Cosmic Microwave Background Polarization Receivers: QUIJOTE Experiment

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***Abstract*— The QUIJOTE (Q U I JOint TEnerife) Experiment will characterize the polarization of Cosmic Microwave Background radiation and other galactic and extragalactic emissions in the frequency range from 10 to 30 GHz, and at large angular scales. The polarimeter receivers at 11, 13, 17, 19 and 30 GHz are radiometers based on broadband waveguide rotating polar modulators and broadband orthomode transducers. High sensitivity of polarimeters is achieved with very low noise cryogenic amplifiers (Noise temperature < 15 K in 11-19 GHz channels and < 20 K in 30 GHz channel). Subsystems test results and integration measurements of front-end and back-end units show wideband operation in all channels.**

I. INTRODUCTION

Instruments for QUIJOTE experiment will be installed and operated at El Teide Observatory, Tenerife (Spain). The main scientific objective of the project is to cover daily a sky area of 10,000 square degrees, with sensitivity between 1-2 μK after a year of observation and the adequate data signal processing, and an angular resolution of 1° at 11, 13, 17, 19 and 30 GHz. These measurements will complement at low frequency, and correct from galactic contamination, those to be obtained by the Planck satellite. They will be the most sensitive measurements obtained for the characterization of the synchrotron and anomalous microwave emission in our Galaxy at those frequencies.

First phase of the project includes the construction of one telescope, a first multifrequency instrument providing the channels from 11 to 30 GHz, a second instrument with 15 polarimeters at 30 GHz, and a dedicated "source subtractor" facility to measure the polarization of radiosources at 30 GHz.

II. INSTRUMENT DESCRIPTION

The polarimeter receiver system is depicted in Fig. 1. The polarimetric radiometers are used to find the so-called Stokes parameters which enable to determine the polarization state of an electromagnetic radiation. The Stokes representation is advantageous as all elements possess the same units and are real and measurable quantities [1]. The present receivers are designed to perform simultaneous observations of the Q, U and I Stokes parameters. The first and second Stokes parameters, I and Q, are measured conventionally using vertical and horizontal polarized radiometer channels, followed by addition or subtraction of the measured antenna temperatures. The third Stokes parameter, U, can be measured with a conventional two-channel radiometer connected to an orthogonally polarized antenna rotated 45º with respect to the vertical and horizontal directions, and subtracting the measured antenna temperatures [2], [3].

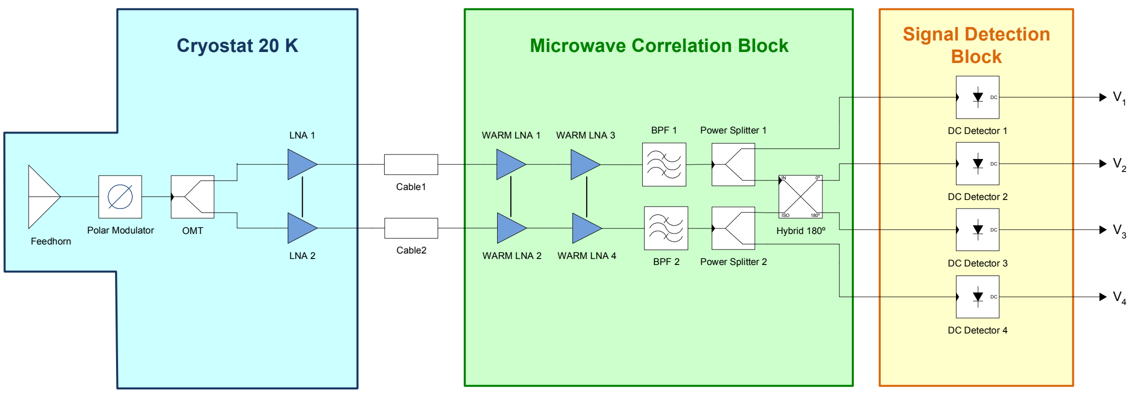


Fig. 1. QUIJOTE polarimeter receiver scheme.

The key component in the receiver is the polar modulator which rotates the reference system for the vertical and horizontal, X and Y, components in the orthomode transducer (OMT). The incoming signal is separated into its orthogonal components in the OMT and then these components are amplified, band-pass filtered and divided into two, through power splitters. One of these two outputs is correlated with one of the other two outputs through a 180º hybrid coupler.

The resulting four outputs give the signals needed to calculate the Stokes parameters Q and U simultaneously (X, Y, X+Y and X-Y). Output detected voltage from each channel is

$$V = \frac{1}{2} I + \frac{1}{2} Q \cos(4\varphi) + \frac{1}{2} U \sin(4\varphi) \qquad (1)$$

Where Q, U and I are the Stokes parameters and φ is the position angle of the polar modulator. All these four variables depend on the time and on the channel. Basic QUIJOTE experiment features are in Table I. The beam pixel size is defined as a square with each side is FWHM (Full Width at Half Maximum) of the beam.

TABLE I
QUIJOTE EXPERIMENT BASIC FEATURES

	First Instrument					**Second Instrument**
Frequency (GHz)	11	13	17	19	30	30.0
Bandwidth (GHz)	2	2	2	2	10	10.0
Number of channels	8	8	8	8	2	30
Beam pixel FWHM (deg)	0.92	0.92	0.60	0.60	2	0.37
System noise temp. (K)	20.0	20.0	20.0	20.0	30.0	20.0
Sensitivity (mK $s^{1/2}$)	0.22	0.22	0.22	0.22	0.30	0.05
Sensitivity per beam (Jy $s^{1/2}$)	0.24	0.34	0.24	0.30	0.38	0.07

The first instrument has five feed-horns: two for 11-13 GHz, two for 17-19 GHz and one for 30 GHz. A view of the focal plane array is in Fig. 2.

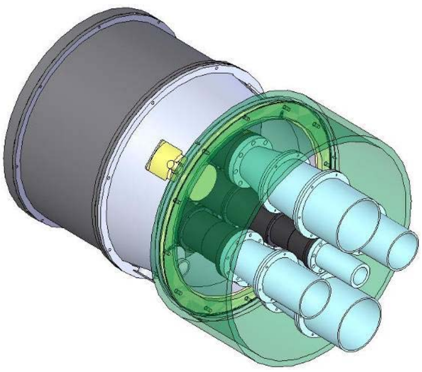


Fig. 2. First Instrument focal plane array.

III. Polar Modulator

Earlier designs of polar modulator have included rotating grids held at λ /4 over reflecting plates such as in the COFE/B-machine [4]. This leads to a complicated optical arrangement and has until recently been narrow band (< 20%). Recent designs of dielectric half-wave plates [5] which are transmission rather than reflection based have produced very low loss and wide band designs.

The polar modulator designed for QUIJOTE is made from waveguide components. The advantage of this is that it can be made smaller than a grid or dielectric modulator and thus can be spun faster and therefore can be used in radiometers that suffer significant 1/f noise. It is also inserted into the radiometer circuit after the feedhorn. This means that effectively the feedhorn defines the level of cross-polarization of the optical assembly rather than the modulator.

If the modulator rotation frequency is high enough then the polar cycle is faster than the low frequency gain fluctuations and hence its effect is eliminated from the output signal. In the presented configuration the angular positions are repeated four times per turn, therefore the polar cycle is four times the rotation frequency. Since the polar modulators can be rotated at a frequency in the 10 – 40 Hz range then the limit for the knee frequency of the receiver 1/f noise is set to f_{knee} < 160 Hz.

The polar modulator has been originally designed for the WR75 (10 - 15 GHz) band and then successfully scaled to the WR51 (14.5 – 22 GHz) band and the WR28 (26.5 – 40 GHz) band. Picture on Fig. 3 depicts the relative size of three units according to their frequency bands.

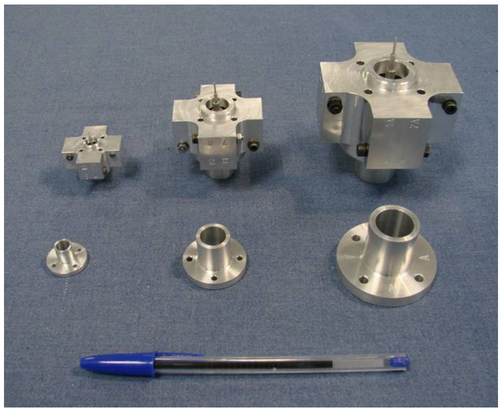


Fig. 3. From right to left: polar modulators at 10-15, 14-22 and 26-40 GHz

IV. Orthomode Transducer

The OMT is an important component in the polarimeter since it separates linear orthogonal polar components and therefore sets a limit on the cross-polarization. The OMT designed for this radiometer is based on the turnstile junction. The scatterer used in the turnstile junction is designed as a four-step cylindrical structure. It is machined separately and then screwed on to the OMT body to obtain a good electrical contact. It is a single unit which can be easily interchanged to provide bandwidth tuning. The structure of the OMT is in Fig. 4.

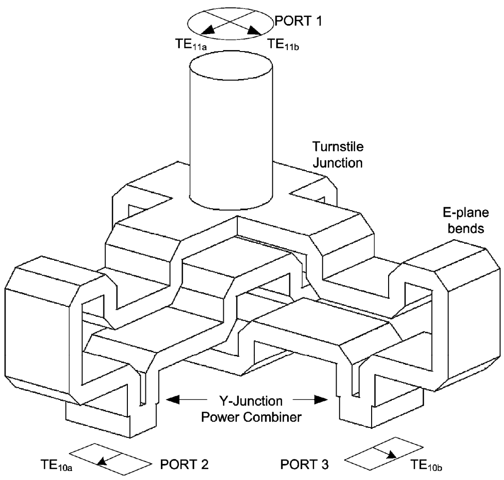


Fig. 4. Orthomode transducer structure

Single mitered E-plane bends and single-step power dividers in reduced height waveguides (a = 4b) are used in this OMT to improve bandwidth, phase equality and return losses by carefully avoiding high order mode propagation. To achieve phase matched outputs special care has been taken during mechanical design to maintain symmetry in both arms of the structure as well as to provide outputs in the same physical plane to help the receiver design [6]. An internal view of the OMT is shown in Fig. 5.

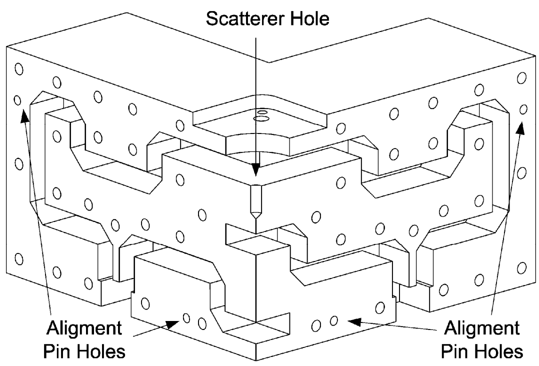
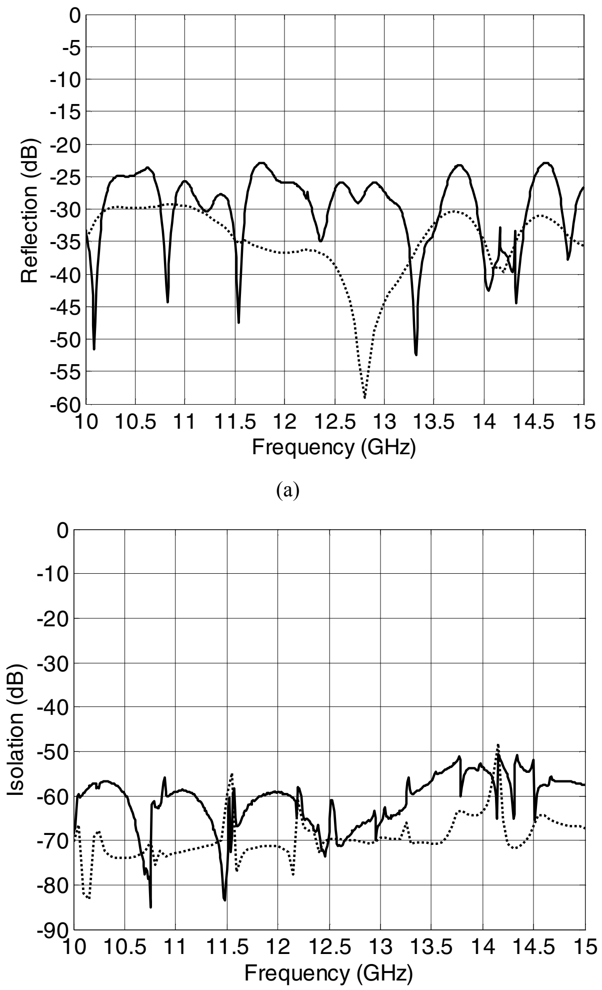


Fig. 5 Internal view of the OMT

This OMT structure has provided very good results in terms of return loss, insertion loss, isolation and phase balance. Some results for the 10-15 GHz OMT are in Fig. 6.

Experimental results for the 10-15 GHz OMT have given: insertion loss < 0.06 dB, return loss > 23 dB, isolation > 50 dB, phase unbalance between rectangular outputs < 0.7º. The structure is fully scalable and three different units have been manufactured for the WR75, WR51 and WR28 bands with similar test results. A picture of the three units is in Fig. 7.



(a)

(b)

Fig. 6. OMT tests: (a) Input return loss, (b) Isolation between output ports. 3D EM simulation (HFSS) results are presented in dashed line whereas measurement results are plotted with solid line.

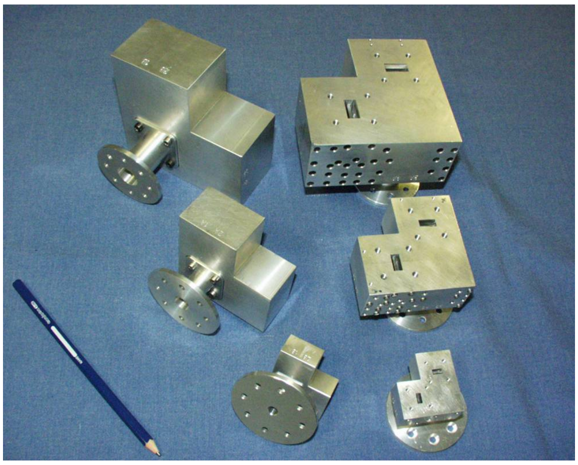


Fig. 7. From top to bottom: OMT units at 10-15, 14-22 and 26-40 GHz.

V. CRYOGENIC LOW NOISE AMPLIFIERS

The high sensitivity of the receivers is achieved with the front-end cryogenic LNA. Insertion gain and noise temperature plots of an amplifier for 26-36 GHz band are depicted in Fig. 8.

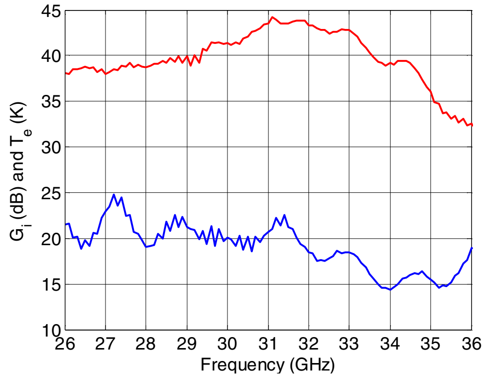


Fig. 8. Insertion gain (red line) and noise temperature (blue line) of a cryogenic LNA for 26-36 GHz band.

The good noise results presented in Fig. 8 are achieved using InP HEMT technology [7] at an ambient temperature of 15 K. This LNA requires 56 mW of power consumption. Typical equivalent noise temperatures of LNA units are about 10 K in the low frequency channels and about 20 K for the highest frequency channel as shown in Fig. 8.

VI. BACK END MODULES

Back-End modules (BEM) provide further amplification and fix the bandwidth of each channel by band pass filters. Microwave signals are converted to DC with broadband Schottky diode detectors working as quadratic law converters. The scheme of the designed BEM for the 26 – 36 GHz channel is presented in Fig. 9 which is based in [8]. This BEM is slightly different to the scheme presented in Fig. 1 since it does not use power splitters and the hybrid.

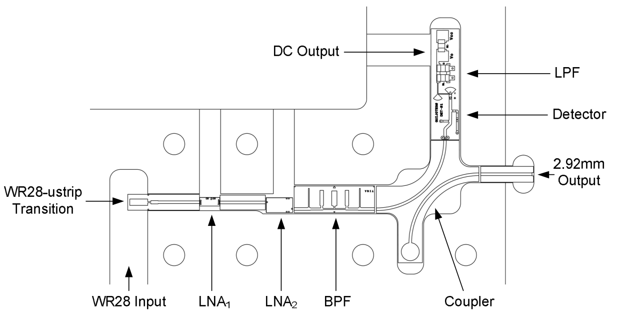


Fig. 9. Scheme of the designed BEM for the 26 – 36 GHz band. The incoming signal is amplified, filtered and detected. The coupler provides a sample of the RF signal.

This BEM uses commercially available MMIC LNA chips to provide adequate RF signal levels. The RF to DC conversion response for an input signal frequency sweep with P_{in} = -53 dBm (expected incoming power) is presented in Fig. 10.

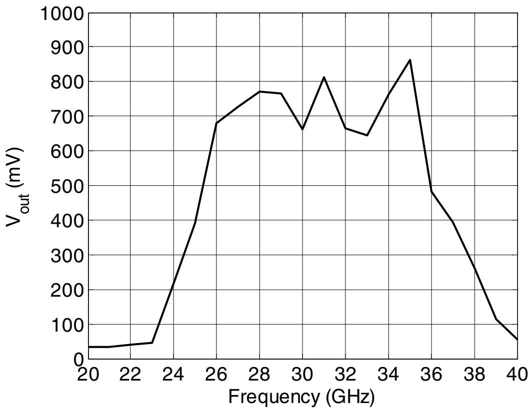


Fig. 10. DC output voltage vs. frequency.

The designed BEM for the highest frequency band provides around 32 dB gain in the band with 10 dB return loss and a noise figure below 3.5 dB in the whole band. The output voltage presented in Fig. 10 is measured after a DC amplifier that provides suitable levels for the post-processing stage. From Fig. 10 the BEM effective bandwidth is calculated obtaining 13.1 GHz.

VII. CONCLUSIONS

The high sensitivity receivers of an experiment to measure the Cosmic Microwave Background polarization from 11 to 36 GHz have been described. Main test results of passive and active subsystems are presented. Their performances are in accordance with the system specifications.

ACKNOWLEDGMENT

This work has been funded by the Ministerio de Educación y Ciencia (Spain) under Astronomy and Astrophysics program, reference AYA2007-68058-C03.

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