

A Miniaturized Ultra Wide-band Band-pass Filter for the Tenerife Microwave Spectrometer

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Abstract: The QUIJOTE Experiment has been built to study the polarization of the Cosmic Microwave Background (CMB). The study of the CMB provides one of the most powerful tools in modern cosmology. In particular, CMB polarization offers a new window onto the inflationary phase of the Universe, some 10-35 seconds after the Big Bang. Measurement of the CMB spectrum to an accuracy that will reveal interesting science (micro-kelvin variations) is particularly difficult because there are many systematics that lead to effects higher than this level. There are several instruments that have been designed for CMB spectral measurement (FIRAS-COBE, ARCADE, PIXIE). The present plan is to extend the goals of QUIJOTE by building a new and unique microwave spectrometer in the frequency range 10-20 GHz, with the aim of characterizing the spectral signals associated with the reionization epoch and dark ages in the Universe. This document describes the first component for the Tenerife Microwave Spectrometer (TMS), an ultra-wideband bandpass filter (BPF). A filter prototype covering the 10-20 GHz band has been successfully designed, manufactured, and measured in the laboratory to compare results and simulations.

Keywords: Cosmic microwave background, Radio-astronomy, Microwaves, Cosmology, Ultra-wide band, Filters.

1. Introduction

In this section, the TMS is briefly described. Fig. 1 shows the preliminary schematic diagram of a microwave spectrometer for measuring CMB spectra between 10 and 20 GHz. In order to achieve sufficient sensitivity the front end of a radiometer is cooled in a cryostat to 4-10 K. The cryogenic reference load, optomechanics, and ultra-LNAs are cooled by a 4 K closed cycle helium gas cooler and maintained at a constant temperature slightly higher than 4 K by actively heating the cold stage.

The radiometer consists of a pair of feedhorns, one pointed at a cold black body and the other looking out of the cryostat through a transparent window. These

feedhorns are both followed by broad-band 10-20 GHz waveguide OMTs to couple the two linear polarizations. The polar outputs of both sky and load horns are fed to either arm of a radiometer correlator that employs both cold and warm gain and 180° broad-band phase switch to switch the outputs. The correlating elements are 90° hybrid couplers or ridged waveguide hybrid tees. Each correlator contains two similar LNAs with a noise temperature lower than 10 K followed by further amplification and a 180° phase switch in each branch. The phase switches are housed in the BEM. Finally, the load and sky signals are decorrelated in a similar 90° hybrid coupler or ridged waveguide hybrid tee to that of the input. The outputs of these two hybrids are sent to the novel full-

band FT-spectrometers bank. The DC output is amplified and then digitized for post processing in an ADC unit.

Regarding the detector unit, a novel correlator based on a Fourier filter chain is being developed. An elegant and simple three-channel design of a

Reflection Mode Discriminator receiver for IFM has been converted into an innovative wideband autocorrelator for a novel Fourier Transform technique based spectrometer. See reference [8] in order to know more.

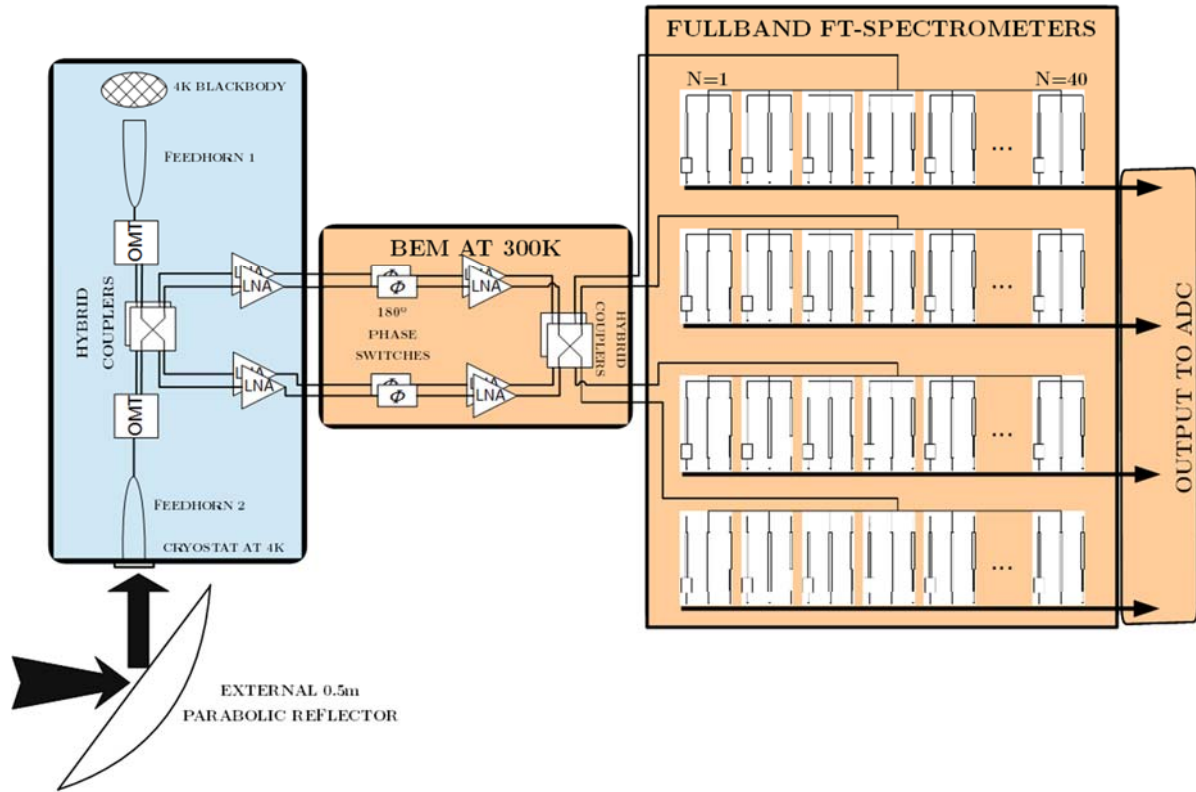


Fig. 1. TMS General Schematic.

In this device, three channels with relative phase-shifts of 0, 120 and 240 degrees produce three signal-output voltages.

Each of the three channels introduces a total path delay in the signal by using delay path length and differential impedance in the transmission lines.

The unit uses square law detectors being able to extract the real voltage signal. In this development, the 75 Ohm resistance is formed by a parallel square law detector (diode+resistor) and since power and voltage are $\pi/2$ shifted, at frequencies where the electric length of a short circuited line is a m multiple of $\lambda/2$ all the input power will be dissipated in the resistor, whereas at n odd multiples of $\lambda/4$ the resistor and there the detector sees no power because of a SWR effect. This situation is inverted for a line finished with an open circuit. This is represented in the Fig. 2.

Regarding the wide band feedhorns, we have developed a new technique based on metamaterials in order to design an innovative meta-rings system, improving the behavior of the corrugated horns in a consistent way.

It can be demonstrated that the surface impedance of a horn walls is the more important characteristic in order to keep the values of cross-polarization levels,

side-lobe levels, return-loss, etc. under reasonable limits for observations in radioastronomy. Thus, our metahorn design is able to give a 2:1 bandwidth factor or more for first time.

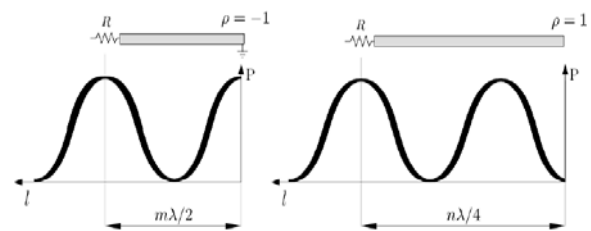


Fig. 2. Power standing wave pattern for a short circuited transmission line (left) and for a transmission line finished in an open circuit (right).

This novel design and its theory can be consulted in the references [9] and [10].

Here, an element to design now is a microwave filter covering the entire band, of the experiment; that is, with a 2:1 bandwidth factor, which is challenging since most microwave filters are designed to cover a few tens or hundreds of megahertz.

In the following sections the given solution is described, leading to an excellent device which satisfies all the system requirements.

2. System Requirements and Designing

In order to satisfy the general requirements of the project, the design specifications are:

- Pass band attenuation: 3.01 dB;
- Stop band attenuation: 40 dB;
- Impedance: 50 Ω ;
- Pass band frequency: 15 GHz;
- Pass band width: 10 GHz;
- Stop band frequency: dependent on the filter order (N) (N < 9 is desirable because of size requirements).

The design of microwave filters has been adequately treated by multiple authors [1]. An ultra-wideband bandpass filter (10 to 20 GHz) will be developed in this project through the use resonant LC circuits, microwave inverters, and both Richard's Transformations [2] in order to convert lumped elements to transmission line sections and Kuroda's Identities [3] to physically separate filter elements by using transmission line sections. A complete treatment of these theoretical transformations can be found by consulting the references indicated at the end of this document.

It is important to note that since there are no commercial devices optimized for the ultra wide 10-20 GHz band, the filter must be designed from scratch for this experiment.

The design will be computer-assisted by CST Microwave Studio Suite®.

Some typical terminated periodic structures (i.e. topologies) for microwave filters have been tested

(*Minimum Segments, Minimum Stubs, Stepped Impedance, Open Stub Resonators, Parallel Edge, Hairpin Resonators*, etc.). Because of the ultra-wide band that is desired for this filter, it has been found that the topology offering the best response is formed by *Shunt Stub Resonators*. This filter topology, with origins commonly attributed to crystals and/or composite filters, uses the resonance properties of the LC circuits in order to make a frequency selection over a received signal, i.e. there exists a resonant frequency at which the inductive and capacitive reactances are equal in magnitude. Therefore, the impedance will be minimal and equal to the ohmic resistance.

A Butterworth type filter (also referred to as a maximally flat magnitude or binomial filter) was designed (using the Insertion-loss IL method) for the 8th order, which optimized the stop band frequency in the range considered. For this, a theoretical circuit was first designed using lumped elements (resistors, capacitors, inductors, etc.) following the theoretical framework published by many authors [1].

This circuit is shown in Fig. 3. It is important to note that the capacitance, impedance, and resistance values shown in Fig. 3 are the consequence of a theoretical design and have not been already optimized. However, the response of the concentrated elements (resistors, capacitors, etc.) is typically not good over wide bandwidths. The elements making up a lumped element system are theoretically concentrated at singular points in space. Therefore, the physical quantities, current and voltage, are functions which depends only on time (and not space). The real filter implementation could now be obtained using Richard's Transformations in order to replace lumped elements with short circuit (S.C.) or open circuit (O.C.) stub transmission lines.

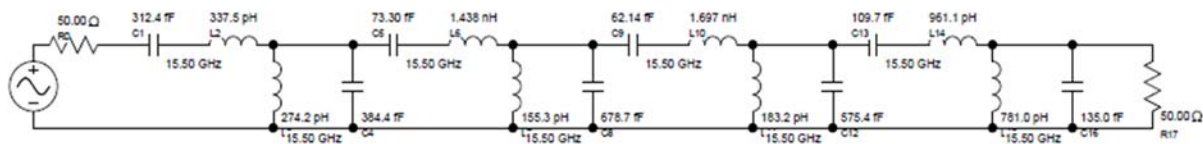


Fig. 3. Theoretical design of 8th order BPF based on lumped elements.

Richard's Transformations transforms frequencies from a ω -domain to a Ω -domain. This is:

$$\Omega = \tan(\beta l) = \tan(\omega l/V_p), \quad (1)$$

where $\beta = 2\pi/l$ and l is the transmission line length. In the Ω -plane, the functions are $\omega l/V_p = 2\pi$ periodic. This transformation synthesizes LC-networks using open-circuited (O.C.) and short-circuited (S.C.) transmission line stubs. Since the transformation ω -domain to a Ω -domain is established, it is possible to affirm that the reactance of an inductor is given by $jX_L = j\Omega L = jL \tan(\beta l)$ and the susceptance of a capacitor is $jB_C = j\Omega C = jC \tan(\beta l)$. This express that

an inductor can be replaced with a short circuited (S.C.) stub transmission line of length βl and impedance equal L , while a lumped capacitor can be replaced with an open circuit (O.C.) transmission line stub of length βl and characteristic impedance $1/C$.

The Kuroda Identities (Fig. 4) then allow us to obtain a more practical filter implementation. A progressive process of design optimization based on simulations and successive improvements is then carried out.

Note that shielding to avoid electromagnetic interactions between stubs and resonances in cavities has been added in the design shown in Fig. 3.

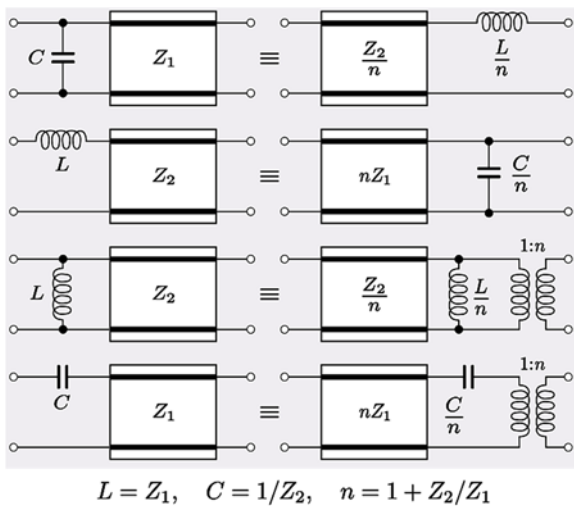


Fig. 4. Kuroda's identities (licensed under the Creative Commons Attribution-ShareAlike 3.0 License. Courtesy Spinningspark at Wikipedia).

3. Prototype Results

The filter was fabricated with an LPKF machine model ProtoMat-S100 on a PCB (Rogers 4003-C) circuit. The objective of the final stage is to compare the simulated model with the manufactured model and the requirements, in case of discrepancies between them, to return to the design stage with the objective of investigating and solving them. Several iterations were necessary. An image of the manufactured filter and the results of the test measurements made on it are shown in Figs. 5 and 6. For the measurements a Keysight model PNA-X N5245A machine was used.

4. Discussion

The preliminary design requirements are successfully satisfied, with an excellent adaptation, correct attenuation in the pass and stop bands and an attenuation better than -10 dB over the entire 10-20 GHz range. Note that, given the design characteristics of the stubs (where the length of the transmission lines is $\lambda/8$ at the cut-off frequency), the response is periodically repeated at intervals of four times the cut-off frequency (Fig. 6).

It has been verified that the results of the software simulation and the measurements on the manufactured filter are reasonably similar. This makes it possible to double-check, on the one hand, by checking that the software is reasonably reliable and, on the other hand, that significant errors have not been made during the manufacturing and assembly phase, with the manufacturing tolerances being within a reliable limit.

With a view to future improvement of the design, a trial with computer-assisted optimization has been carried out, with the result that the filter design would be difficult to improve. This enables us to conclude that the design is excellent, and that the results are difficult to surpass.

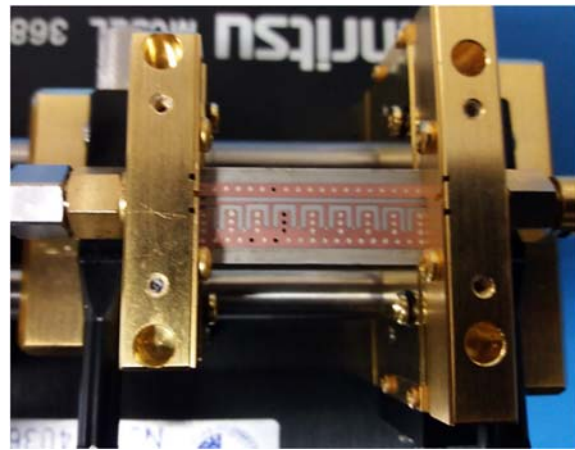


Fig. 5. 8th order BPF prototype while measuring in the laboratory using SMA-port adaptors.

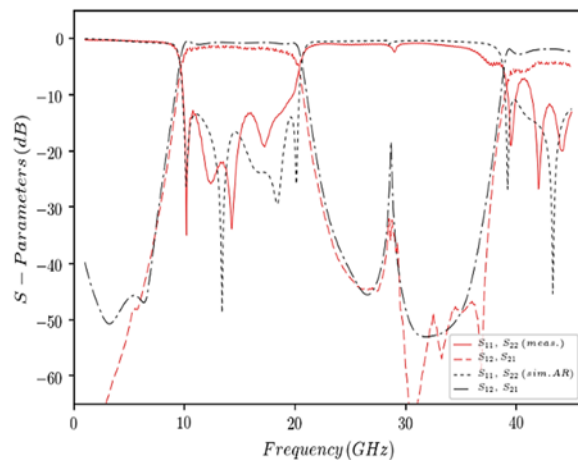


Fig. 6. 8th order BPF results.

A high quality ultra band-pass filter covering the range 10 to 20 GHz was designed and fabricated to meet the technical specifications. This was a technological challenge, since there are not many references to bandpass filters of such a width in frequency, and those that exist do not present such a satisfactory response.

In addition, it is a robust design of astonishing simplicity and very cheap to manufacture, which would allow its replacement in case of damage due to the filter is relatively compact (dimensions 25.6×3.6 mm approximately), so no additional miniaturization is required. This device will be ready to be installed in the spectrometer and efficiently filter the CMB in the desired spectral range.

Acknowledgements


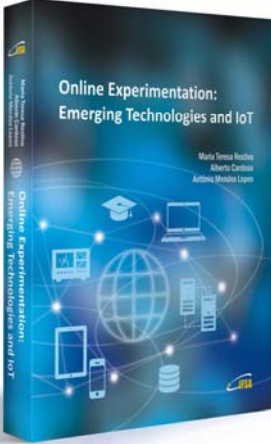
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