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An Ultra Low Noise Cryogenic 70 GHz Wide Band Continuous Comparator Receiver

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Abstract

Elegant Breadboard Model of an ultra low noise 70 GHz continuous comparator total power radiometer with 20 % frequency bandwidth has been built for the ESA Planck Mission. Over 35 dB gain in the Front-End Module (FEM) was measured and an average 30 K noise temperature has been reached at 20 K physical temperature. This continuous comparison receiver is based on use of a structure of similar to a balanced amplifier in the FEM. In addition to this, phase shifters are placed between the FEM hybrids to facilitate DPDT-switching capability. The switching capability is used to remove $1/f$ noise at the Back-End Module (BEM) amplifier chain. The switching rate is 1 kHz. A 20 dB isolation between the signal and reference channel has been obtained at 20 K physical temperature. The FEM LNAs are based on state-of-the-art InP HEMTs processed at NGST (ex. TRW). A Back-End Module (BEM) having 20 dB RF gain and 20 dB post detection voltage gain have also been build and measured with FEM cooled to cryogenic temperature.

Keywords: mm-wave receiver, cryogenic, Planck mission

1. INTRODUCTION

The ESA Planck mission will be launched in 2007. The purpose is to map the Cosmic Microwave Background (CMB) twice, over the complete sky during its planned one year operational lifetime. Planck has two instruments: Low Frequency Instruments (LFI) and High Frequency Instruments (HFI). The LFI will have multipixel radiometer receiver channels at 30, 44 and 70 GHz. The number of dual polarized receiving horn antennas will be 2, 3 and 6, respectively. The HFI will have six channels and a total of 48 bolometer receivers covering 100 – 850 GHz frequency range, operating at 0.1 K. The LFI is cooled to a 20 K physical temperature to minimize additional noise from the InP HEMT LNAs in the receiver FEM. [1,2]

Many InP HEMT based mm-wave receivers have been recently built e.g. [3,4,5]. These receivers have been found to have a high $1/f$ -knee frequency, because of InP HEMT LNA gain variations. The $1/f$ -knee frequency can be minimized by using continuous comparator receiver technique [6,7,8]. The recently launched MAP satellite has such receivers, where phase comparison is performed within the room temperature receiver back ends assemblies, this design requiring phase-matched waveguide between cooled front-end and back-end assemblies. Within the Planck satellite receivers the cooled front-end receivers contain LNA's and phase shifters and use non-phase matched waveguides between front- and back-ends. A block diagram of the EBB receiver is shown in Fig. 1.

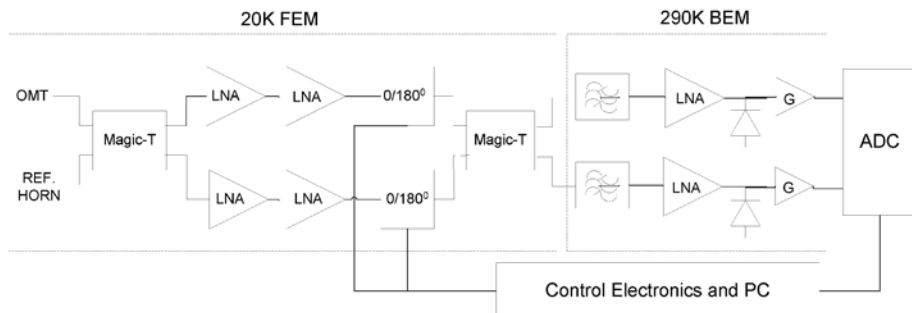


Fig. 1. A block diagram of the Planck mission 70 GHz Elegant BreadBoard (EBB) receiver i.e. half of the two polarization receiver.

2. RECEIVER DESIGN

The FEM operational requirements are 35 dB small signal gain, over the 20 % frequency bandwidth at 70 GHz center frequency, 25.7 K noise temperature at 20 K physical temperature and 20 dB isolation between different phase switching states. Given envelope for the FEM is 45.1mm x 28.7mm x 15mm for one polarization and maximum power consumption is 20.8 mW. The required RF and video gain in the BEM are 20 dB while the maximum noise temperature should be 450 K. Maximum power-consumption for the BEM is 160 mW and given envelope 15 mm x 30 mm x 90 mm. The total radiometer sensitivity $\Delta T/T$ should be better than $16.9 \cdot 10^{-6}$ and maximum 1/f-knee frequency less than 50 mHz. The EBB FEM as formed from two same kind of pieces shown in Fig. 2. The EBB BEM contains both two channels in one mechanical structure and the other half is used in the EBB tests.

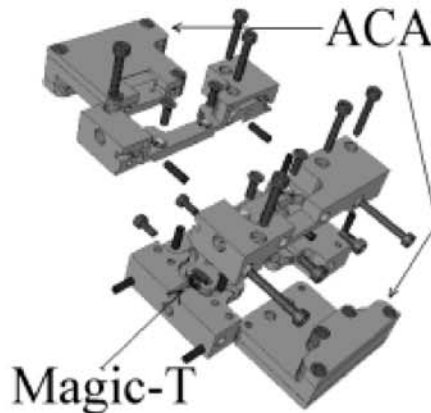


Figure 2. One half of the FEM structure.

The FEM was designed to have identical pairs of Amplifier Chain Assemblies (ACA) allowing maximum flexibility in manufacturing and integration, especially when selecting pairs with similar performance. The final ACA design is shown in Fig. 3. In the ACA the bias voltages are transmitted through small feed-throughs (Thunderline TL-1597-03) for active parts from the backside bias protection circuit. The 0.1 mm thick Alumina substrates between MMICs have been manufactured by Ultrasource co. and the physical size is same as possible needed attenuators between active parts to improve internal matching. The selected bias connector is Nanonics NDDP9S-UGN-150N.

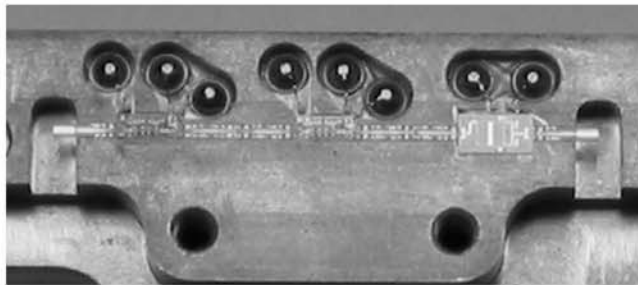


Fig. 3. FEM ACA without a lid. The first two MMICs are LNAs and the third is phase shifter.

The InP HEMT LNAs have been selected to be manufactured using the NGST (ex TRW) 0.1 μm gate length InP process. More detail design is presented in [2]. Some of the LNAs were on-wafer tested individually at cryogenic temperatures and selected designs (CRYO4 70LNA4B) were mounted to WR-15 packages to test individual packages LNAs at 20 K temperature. The LNAs had 20-25 K noise temperature at 20K physical temperature and 20-25dB gain while the power consumption was 10-15mW. The phase shifters are InP PIN-diode based 0-180° phase shifters and they were tested on wafer having less than 2 dB loss and 4° phase error.

The WR-12 magic-Ts were simulated to have 20 dB isolation, < 0.5 dB loss and better than -15 dB input match over 20 % operation frequency bandwidth. Waveguide to microstrip transmission lines were also simulated and measured individually. The design of these transitions was based on [9]. Transmission lines were mounted in a WR-12 package for cryogenic testing, showing better than -20 dB input match and about 0.1 dB insertion loss over the operation frequency band. The reference horn was simulated to have 11.1dB gain, <-23 dB side lobes and 30° -3dB half beamwidth. The final horn version with $\lambda/4$ -chokes around the horn aperture was measured to have 11 dB gain, 30° -3dB half beam width and about -30 dB side lobe level and better than -25 dB input match.

The receiver operational bandwidth is limited in the BEM with band-pass H-plane filters and the RF-signal is amplified about 20 dB to be in the square law region of the diode detector. The final filter structure was simulated with HFFS. The frequency responses of measured BEM waveguide filters are shown in Fig. 4.

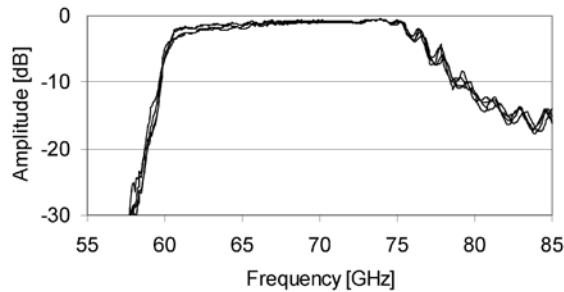


Fig. 4. Measured S_{21} of 6-cavity H-plane WR-12 waveguide BEM filters.

The detector design is based on Agilent HSCH-9161 GaAs Schotky-diodes. The design was chosen to use one diode, although two diode structures could be more sensitive [10]. The design was done with ADS simulator on 0.1 mm Alumina substrate. Diode detectors were measured individually in a split block packages having 630 mV/mW sensitivity at 70 GHz.

Given envelope for the BEM is 15x30x90 mm for four channels with filters, LNAs, detectors, video amplifiers, bias supplies and connectors. The final EBB BEM mechanical structure is shown in Fig. 5. The waveguide filter, LNA-detector module and video amplifiers can be measured individually in the chosen BEM design.

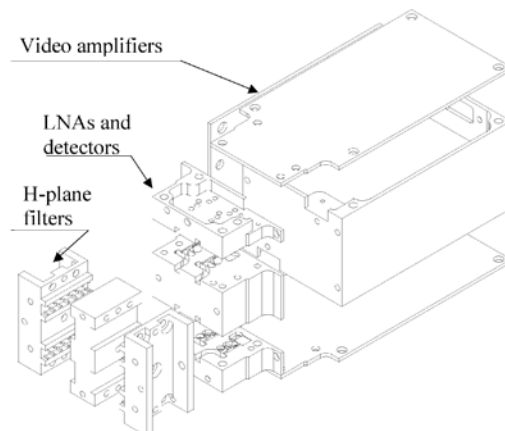


Fig. 5. The final EBB BEM structure.

3. RADIOMETER PERFORMANCE

A Cryogenic Measurement Test System (CMTS) was built for the Planck receiver testing. The CMTS consists of 1.6 m x 1 m x 0.3 m vacuum chamber with 20 K and 4 K closed cycle helium coolers, external electronics to synchronize phase shifters and data collection system and needed monitoring system for bias conditions and temperatures, Fig. 6.



Fig. 6. The CMTS vacuum chamber with radiation shield in the right corner of the chamber.

A 25 dB Temperature Variable Attenuator (TVA) was connected to the OMT channel for the noise measurements. The TVA was cooled to 4 K temperature to simulate the 2.7 K CMB signal. The reference horn was pointing to 4 K absorber load made from Ackard 66 absorber material having reflection coefficient better than -25 dB [11]. The FEM noise measurement was done by heating the TVA to get reasonable Y-factor and the result was compared with external calibrated noise diode results. The S-parameters were measured with HP-8510B and Oleson WR-12 external mm-wave heads. The FEM gain and isolation is shown in Fig. 7.

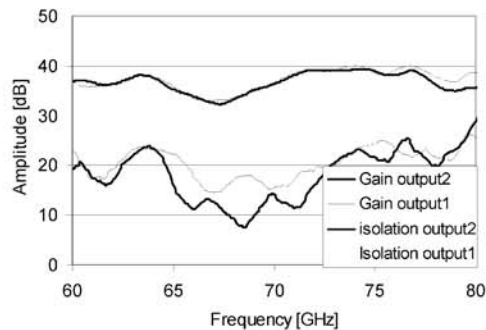


Fig. 7. FEM gain and isolation from the OMT input to the both output in different phase shifter stages.

The receiver bias point was tuned by monitoring one channel gain and noise with HP 8970 B noise test system and then tuning optimum isolation with the second channel. The power consumption in the maximum isolation bias point was 24 mW for the EBB FEM. The FEM noise measurement was done with two separate methods, heating the TVA and with the noise diode. The results with two different methods agreed within +/-5 K accuracy. A typical noise response is shown in Fig. 8.

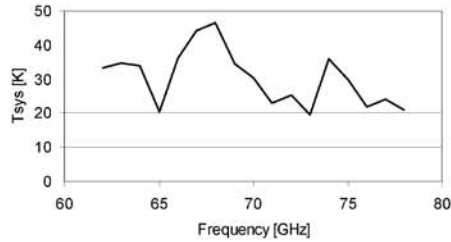


Fig. 8. A typical FEM noise temperature measured with the noise diode.

The frequency dependent sensitivity factor of the radiometer was measured using CW-signal over the operating frequency range and monitoring the output voltage. The sensitivity is shown in Fig. 9.

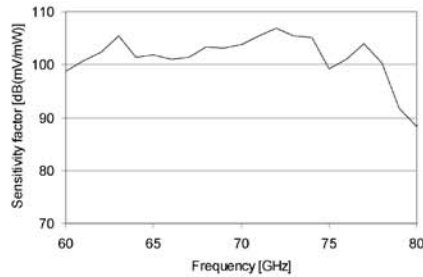


Fig. 9. Radiometer sensitivity factor.

Averaged $1 \cdot 10^{10}$ mV/mW sensitivity factor was reached over the operating bandwidth with complete radiometer i.e. about 2 mV/ μ K with ideal 14 GHz bandwidth.

Radiometer 1/f-noise was measured by switching phase shifters at 1 kHz frequency and measure the output voltage in each phase stages. The output voltage comparison was made in post calculation multiplying the OMT-port signal with calculated r-value. The r-value is division of the OMT 8 K and the reference horn 5 K signals. The time-domain and frequency converted signals are shown in Figs 10 and 11, respectively.

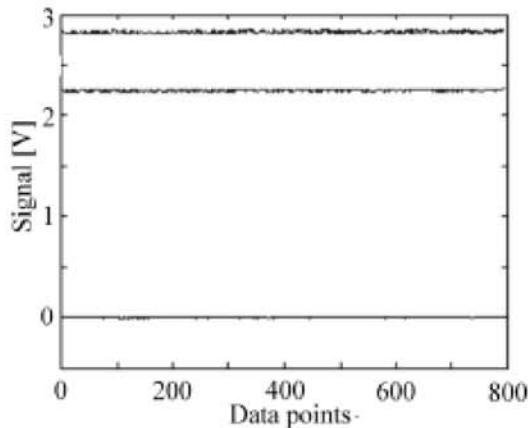


Fig. 10. a) 1/f noise time-domain noise data. The highest line is OMT-signal, middle line is reference horn signal and lowest line is OMT-r*ref ($r=1/0.7945$).

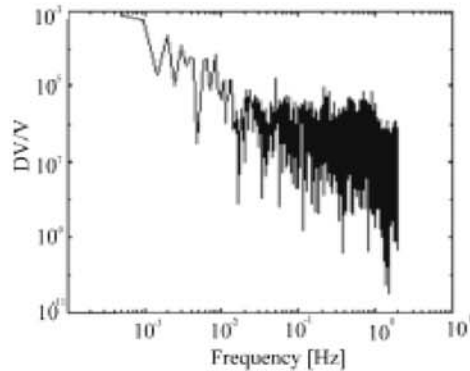


Fig. 11. $\Delta V/V$ PSD of the post calculated data with 0.5s integration time

An ideal $1.69 \cdot 10^{-5}$ $\Delta V/V$ -level ($\Delta V/V = \sqrt{(2/b\tau)}$, $b = 14$ GHz, $\tau = 0.5$ s) is reached about at 25 mHz. It have to be noted that used ideal 14 GHz bandwidth is larger because of BEM filters limits the operational frequency band to about 61-77GHz. Using 0.5 s post integration time and 2 DAC voltage gain in the PSD generation the white noise level ($\Delta V/V$) is averaged to $1.264 \cdot 10^{-5}$ i.e. 17.7 GHz effective bandwidth. Calculated effective bandwidth agrees quite well with measured BEM filter 16.1 GHz bandwidth giving $1.57 \cdot 10^{-5}$ $\Delta V/V$ -level. From the 1/f-noise data the over all radiometer noise temperature was calculated to be 23 K.

4. CONCLUSIONS

A very low noise 70 GHz Elegant Bread Board model receiver for the Planck LFI was built. Averaged $1 \cdot 10^{10}$ mV/mW sensitivity factor for the total radiometer was measured. About 25 mHz 1/f-knee frequency was measured using voltage across diodes sampling technique. A 23 K radiometer noise temperature was calculated from 1/f measurement results and averaged 30 K noise temperature was measured with TVA and noise diode. The difference between measured noise temperatures is believed to be due to slightly different bias point between measurements. The performance of the EBB is very close to all requirements. Still some work is needed to improve the FEM noise temperature, performance flatness of the bandwidth and power consumption.

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