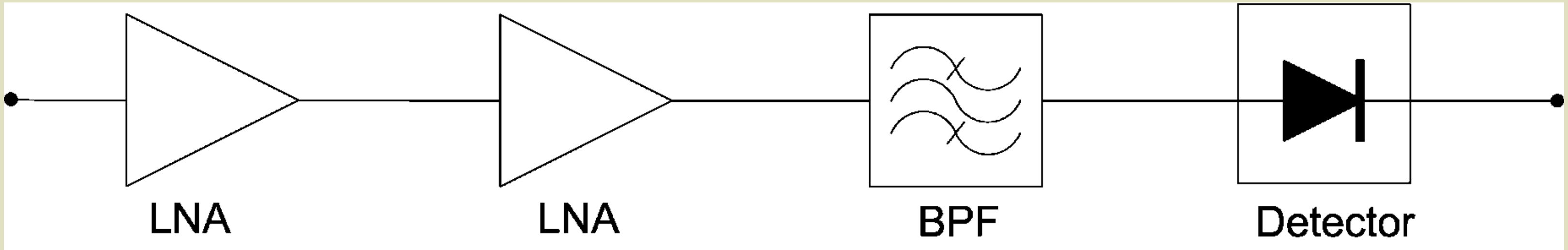


30 GHz BEM (QUIJOTE MFI)

One branch
30 GHz BEM Block diagram

(180º hybrid and video amp not included)



Bandwidth: 26 to 36 GHz
Noise temperature < 500 K

30 GHz BEM (QUIJOTE MFI)

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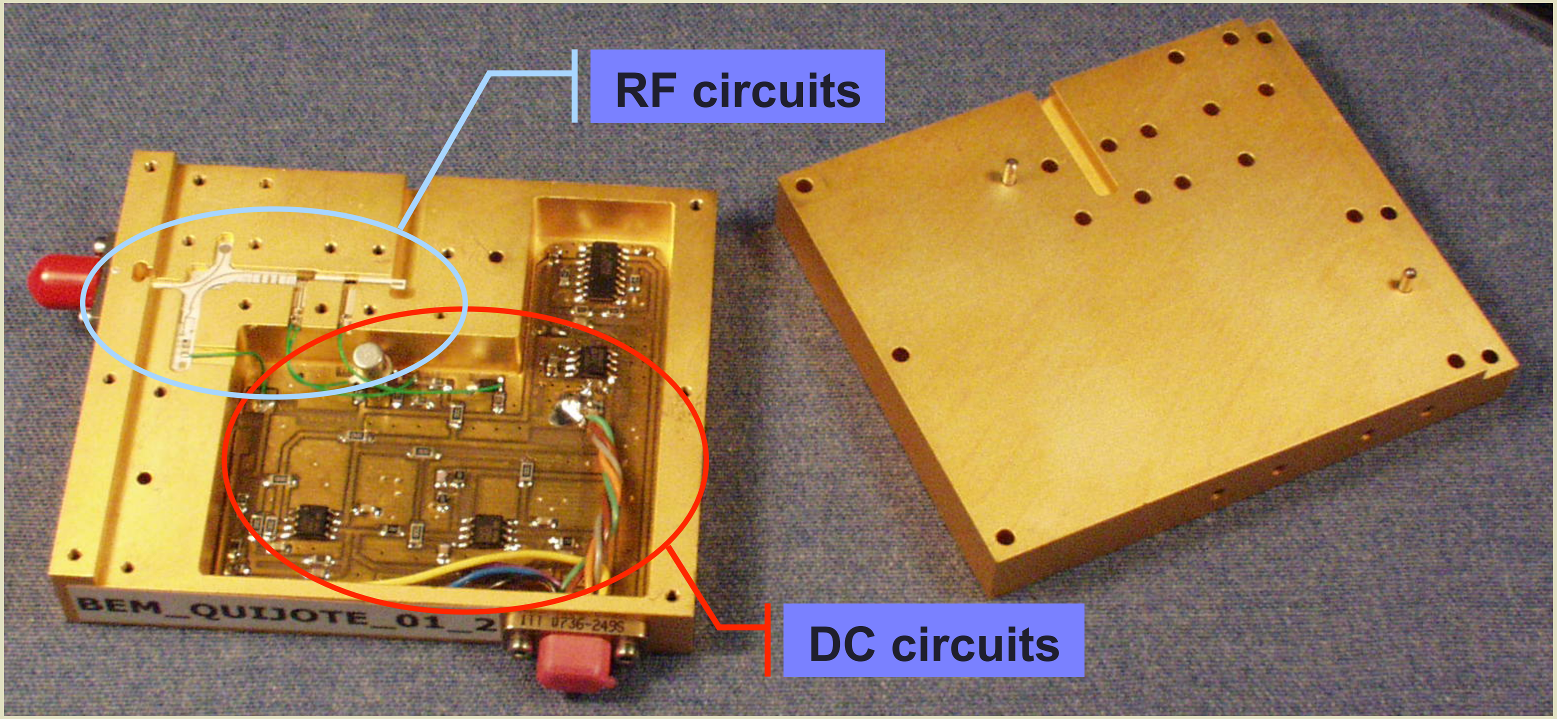
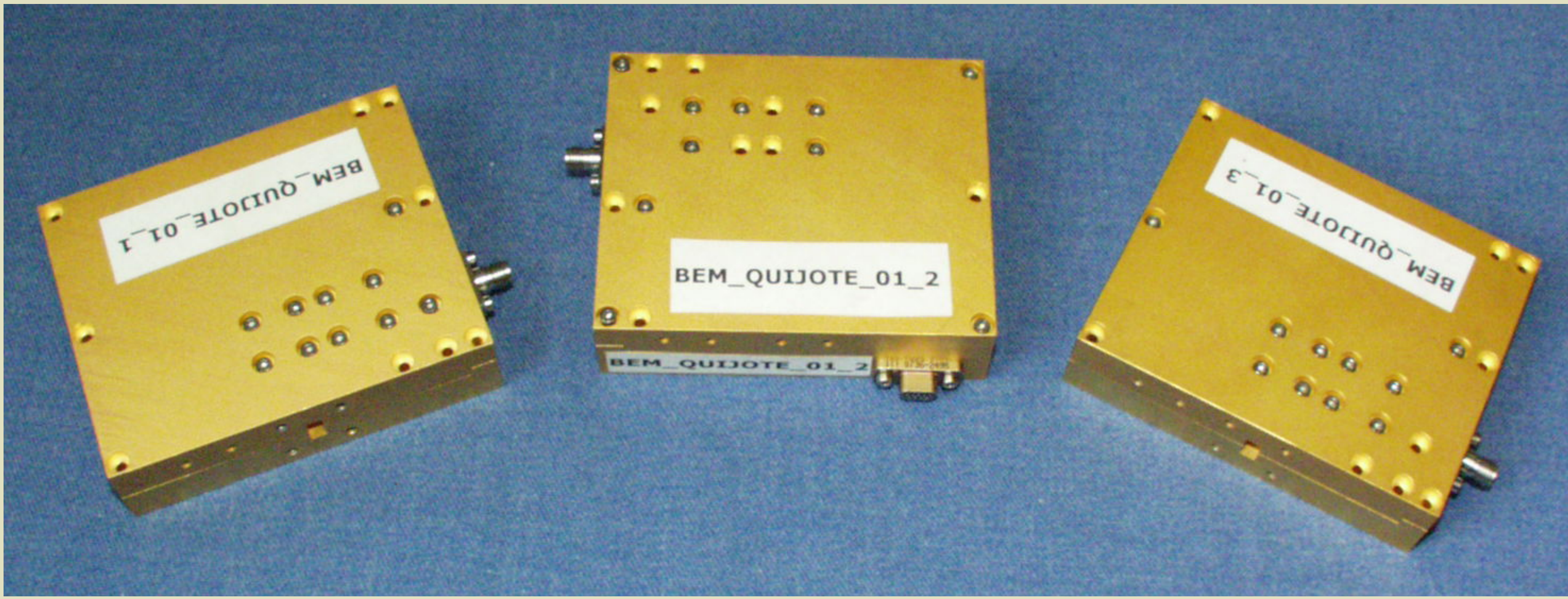


BEM branch (top cover removed)

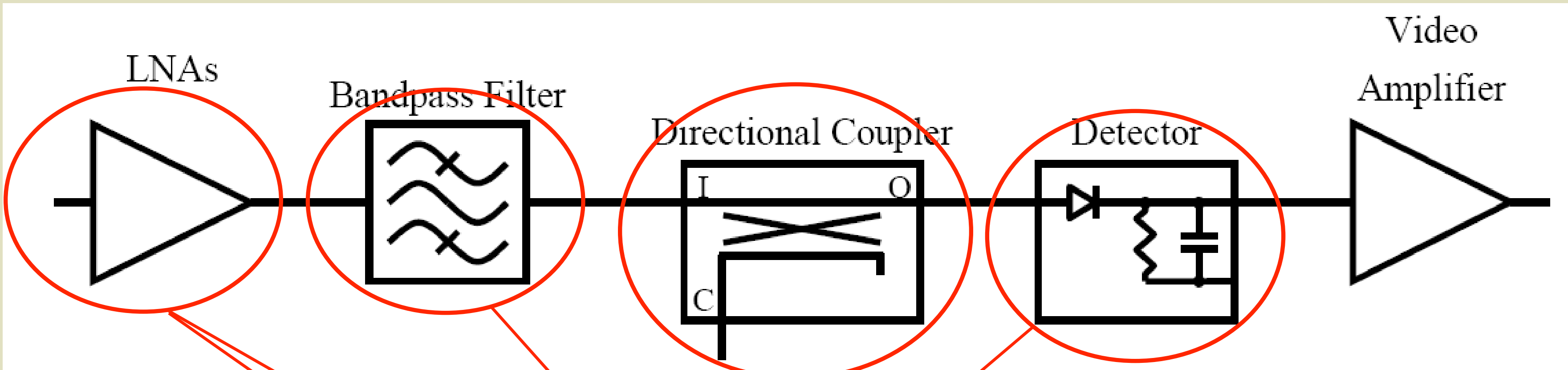
30 GHz BEM (QUIJOTE 1)

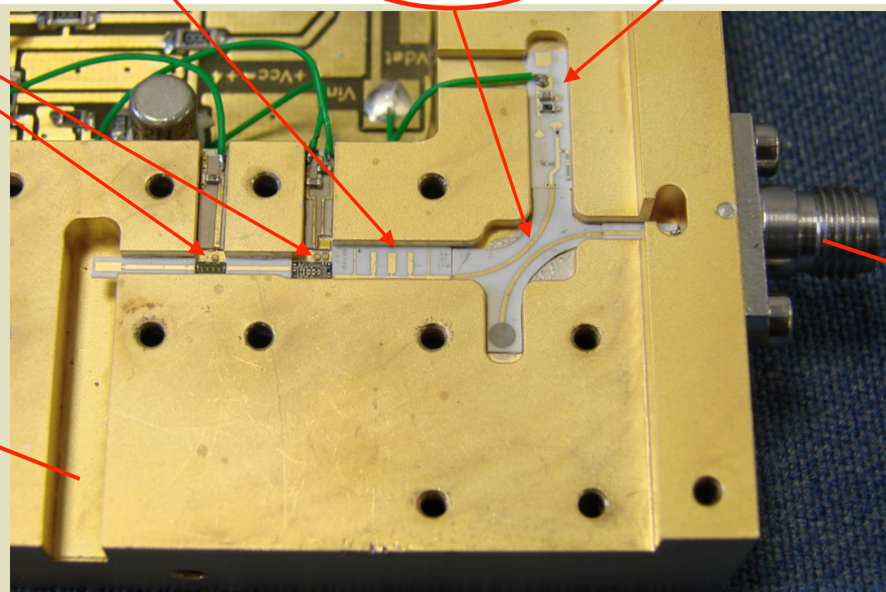
Manufactured BEM units: 2 + 1 (spare)



30 GHz BEM (QUIJOTE MFI)

Original prototype without 180º hybrids





Waveguide input

RF sample output (K connector)

Test results (30 GHz BEM - MFI)

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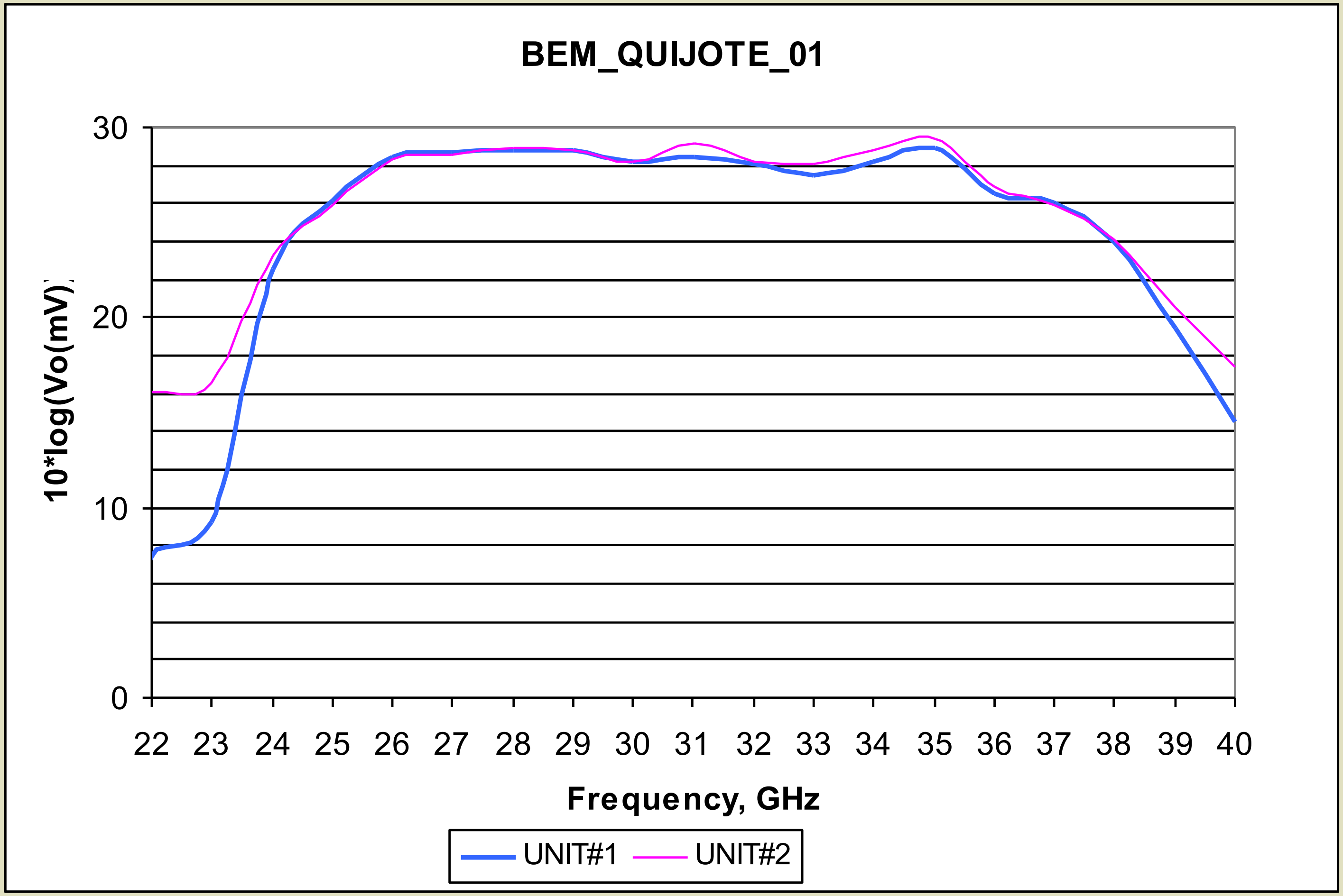

Gain vs. frequency for two units (detector included)

30 GHz BEM (QUIJOTE 1 - MFI)

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Frontal panel of 30 GHz BEM rack

QUIJOTE 2 – 30 GHz Instrument (TGI)

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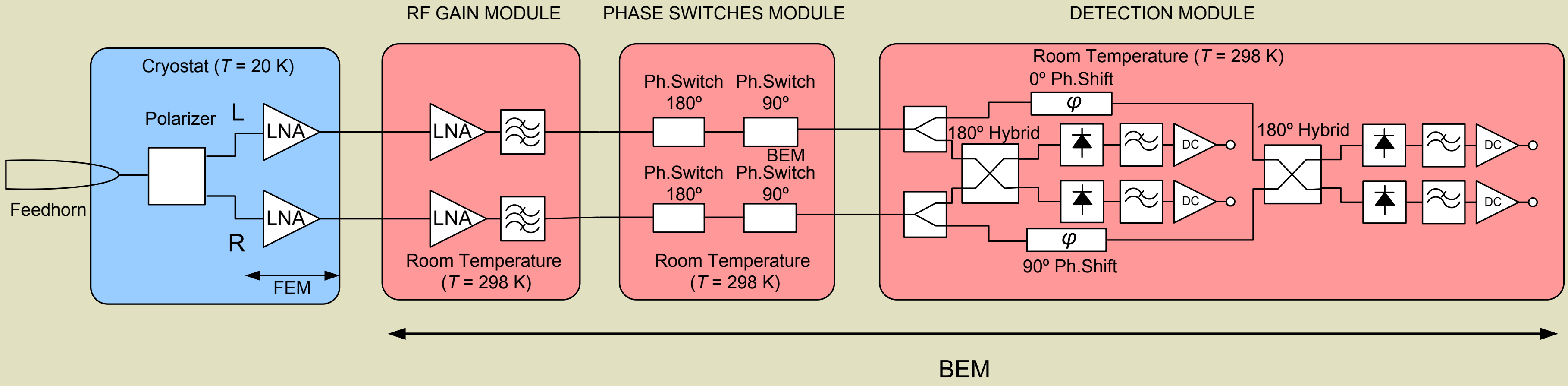
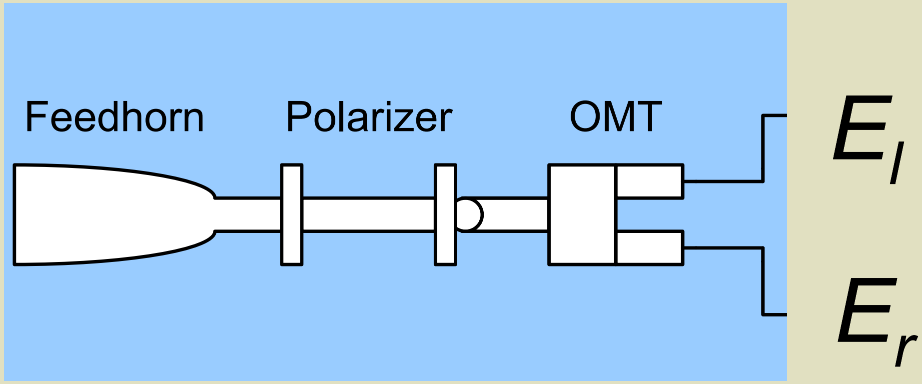


New receiver scheme:

- electronic phase switching in two balanced branches
- microwave correlation (180º hybrid)
- direct detection (Schottky diode)

Principle of operation



Circular components of electric fields

$$\begin{pmatrix} I \\ Q \\ U \end{pmatrix} \equiv \begin{pmatrix} |E_l|^2 + |E_r|^2 \\ 2\,\mathrm{Re}\left(E_l^* E_r\right) \\ -2\,\mathrm{Im}\left(E_l^* E_r\right) \end{pmatrix}$$

Stokes parameters

Stokes parameters from detected voltages

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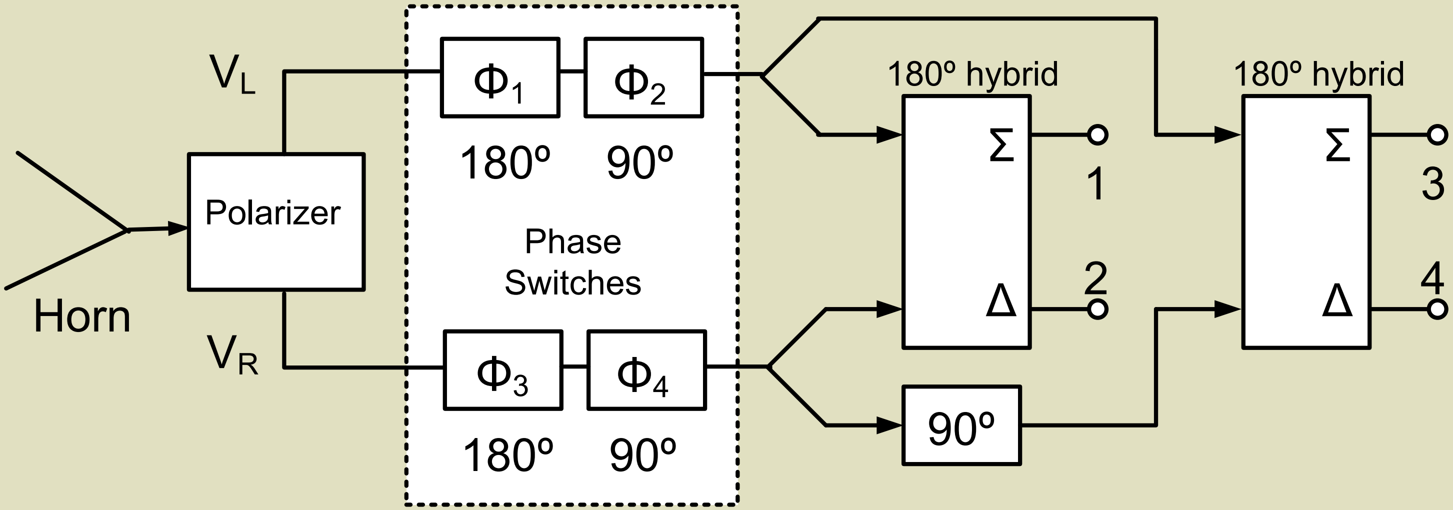

Φ	I	Q	U
0º	Vd1 + Vd2 = Vd3 + Vd4	Vd1 – Vd2	Vd3 – Vd4
90º	Vd1 + Vd2 = Vd3 + Vd4	Vd3 – Vd4	Vd2 – Vd1
180º	Vd1 + Vd2 = Vd3 + Vd4	Vd2 – Vd1	Vd4 – Vd3
270º	Vd1 + Vd2 = Vd3 + Vd4	Vd4 – Vd3	Vd1 – Vd2

Optomechanics QUIJOTE 2 – 30 GHz Instrument

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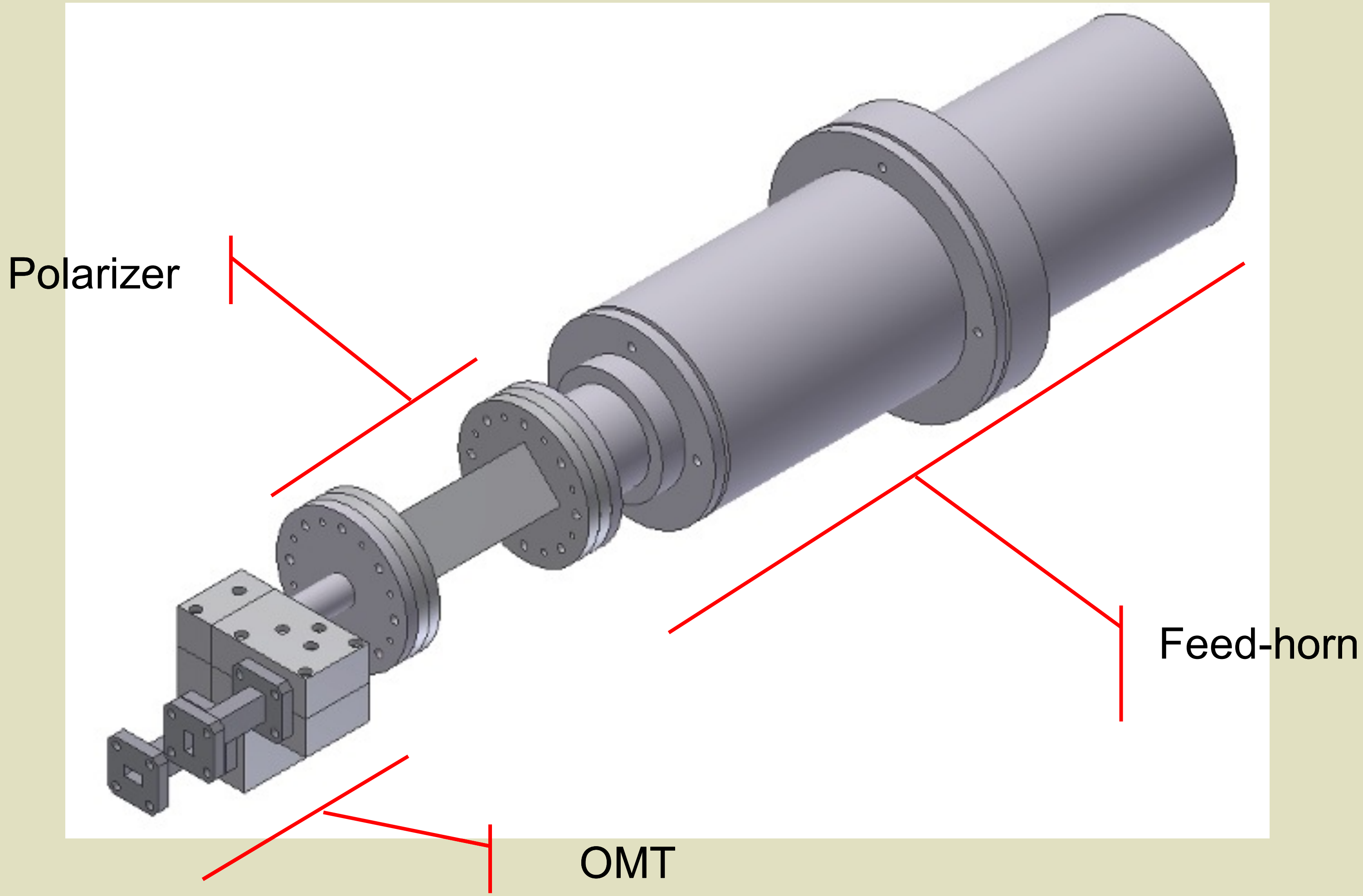

Feed-horn QUIJOTE 2 – 30 GHz Instrument

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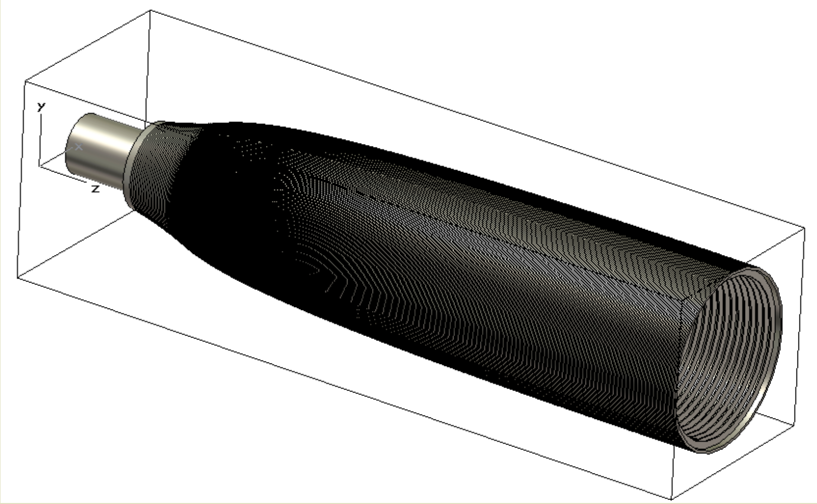
3D model for EM simulations



Feed-horn prototype

Feed-horn QUIJOTE 2 – 30 GHz Instrument

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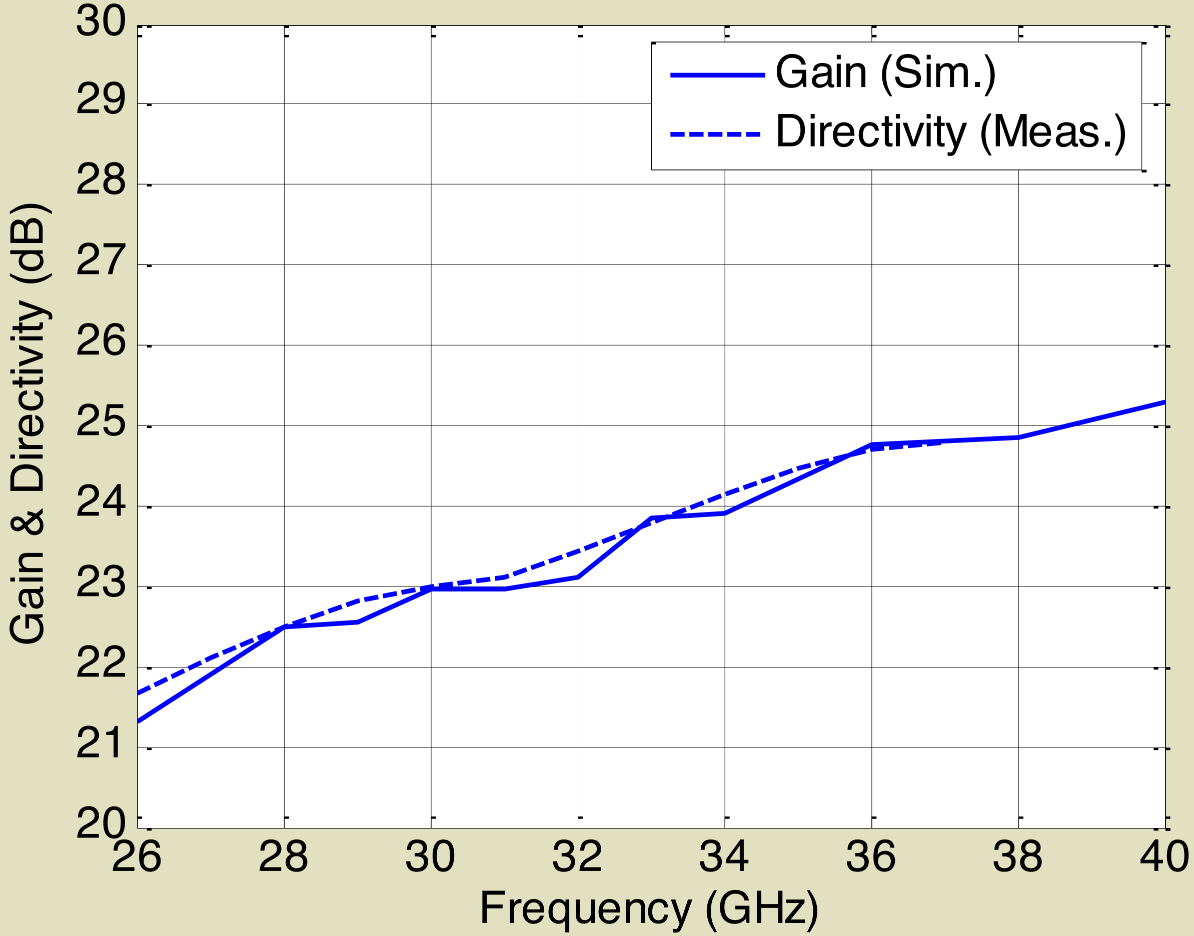
Feed-horn directivity measurements
Feed-horn losses not included. (Loss < 0.5 dB)



Feed-horn QUIJOTE TGI

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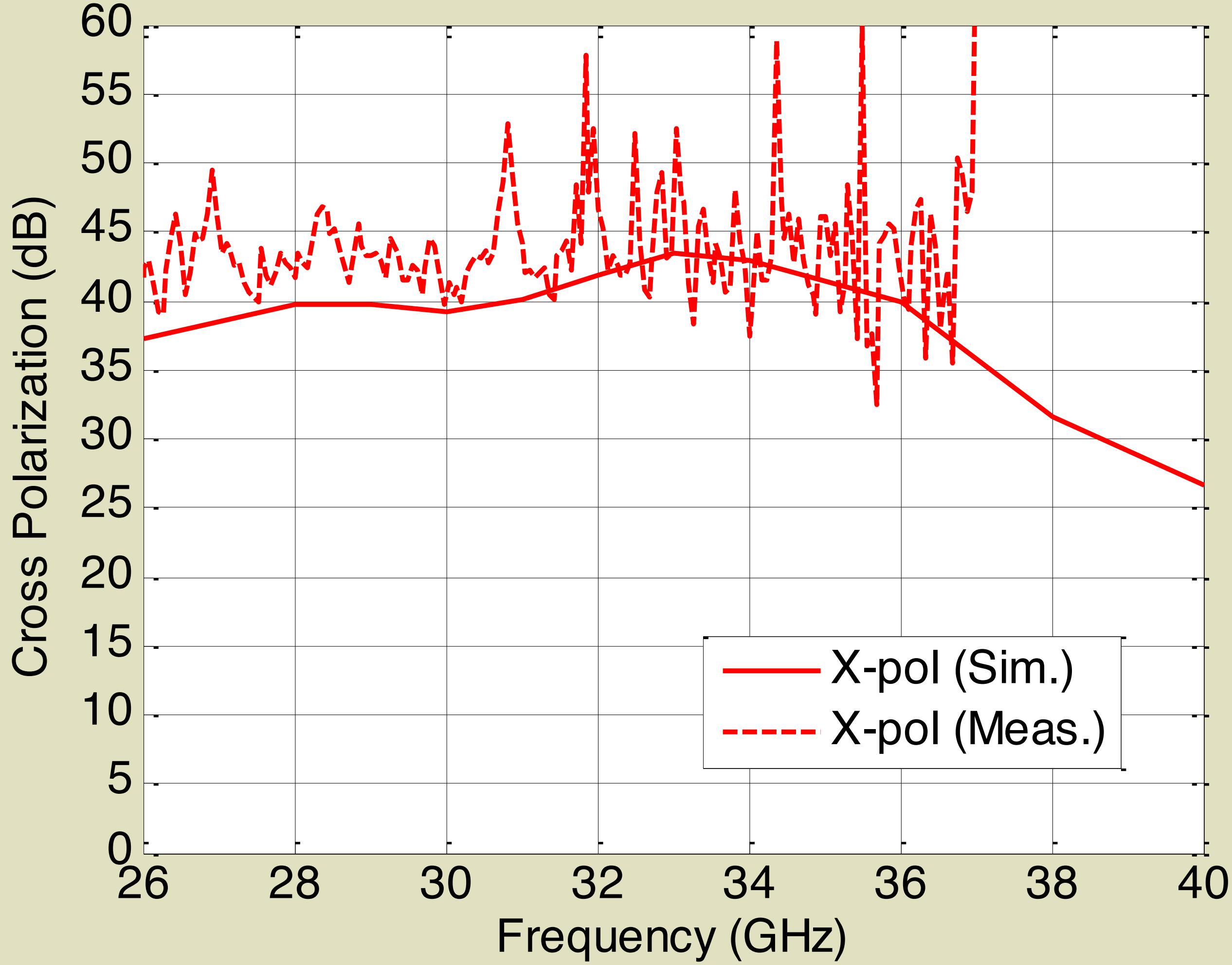
Feed-horn cross-polarization measurements



Feed-horn QUIJOTE TGI

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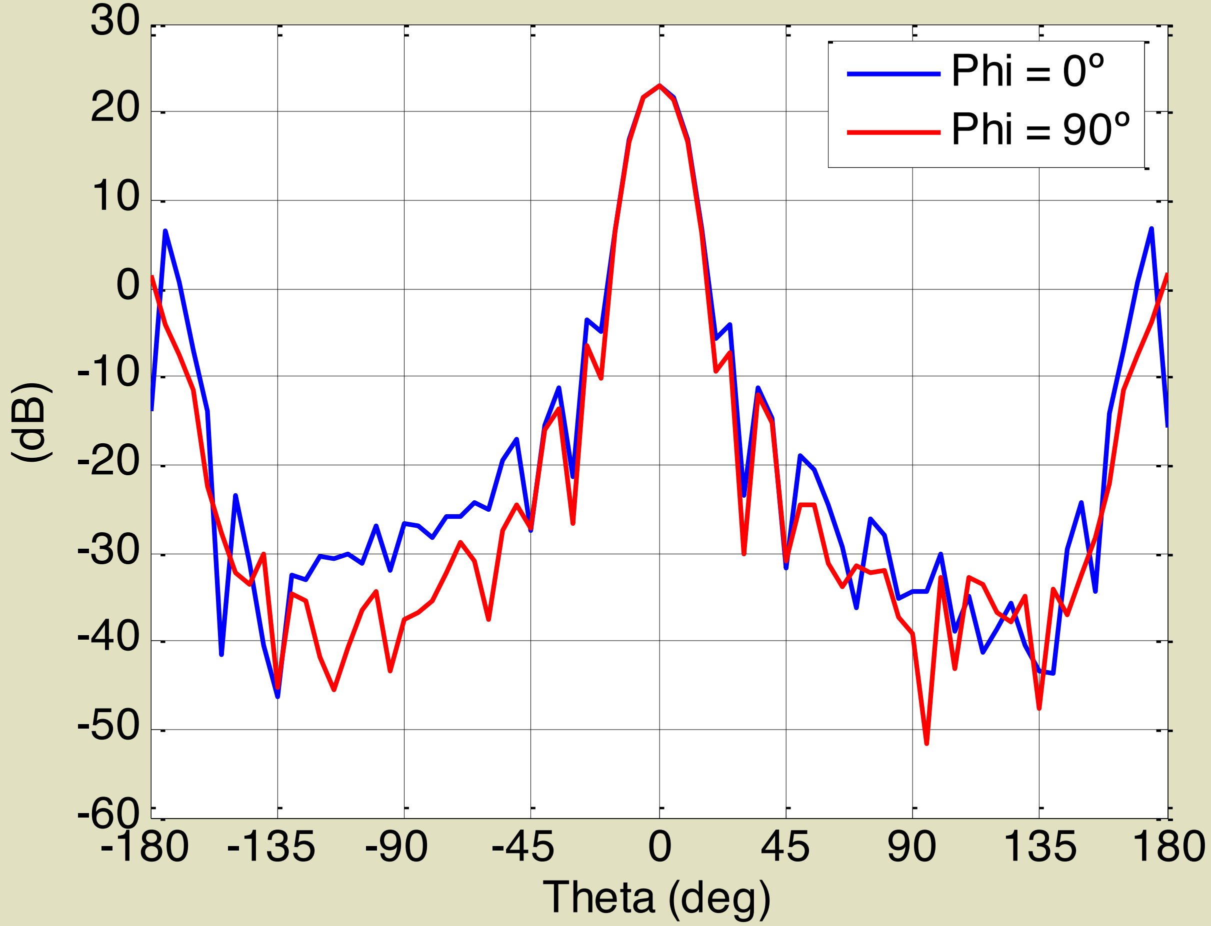
Feed-horn radiation-pattern measurements (at 32 GHz)



Polarizer QUIJOTE TGI

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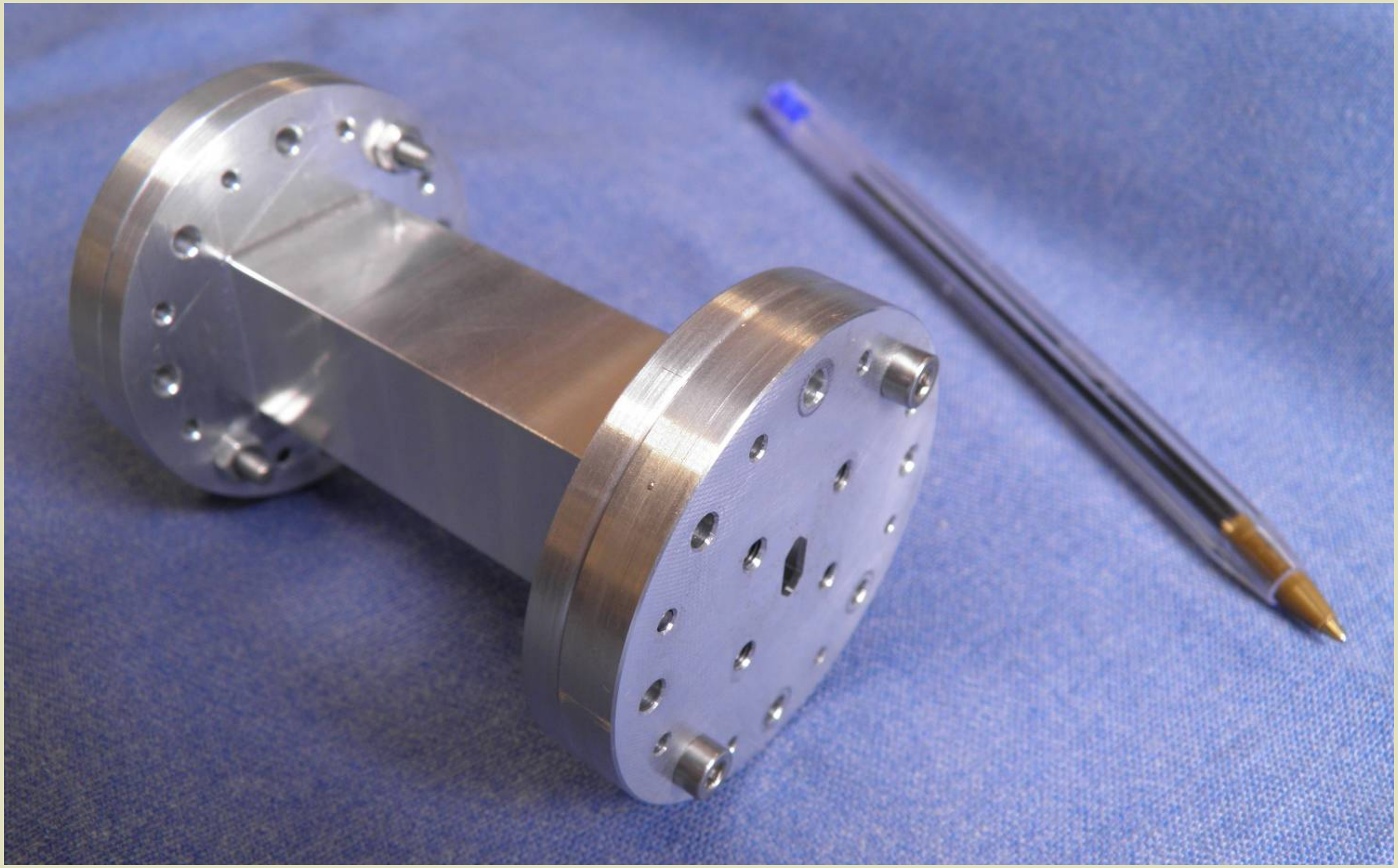
Polarizer (26-36 GHz)

Square waveguide component (internal corrugations)
90º differential phase shift (TE_{10} and TE_{01} orthogonal modes)



Polarizer QUIJOTE 2nd Instrument

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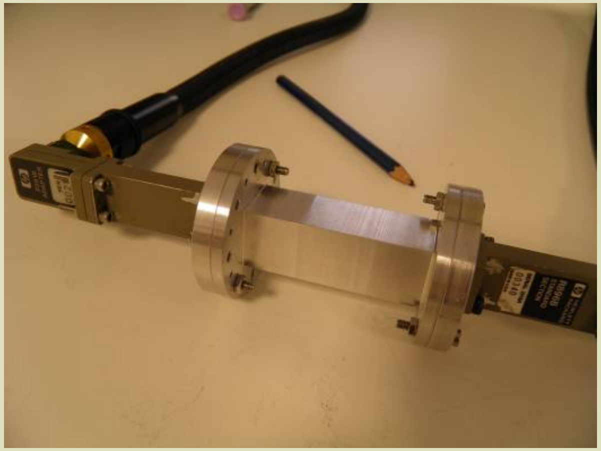
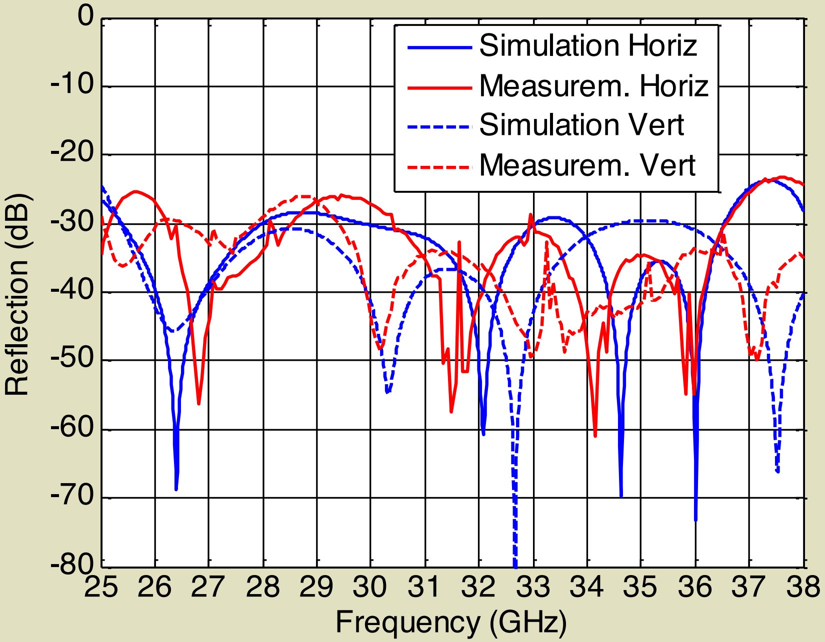
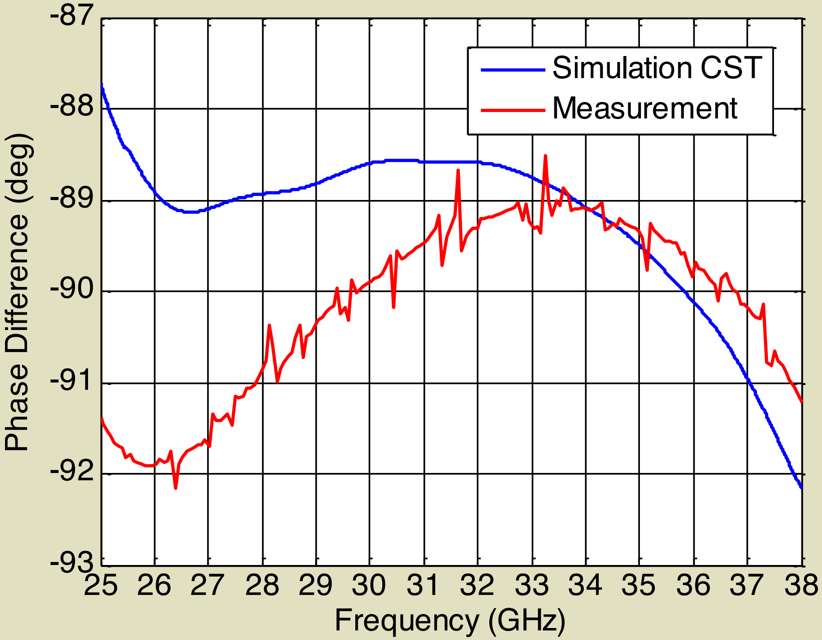
Test results

ΔΦ = 90.5º ± 1.5º
IL < 0.3 dB
26 to 36 Ghz







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34 polarizers (TGI)

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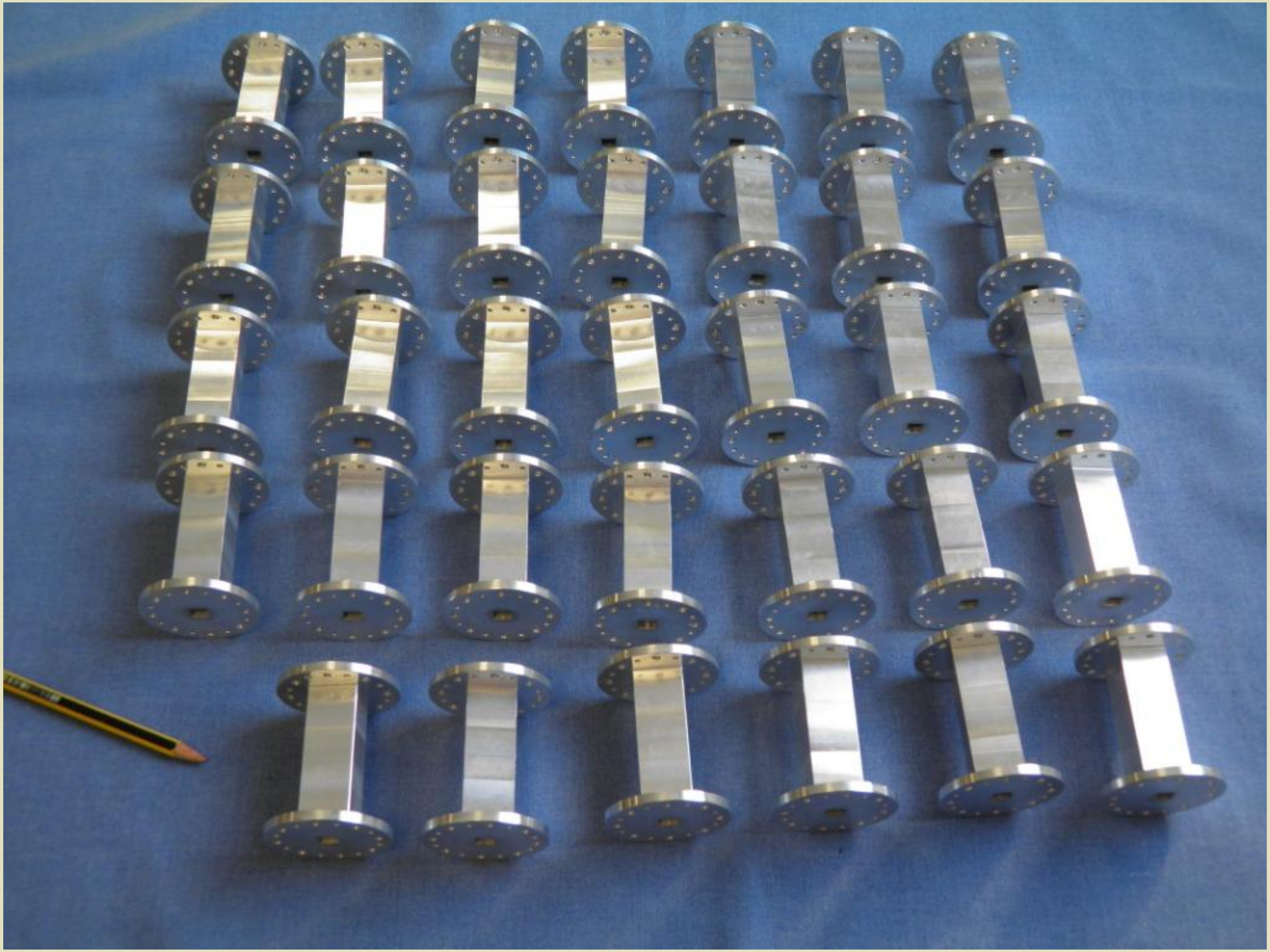

OMT QUIJOTE TGI

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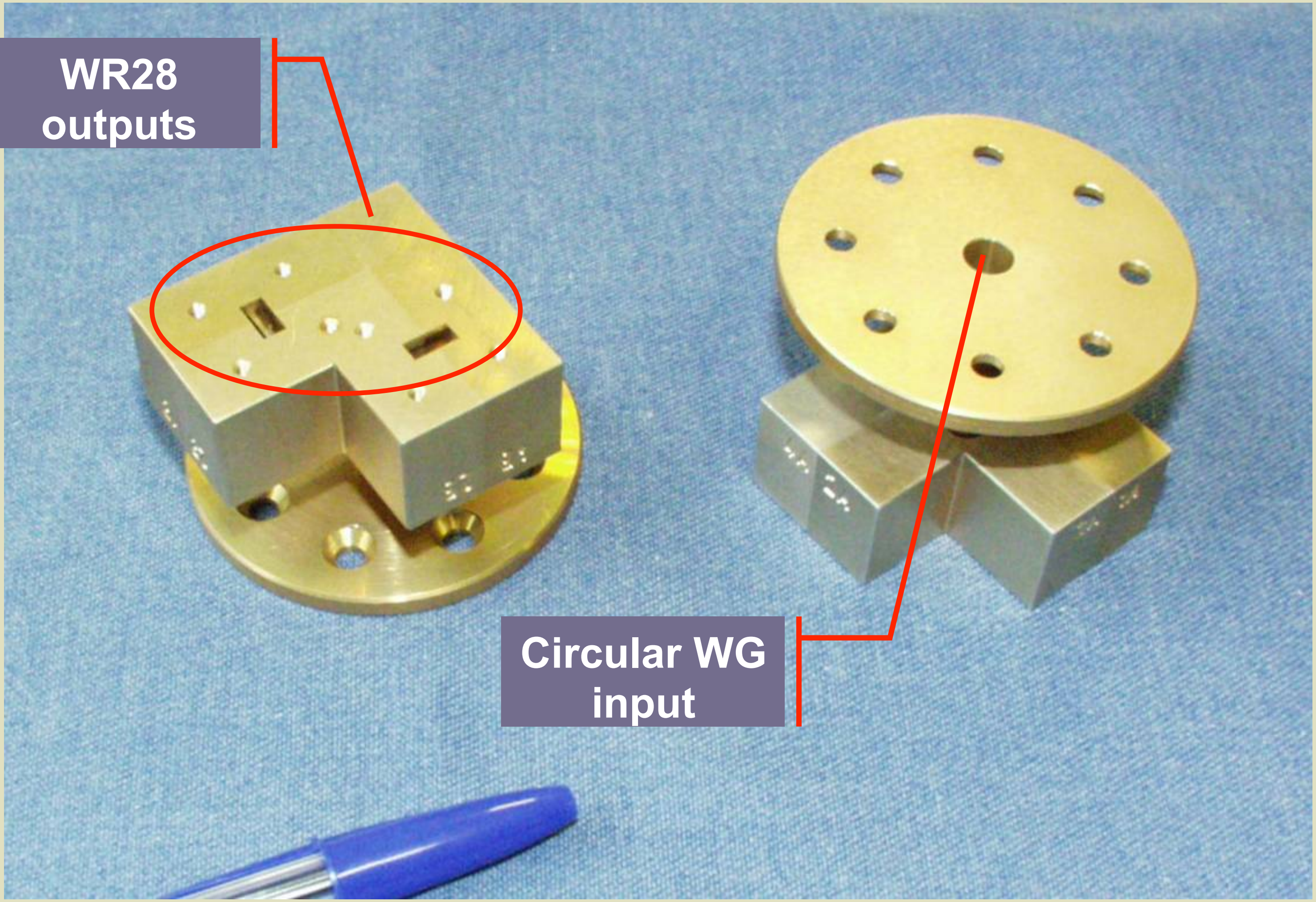
Orthomode Transducer (OMT) (26-36 GHz)
Same component as for the 1st instrument (MFI)



14 OMT (TGI)

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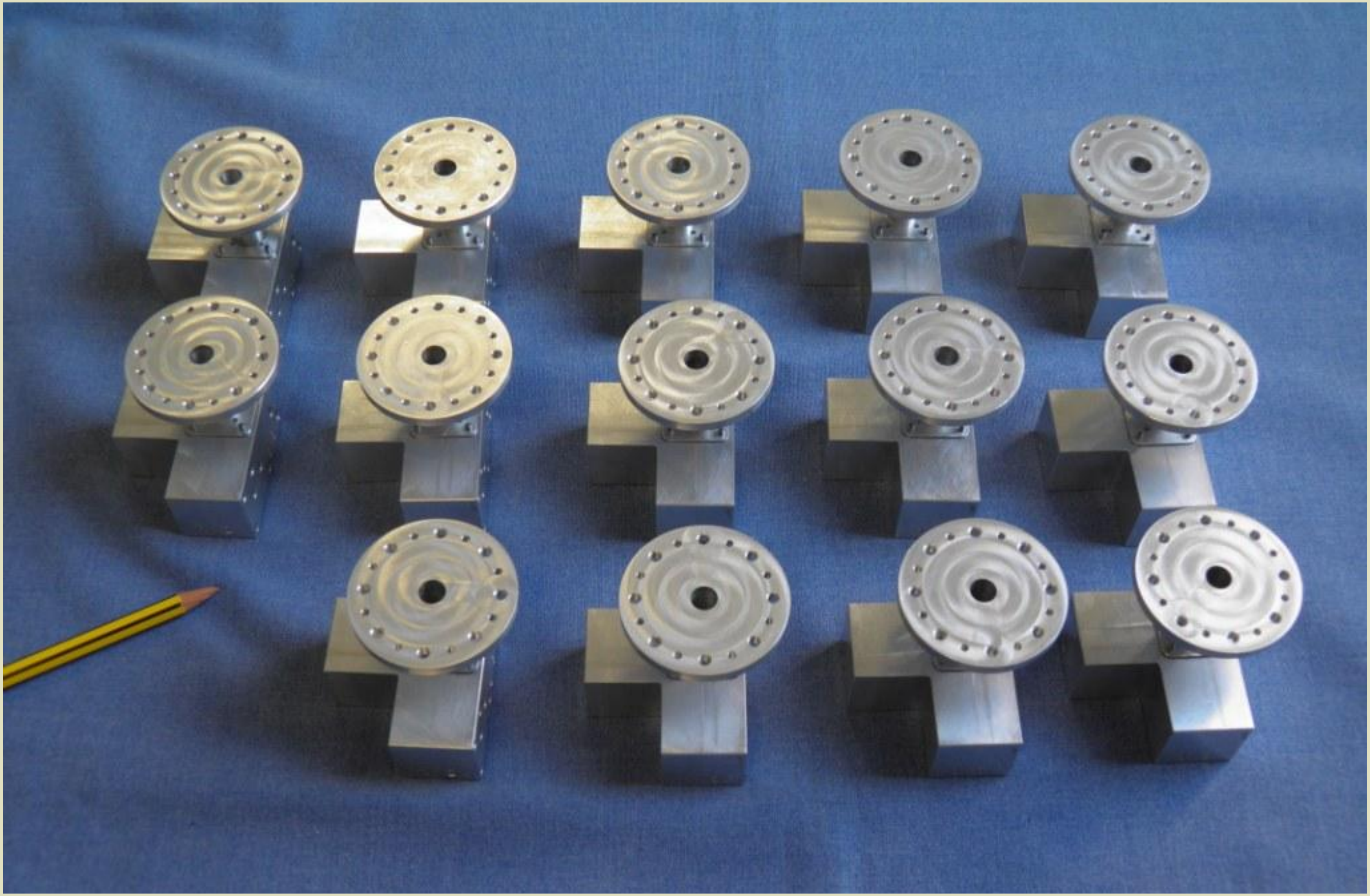

TGI optomechanics assembly

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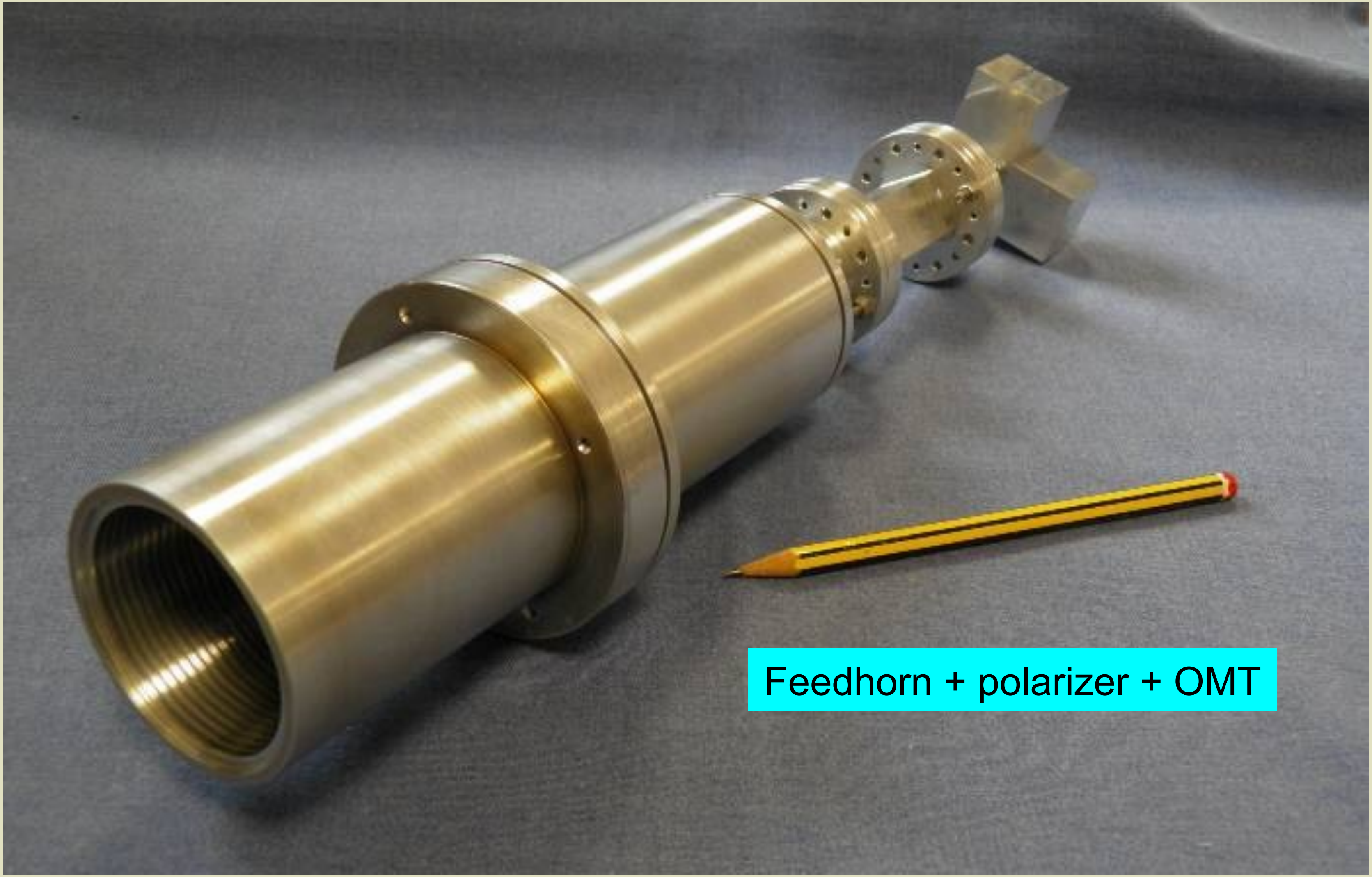
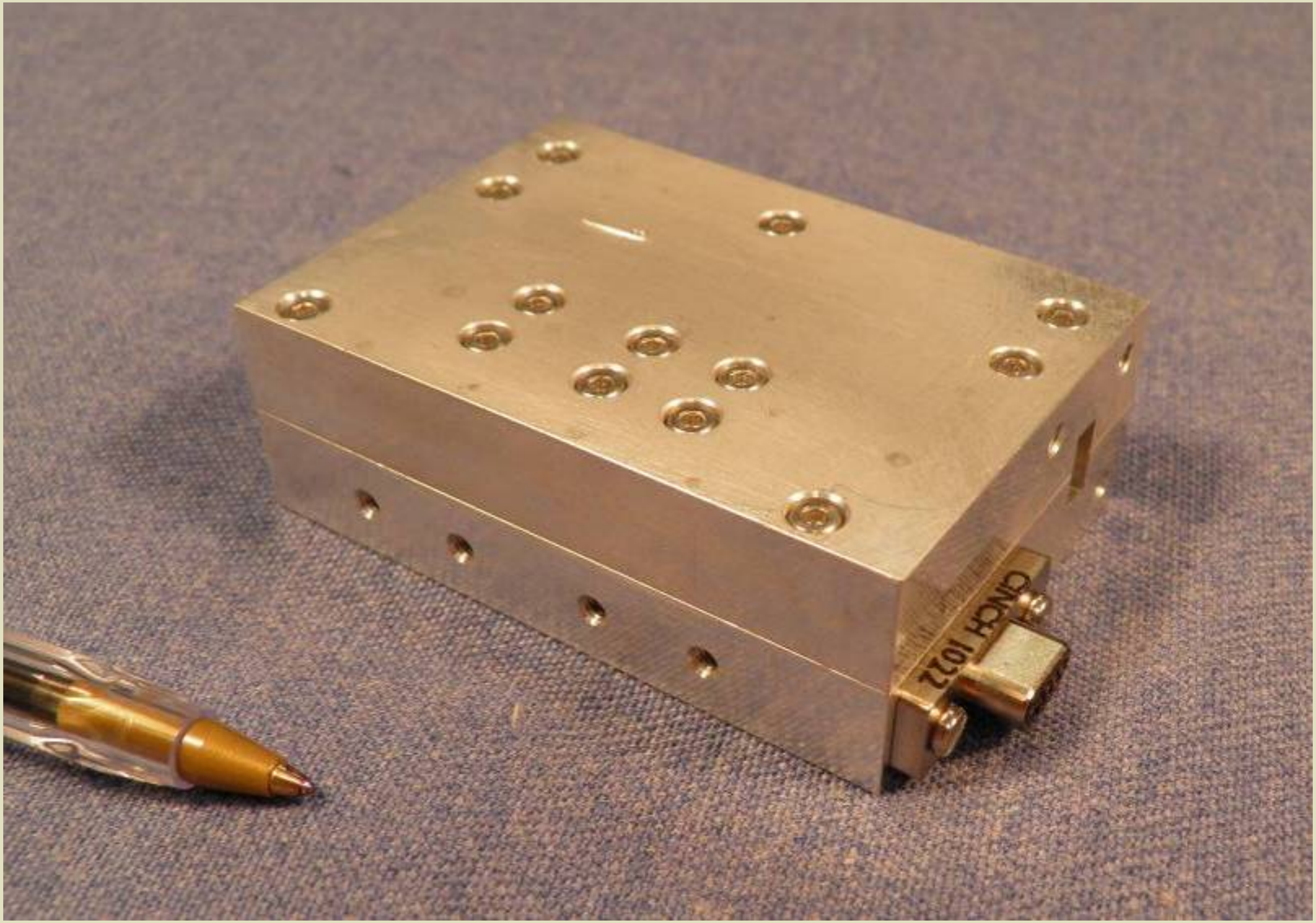


Cryo-LNA (FEM) 26-36 GHz - Prototype



Cryo-LNA (FEM) TGI 26-36 GHz - Prototype

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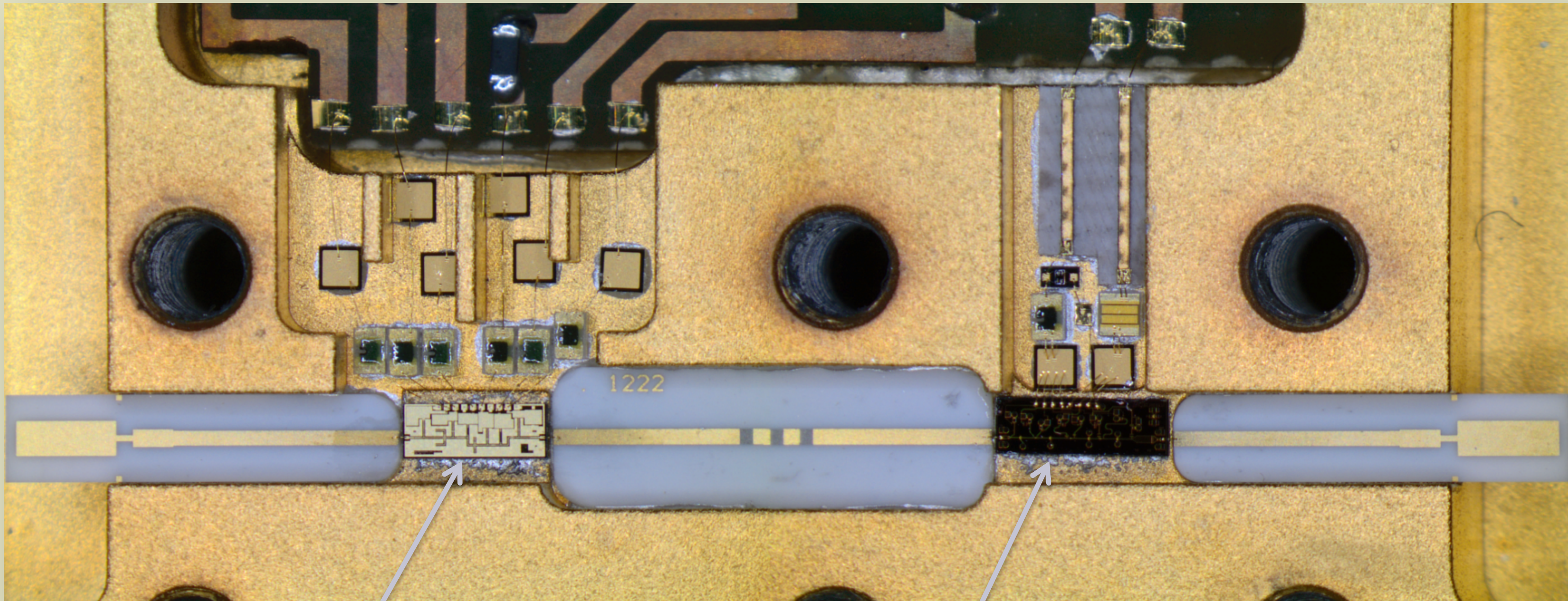

- ✓ ALN002MAKA_AB_S2 (IAF) (C17) + UCL2636CR (OMMIC) (Wafer 6984)
- ✓ 5 dB Attenuator between chips

Cryo-LNA (FEM) TGI 26-36 GHz - Prototype

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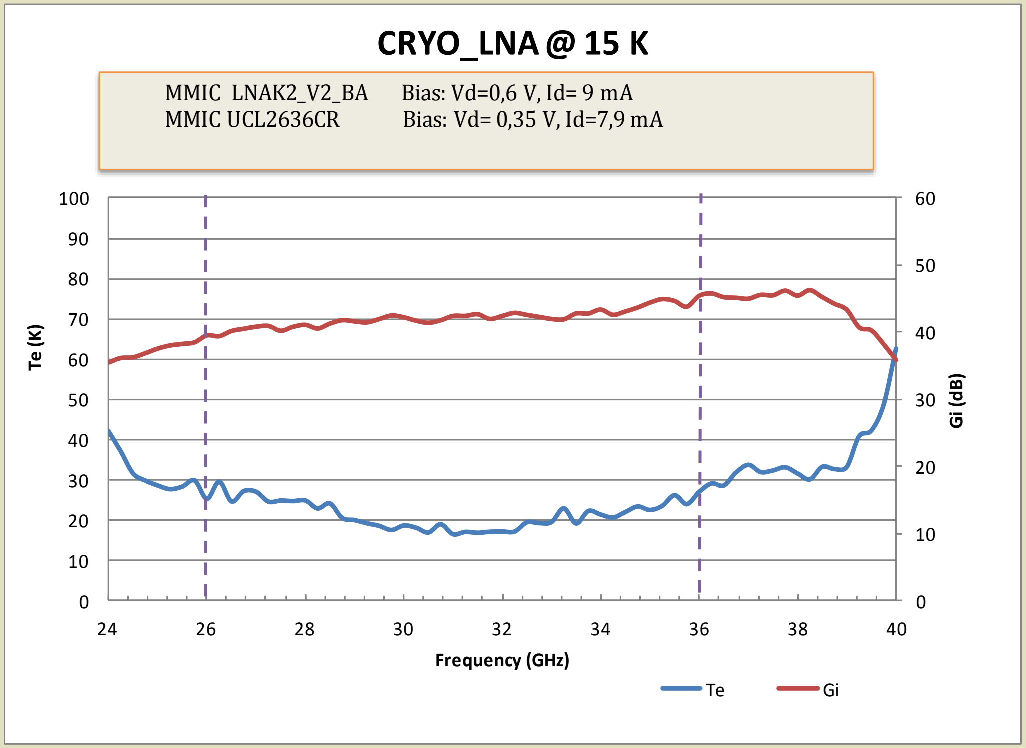
DC consumption (1 cryo_LNA) @ 15K

	Vd	Id	Power
1st MMIC	0.6 Volt.	9 mA	5.4 mW
2nd MMIC	0.35 Volt.	8 mA	2.8 mW
Total			**8.2 mW**



Freq	Te (avg), K	Te (min), K	Gi (avg), dB
26-36 GHz	21,6	16,6	42,1

RF Gain BEM QUIJOTE TGI

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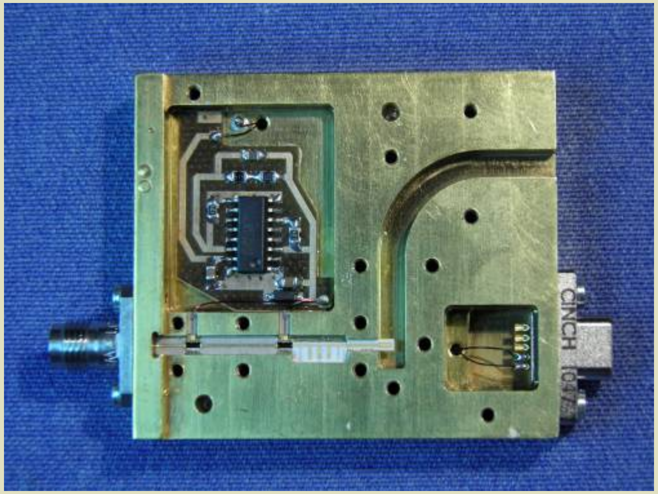
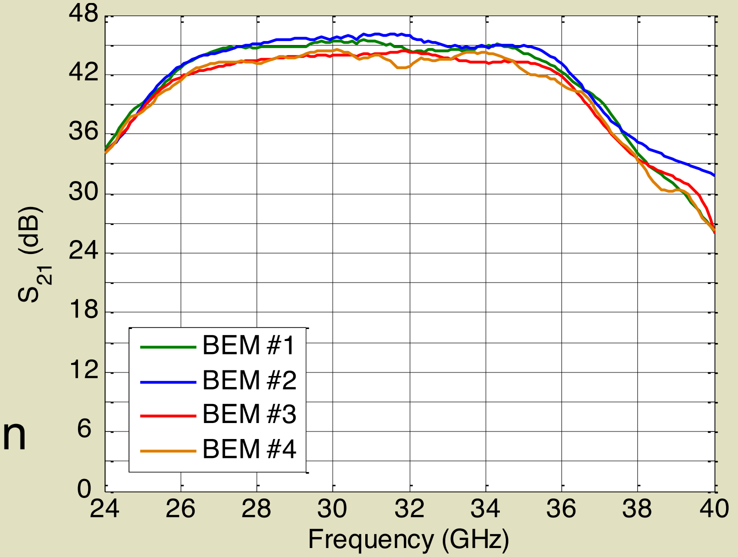
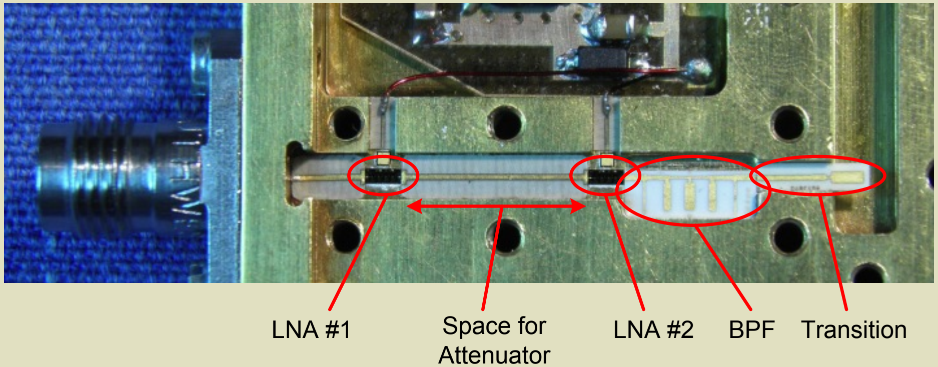
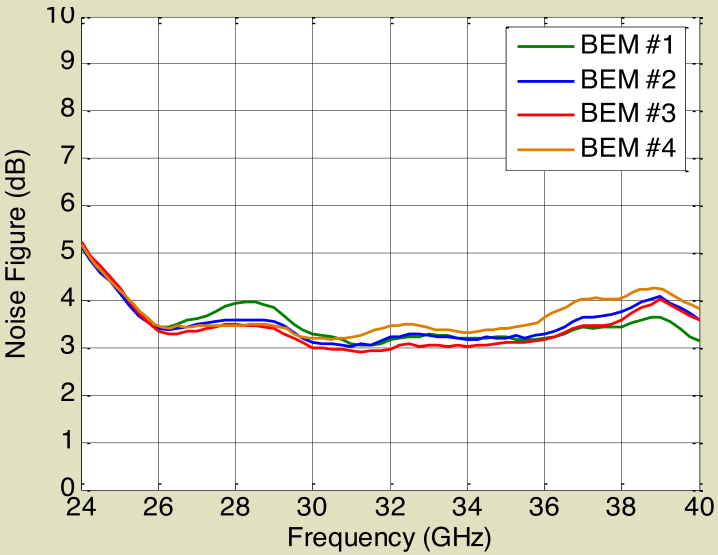
- Gain: G ~ 44 dB
- Noise Figure < 4 dB
- 26-36 GHz



4 units comparison







Manufactured units RF Gain (BEM) TGI

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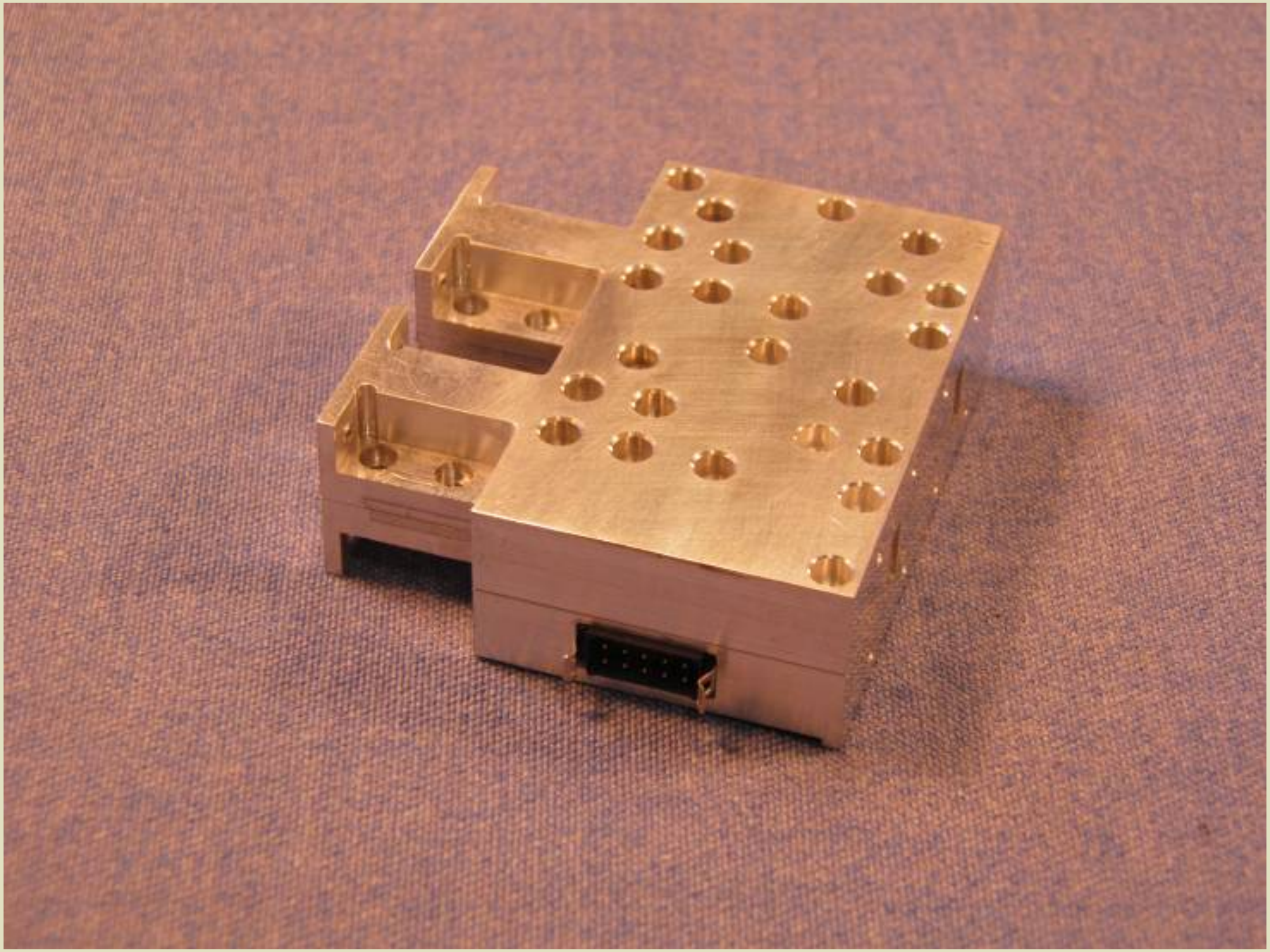
RF Gain (BEM): 32 of 62
(30 in this picture)

Phase Switches Module TGI QUIJOTE



Phase Switches Module TGI QUIJOTE

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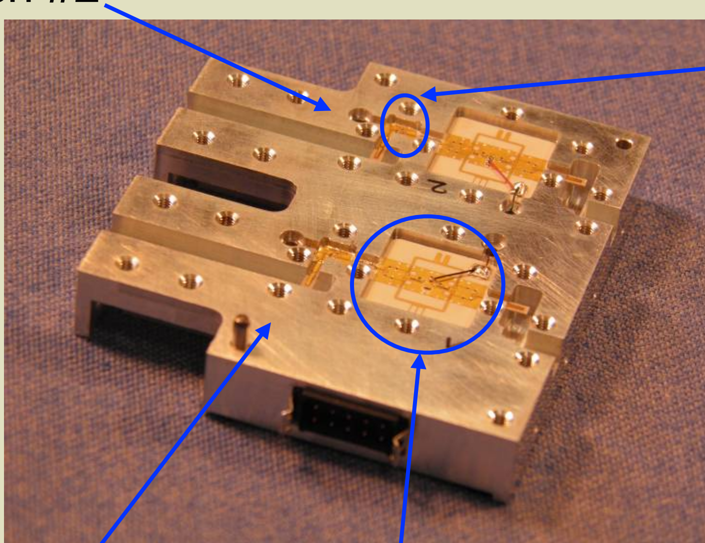
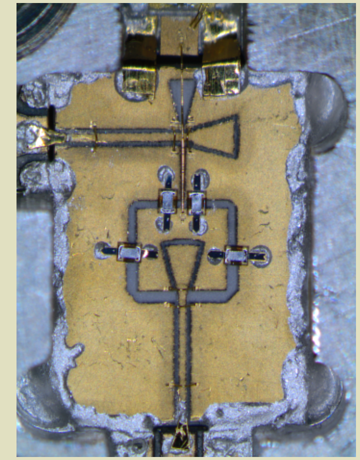
Branch #2

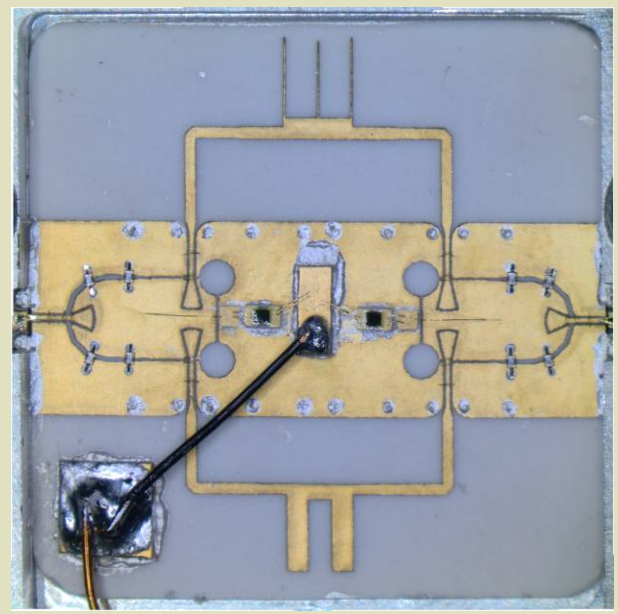


Branch #1

180º Phase Switch



90º Phase Switch



Phase Switch 180º QUIJOTE TGI

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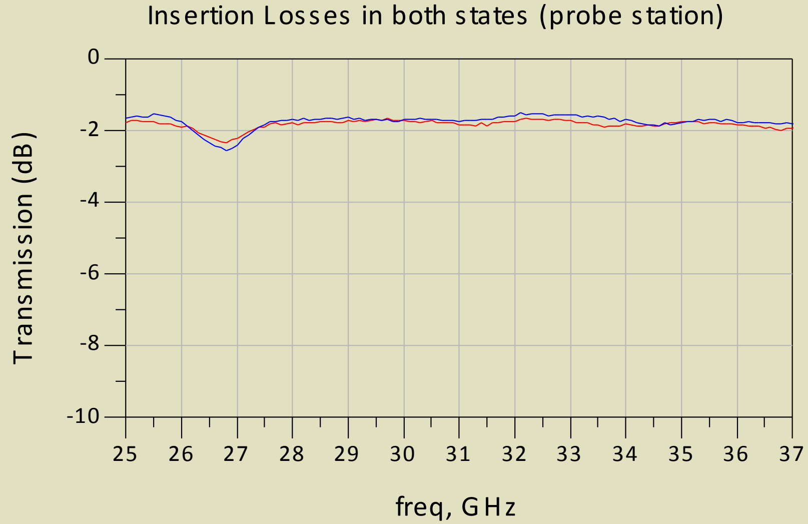
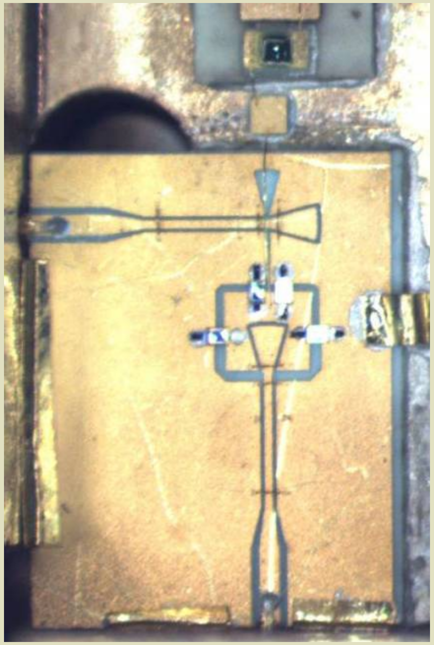
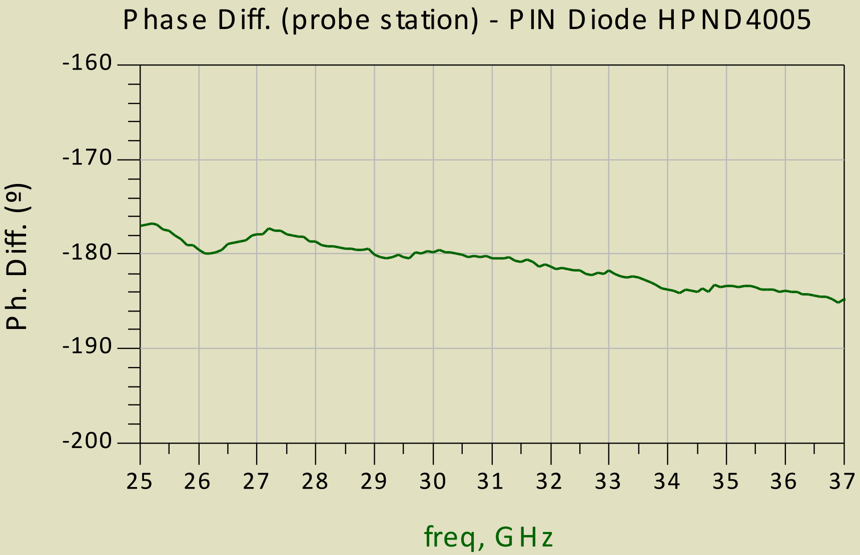
Coplanar-slot switch with PIN diodes







Coplanar probe station tests

I_T = 40 mA

Φ =181º (mean value in 26-36 GHz)

ΔΦ = ± 2.5º

IL imbalance (26-36 GHz) ≤ 0.2 dB

Correlation-detection (BEM) TGI

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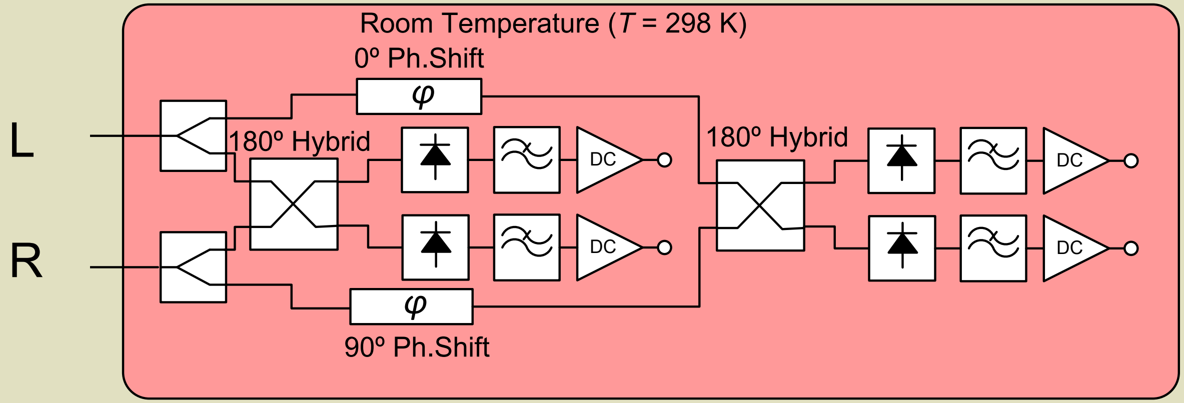
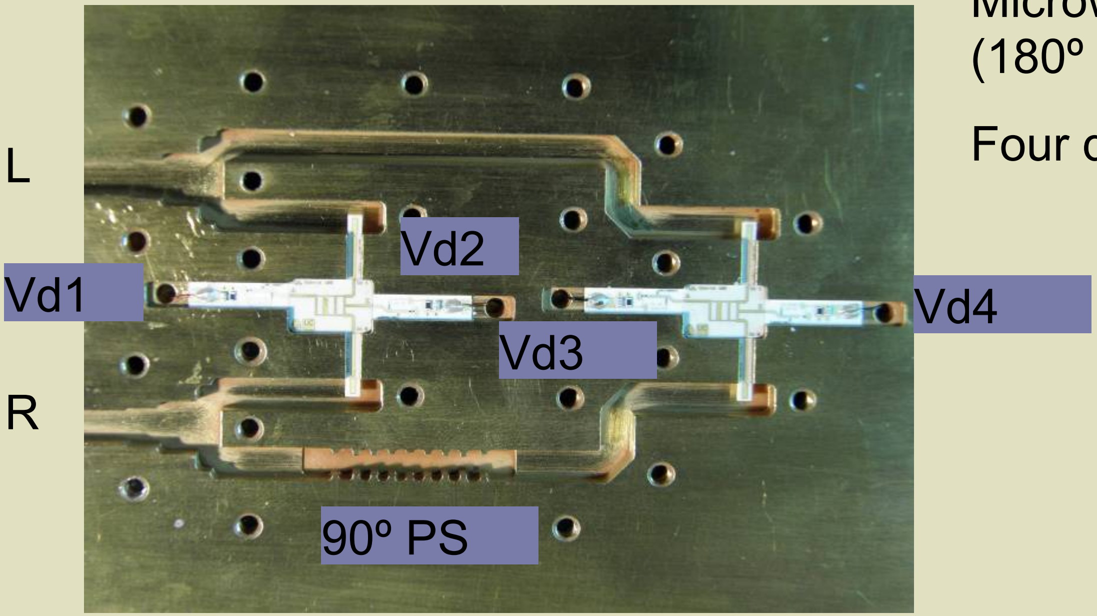
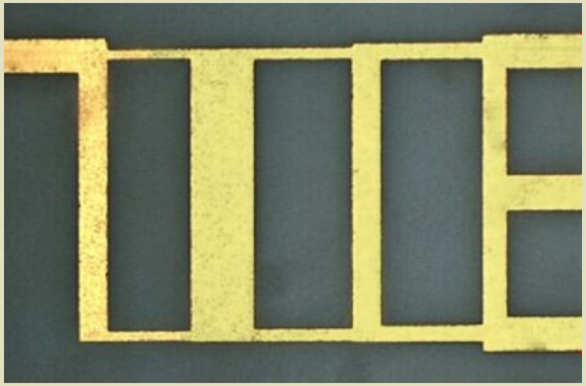




Microwave correlation (26-36 GHz) (180º hybrids)

Four detected outputs



3 dB/180º broadband hybrid

Manufactured units Correlation-Detection TGI

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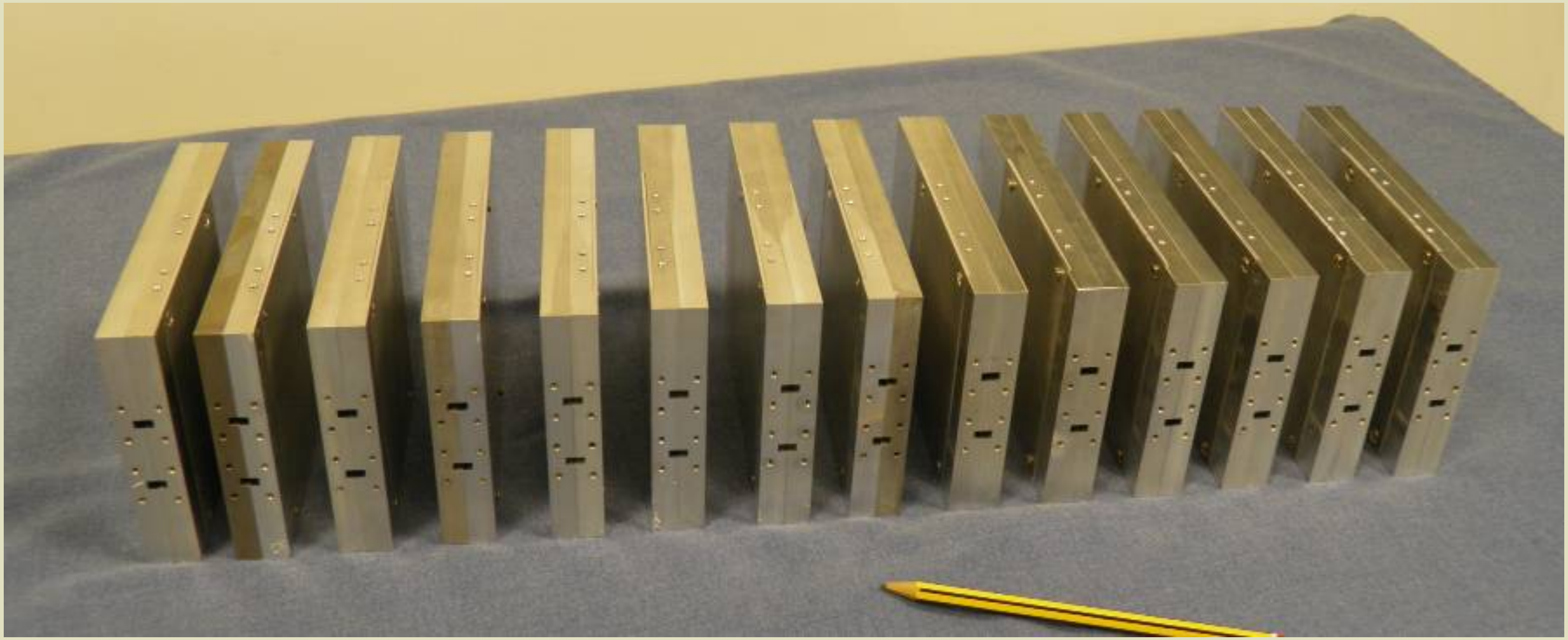

Correlation-Detection (BEM): 20 of 31
(14 in this picture)

BEM rack assembly: 1 unit of 16

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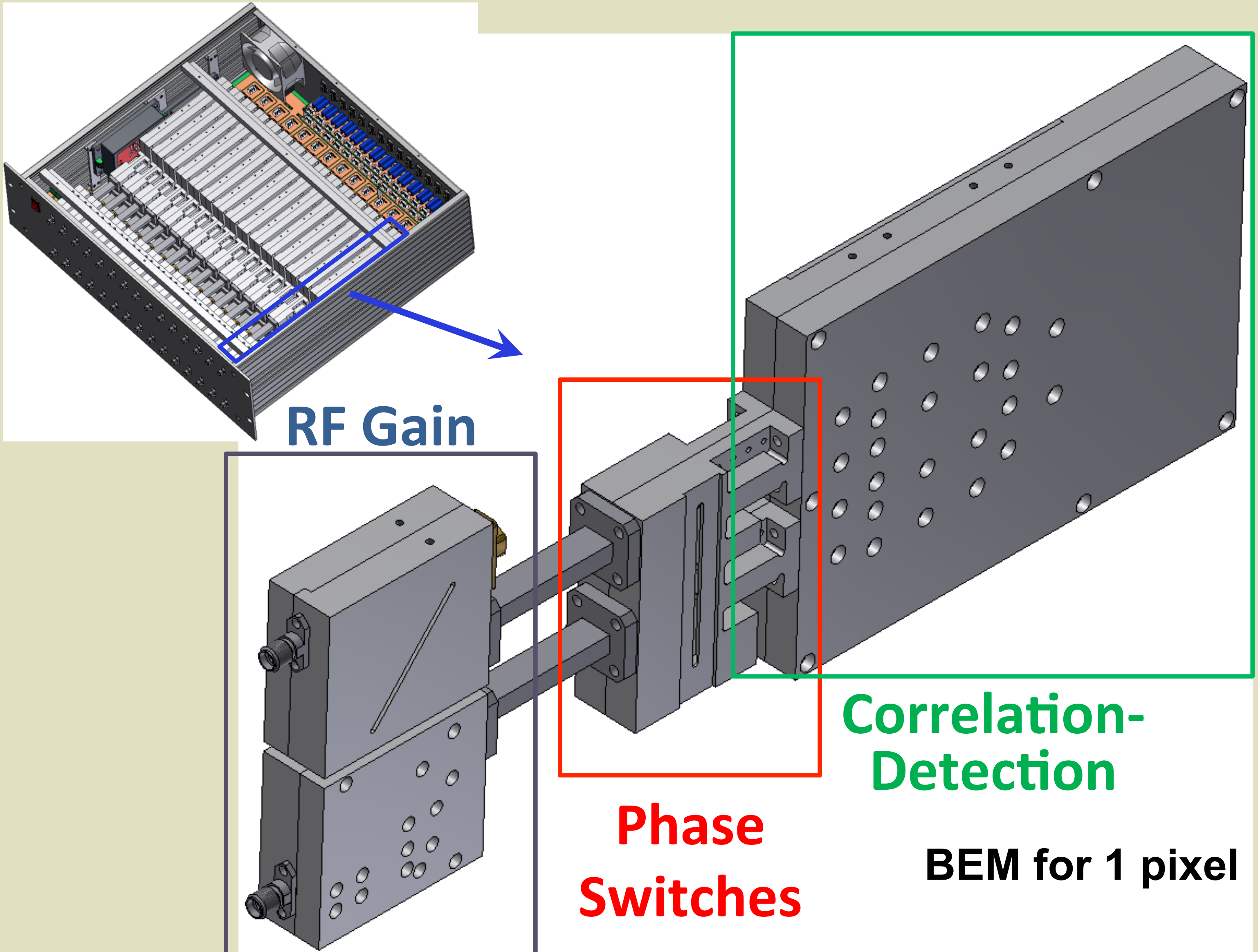

Stokes parameters from detected voltages

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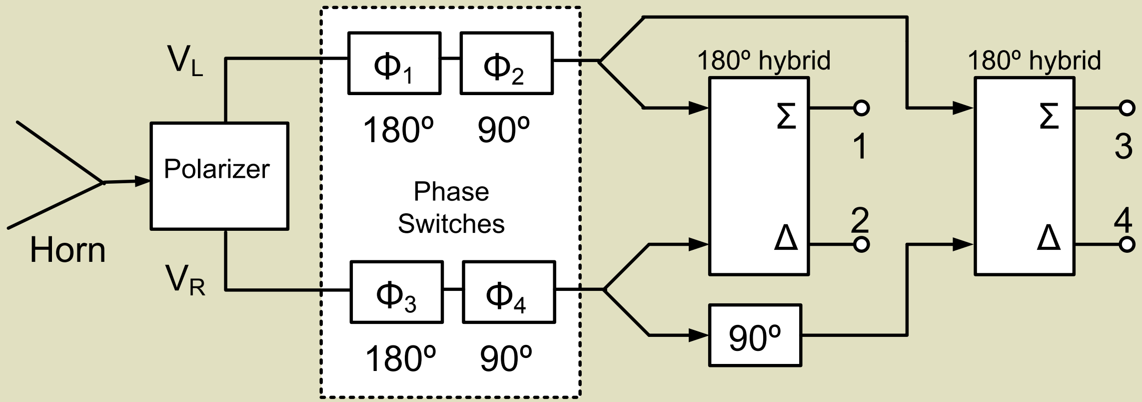

Stokes parameters:

I = Intensity (power)

Q and U = linear polarisation

Φ	I	Q	U
0º	Vd1 + Vd2 = Vd3 + Vd4	Vd1 – Vd2	Vd3 – Vd4
90º	Vd1 + Vd2 = Vd3 + Vd4	Vd3 – Vd4	Vd2 – Vd1
180º	Vd1 + Vd2 = Vd3 + Vd4	Vd2 – Vd1	Vd4 – Vd3
270º	Vd1 + Vd2 = Vd3 + Vd4	Vd4 – Vd3	Vd1 – Vd2

Experimental results. Test signals

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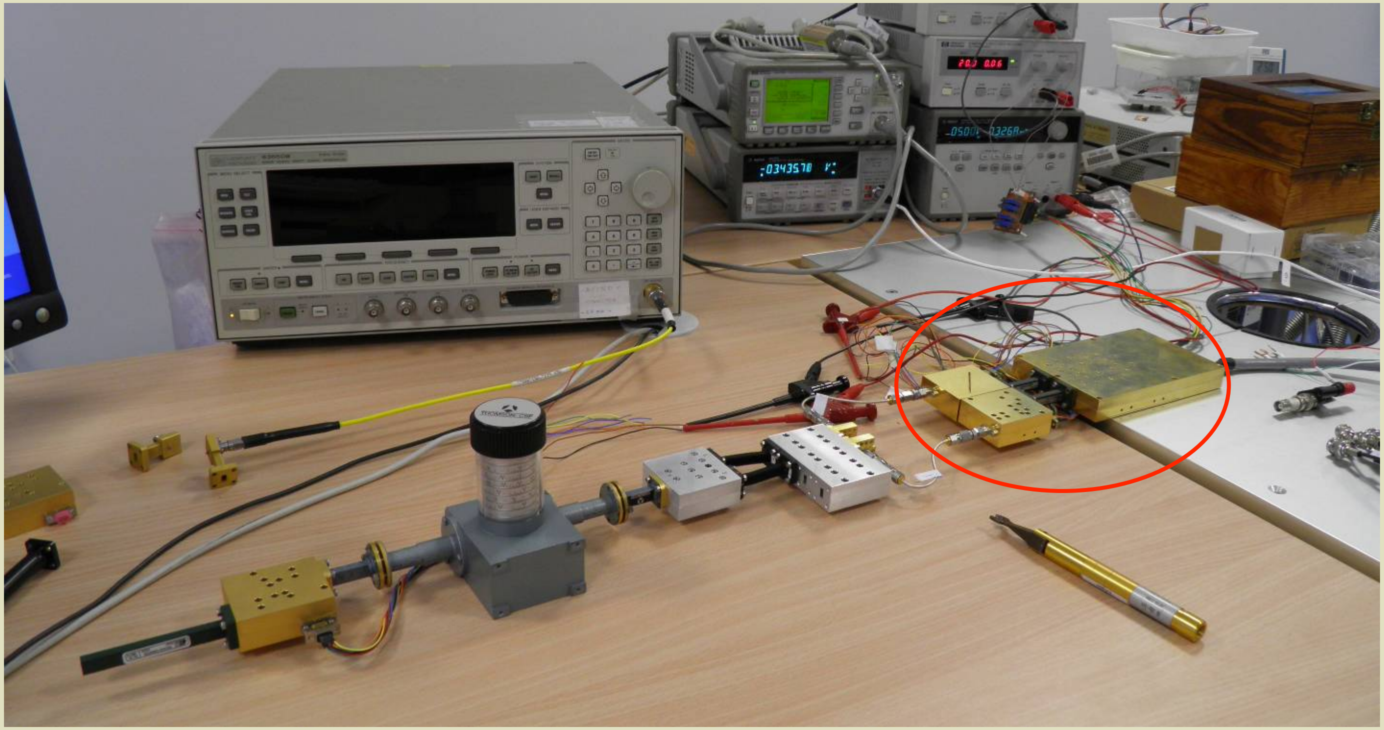
- Linearly polarized wave at feed-horn input ⇒ two signals with the same amplitude and 90º out of phase at the OMT outputs
- In the laboratory: two **broadband** signals generation with the same amplitude and 90º out of phase to be introduced to the BEM.



Experimental results. Test setup

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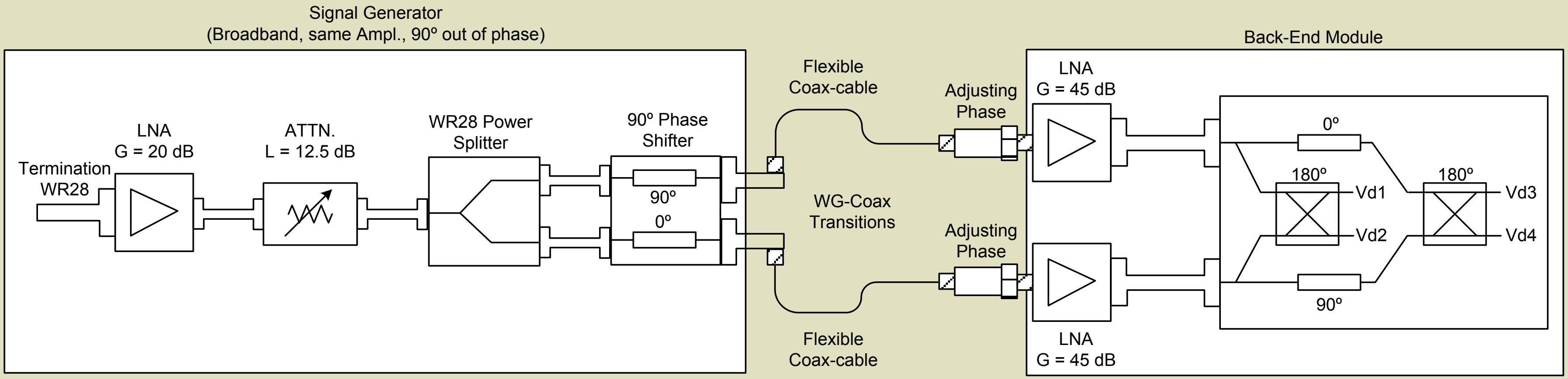

- Input: **Broadband noise**
- Two signals at BEM input: same amplitude, phase shift 90º: -jA and A
- “Adjusting Phase” to minimize difference output (Vd4)

Experimental results (noise inputs 90º)

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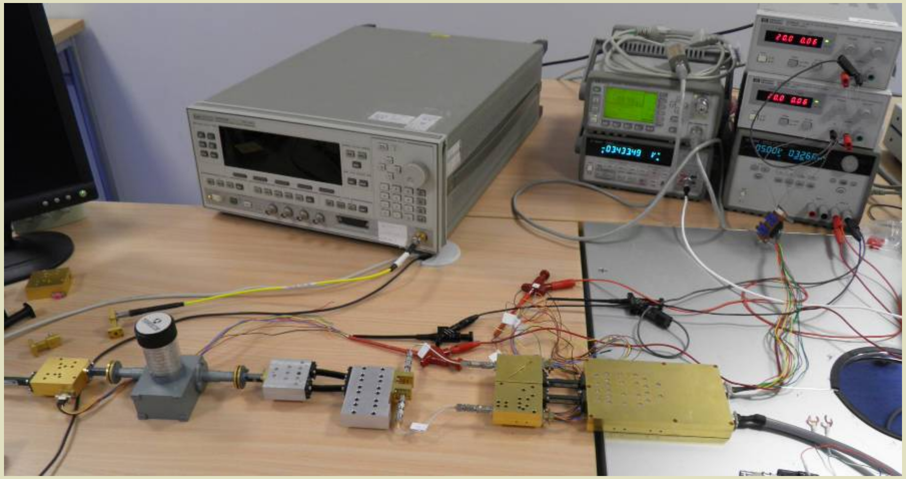

<u>Broadband noise (input)</u>

Detected voltages
(differential outputs of DC amplifiers):

Test result	Theory
Vd1 = 1.75 V	($A^2/2$)
Vd2 = 1.87 V	($A^2/2$)
Vd3 = 3.07 V	(A^2)
Vd4 = 0.92 V	(0)

Stokes parameters (without voltage normalization):

I = Vd1 + Vd2 = 3.62 V (alt. Vd3 + Vd4 = 3.99 V) — $I = A^2$

Q = Vd1 – Vd2 = -0.12 V — Q = 0

U = Vd3 – Vd4 = 2.15 V — $U = A^2$

Isolation parameters (Figures of merit):

Isol1 = 10 log |I/Q| = 14.8 dB (leakage I to Q)

Isol2 = 10 log |U/Q| = 12.5 dB (leakage U to Q)

Frequency sweep results

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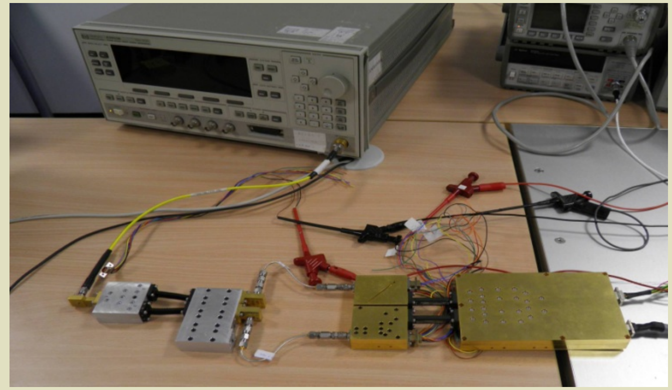
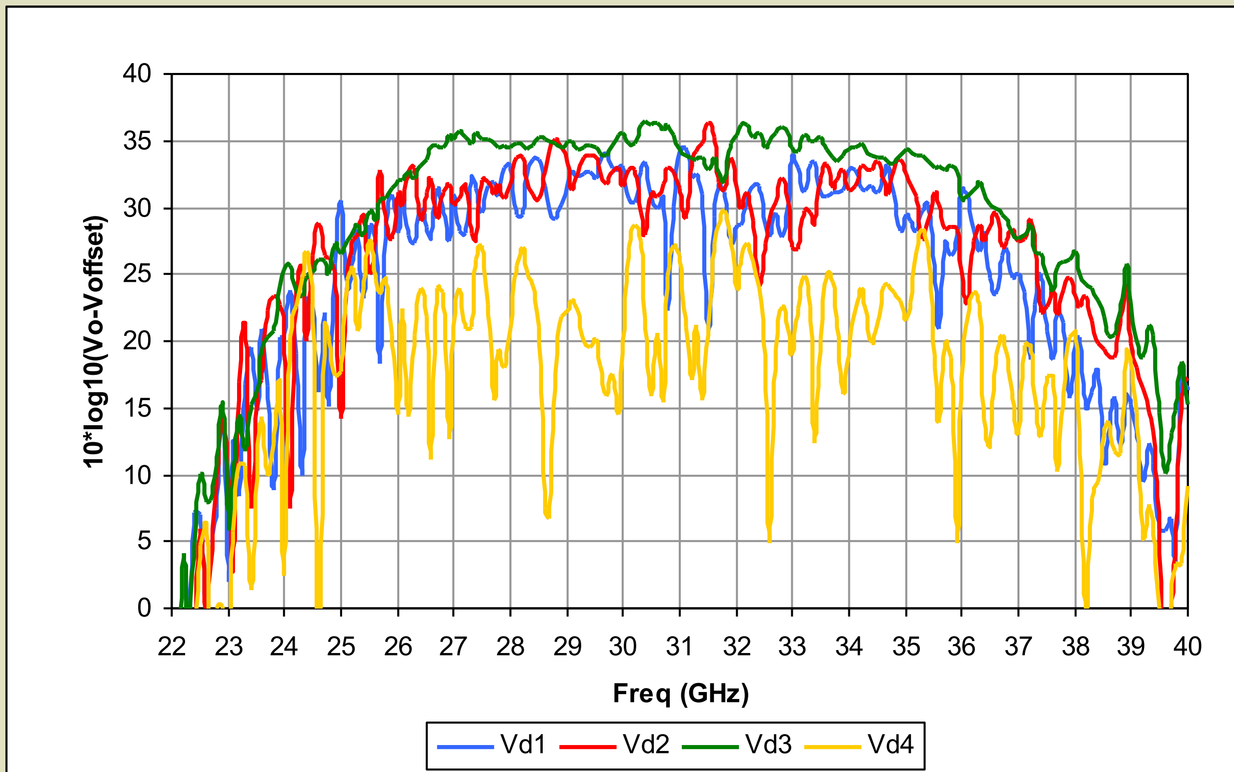
Input: Pgen = -60 dBm
22 to 40 GHz



Theoretical detected outputs

$A^2/2$
$A^2/2$
A^2
0



Test bench results (prototype)

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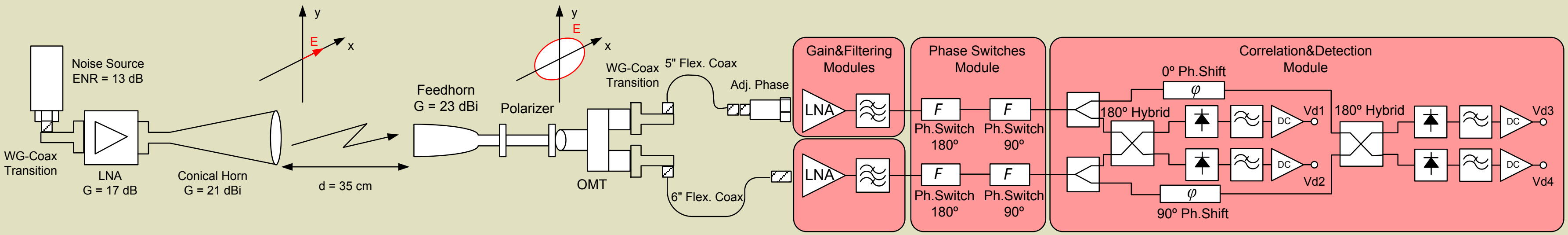
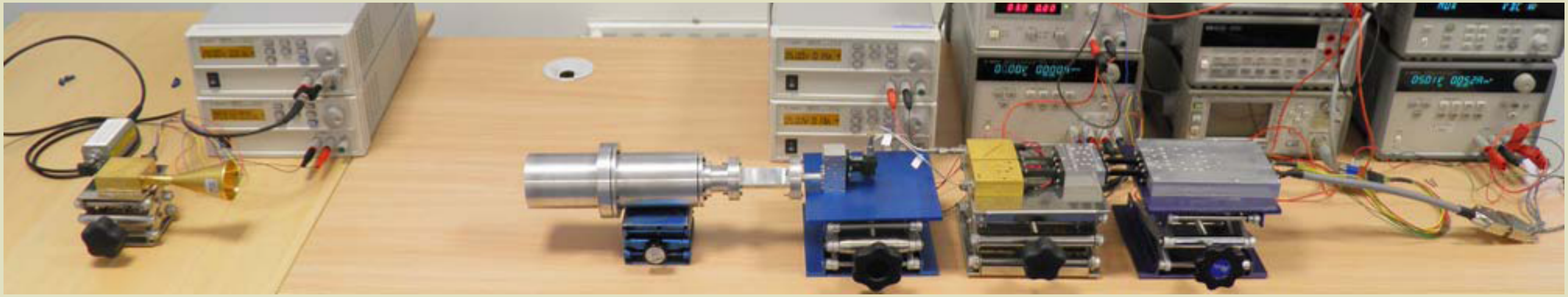
Input: Broadband linearly polarized signal (from a Noise source)

Radiometer outputs (1, 2, 3 and 4): detected signals proportional to power





Test bench results (prototype)

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Test set-up at IFCA laboratory (anti-vibration table)

Test bench results (prototype)

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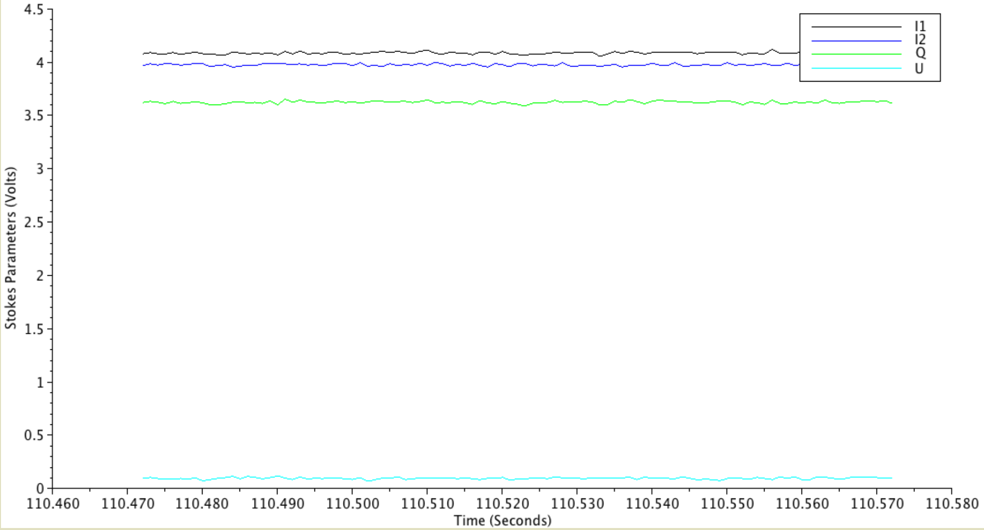
IFCA Instituto de Física de Cantabria

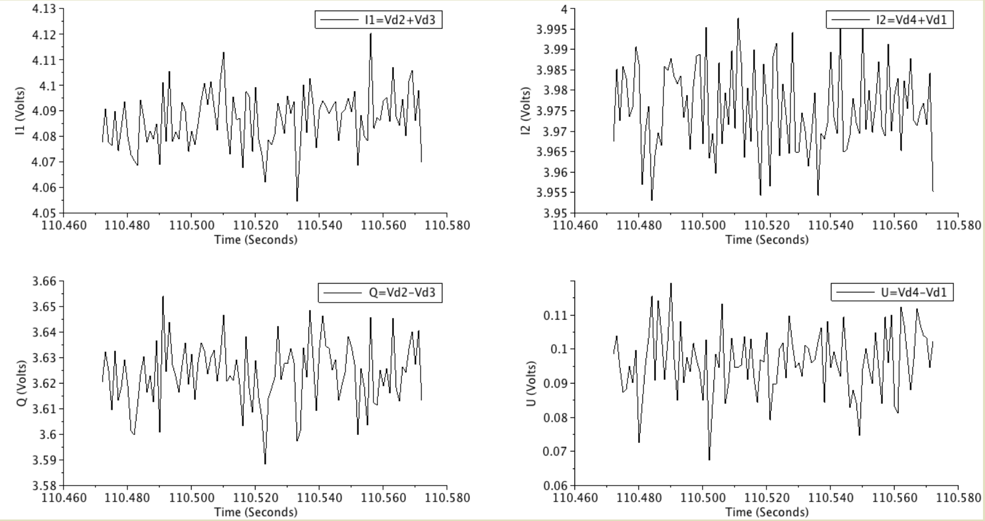
Measurement at 1 Hz sampling frequency



Efficiency = Q/I = 89.8%
Isolation = U/Q = -15.6 dB

Stokes parameters

V2+V3=4.09 ⇒ $I_1 = 1.0$
V4+V1=3.98 ⇒ $I_2 = 0.97$
I=(I1+I2)/2 ⇒ I = 0.98
V2-V3=3.62 ⇒ Q = 0.88
V4-V1=0.1 ⇒ U = 0.024



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30 GHz polarimeter scheme validated

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- Phase switching receiver operation demonstrated experimentally (and confirmed by simulations).
- Good isolation of Stokes parameters requires adjusting phase and amplitude (between the two branches).
- Stokes parameters can be obtained from outputs.
- Receiver FEM and BEM subsystems under manufacturing.

Acknowledgment

QUIJOTE experiment is funded by the Spanish Ministry of Science and Innovation.

Reference: AYA2010-21766-C03

The QUIJOTE CMB Experiment

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For further information visit:
http://www.iac.es/project/cmb/quijote/index.php