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MASTER: A Triple Heterodyne Receiver for Astronomy in the Millimetre and Submillimetre Domain

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Abstract: A progress report of the MASTER project is presented here. MASTER is a system of three heterodyne receivers based on SIS (superconductor–insulator–superconductor) tunnel junction mixers. In our instrument these mixers will allow direct down-conversion from 94, 225, and 345 to 1.5 GHz, the IF where the signal will be detected. This instrument, coupled to a 2–4 m telescope like the one proposed for the DOME C base in Antarctica and in conjunction with an Acusto Optical Spectrometer, can be used to detect emission lines associated with molecular clouds in the interstellar medium. The current status of a 94 GHz receiver, the prototype of MASTER, will be presented too. The study of the optical coupling between the receiver and MITO telescope in the Italian Alps will also be described.

Keywords: instrumentation: detectors — ISM: lines and bands — cosmology: cosmic microwave background — submillimetre

1 Introduction

Above ∼150 GHz heterodyne observation of astronomical sources is hampered by the lack of effective low noise amplifiers, so that the use of low noise mixers is imperative. In the frequency range 90–150 GHz heterodyne systems using SIS mixers (superconductor–insulator–superconductor) are competitive with systems employing low noise preamplifiers. Above 150 GHz and up to several hundreds of GHz SIS mixers are the only choice for coherent detection, while in the THz domain mixers based on hot-electron bolometer technology are the most promising detectors.

Heterodyne systems down-convert the frequency ν_{in} of the signal to be detected, mixing it with a signal from a local oscillator (LO) at frequency ν_{LO} and selecting with a filter the signal at the frequency $\nu_{IF} = |\nu_{in} - \nu_{LO}|$. Typical values for the intermediate frequencies (IF) are in the range of $1 \le \nu_{IF} \le 10$ GHz where low noise HEMT amplifiers (Pospieszalski 1992) operating at cryogenic temperatures are commonly available. The back-end of the receiver is designed according to specific applications.

In this paper, we present a progress report on the MASTER project, a collaboration to realise a multi-frequency receiver operating between 90 and 350 GHz. Details of the 94 GHz channel, single frequency prototype of the final receiver are given.

2 The Receiver

In our triple heterodyne receiver system (94, 225, and 345 GHz) (Figure 1) we use a niobium SIS tunnel junction mixer (Nb/Al−AlO$_x$/Nb). Junctions and mixers are built at IEN Galileo Ferraris of Turin (Lacquaniti, Maggi, & Steni 1996). An additional 345 GHz unit has been manufactured for us by the KOSMA laboratory at the Physics Institute of the University of Cologne, Germany.

Radiation from the sky (seen directly or through a telescope) and from the LO is collected by a corrugated horn. The horns, whose apertures are geometrically scaled, feed three independent mixers tuned at 94, 225, and 345 GHz. The three apertures of 26, 11, and 7 mm give identical beams at the three frequencies, with half power beam-widths of approximately 7°. As LOs we use two Gunn oscillators: one tunable between 88 and 100 GHz for the 94 GHz channel, and a second one tunable between 73 and 87.5 GHz coupled with ×3 and ×4 multipliers which will allow us to produce the 225 GHz and the 345 GHz signals respectively. A phase lock system guarantees stability for all three sources. The LO signals reach the horns via a diplexer, a mylar sheet of thickness of the order of 100 μm, reflecting toward the horns a few per cent of the LO power. The optical layout is still a discussion point: the simplest solution would be not to use the three receivers simultaneously (i.e. three windows in three different positions of the dewar); at the moment we consider this is the final solution (as shown in Figure 1), but we are also studying the possibility of using the three receivers simultaneously by illuminating the horns with three different LOs using two more diplexers. Another interesting solution would be the possibility of multiband observations with only one window and cold (77 or 4 K) diplexers in the dewar (this would be almost necessary if we intend to make continuum observations); in this case we would probably need to inject LO signals via a waveguide. The IF signal
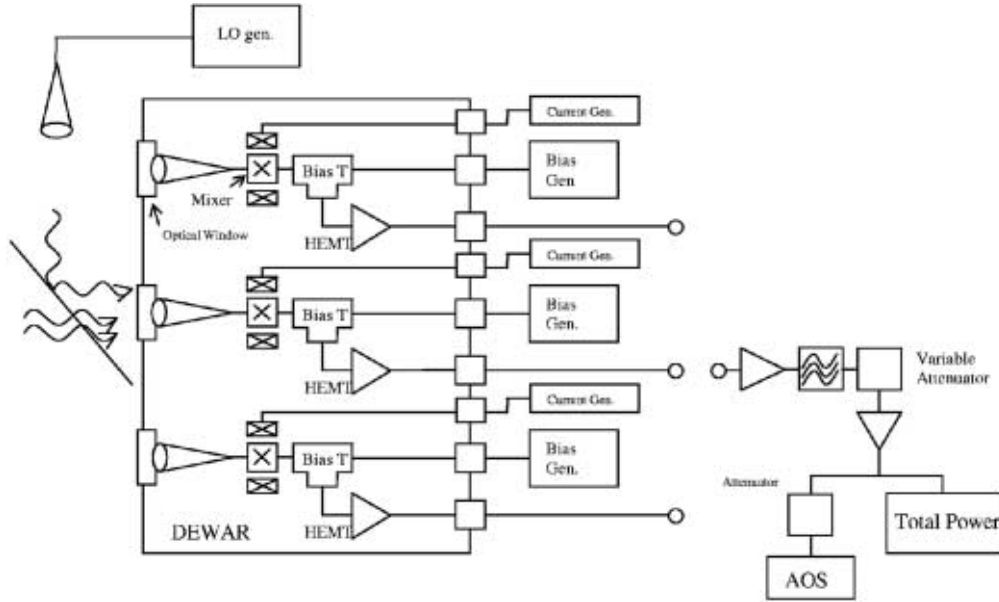
Figure 1 The block diagram of MASTER.

Table 1. The main characteristics of the MASTER receivers

Central frequency (GHz)	94	225	345
IF (GHz)	1.5	1.5	1.5
Inst. bandwidth (GHz)	0.6	0.6	0.6
Estimated DSB T_{sys} (K)	$\simeq$120	$\simeq$140	$\simeq$160
Tuning bandwidth (GHz)	10	20	35

at 1.5 GHz for all three channels is amplified by cryo-genic HEMT amplifiers. In Table 1, system parameters are presented. Here the central frequencies are 'nominal' frequencies. Adjusting the LO the central frequency can be moved inside the tuning bandwidth.

Cryogenic temperatures are needed to guarantee super-conduction on Nb ($T_c = 9.25$ K) and to reduce electronic noise of the receiver. A standard nitrogen–helium dewar to be transformed into a hybrid configuration (cryocooler + liquid helium in order to increase holding time) is used. We are also studying the possibility of using a closed cycle liq-uid helium system, in order to be operative in sites where cryogen availability is difficult. Whatever cooling system is adopted, it cools horns, mixers, and the first IF stage (see Figure 1). All these components are inside a vacuum chamber with vacuum windows in front of the horns made of high density polyethylene (HDPE) followed by quartz powder low-pass filters to cut the IR heat load. For the cali-bration of the system, we have a cold load and a warm load. The cold load is a disc of *Eccosorb AN-72* placed inside the dewar at intermediate temperature (in the nitrogen–helium dewar it is anchored to the 77 K bath), seen by the horns via ellipsoidal mirrors (see Figure 4). The warm load is a similar disc at room temperature. A chopper lets the receiver look alternatively at the sky and the cold and warm reference loads when the calibration procedure is implemented. The back-end of the receiver, common to the three channels, is an acousto-optical spectrometer with


Figure 2 The cold plate of the 94 GHz prototype. From right to left it is possible to see the HEMT amplifier, the feed horn, the mixer housing with the bias tee, the back-short micrometer, and the coils to suppress the Josephson current.

an intrinsic wide band of ~2 GHz for spectroscopy (limi-ted in our system by a band-pass filter 0.6 GHz wide on the IF chain) and a total power channel for continuum measurements.

3 The 94 GHz Prototype

A 94 GHz receiver prototype for MASTER is in the final stage of assembly and in the next few months will undergo extensive tests. The front-end is inside a standard liq-uid He/N$_2$ *INFRARED LABS* dewar (see Figure 2). The waveguide mixer, manufactured by IEN Galileo Ferraris
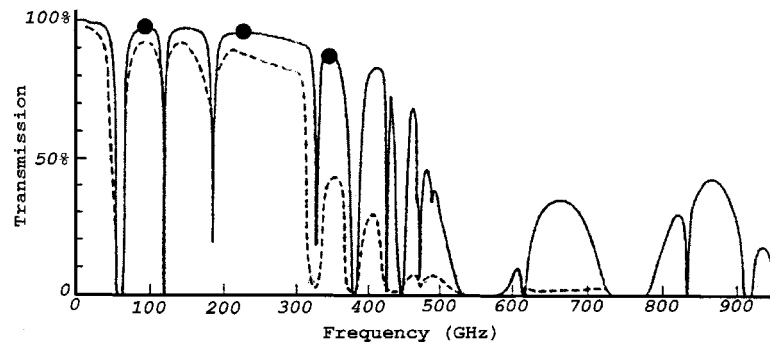
Figure 3 The atmospheric transparency calculated at intermediate latitude at MITO (De Petris et al. 1996) conditions. Solid and dashed lines are for 1 and 4 mm of precipitable water vapour respectively. The black spots indicate the MASTER frequencies, centred on three atmospheric windows.

of Turin, Italy (Lacquaniti et al. 1996), is fed by a corrugated horn identical to the MASTER one and has a tunable back-short for impedance adjustment. A magnetic field parallel to the junction plane necessary to suppress the Josephson current is created by a pair of superconducting niobium Helmoltz coils. The IF output, amplified by a HEMT amplifier cooled at 4 K by the helium bath, is processed as indicated in the block diagram of Figure 1. With this prototype we'll be able to validate the process of fabrication of the junctions and mixers and we will verify the performance of the back-end unit.

4 Observation Sites

At millimetre and submillimetre wavelengths, observation sites play an important role. Since water vapour is the dominant source of opacity at these wavelengths, dry high altitude sites are needed in order to achieve high sensitivity observations (Figure 3). The 225 GHz channel of MASTER, being near an atmospheric absorption line, will be used for transparency site testing (Masson 1994) also.

First measurements with MASTER will be taken using the 2.6 m MITO telescope at Testagrigia Observatory in the Italian Alps, 3480 m above sea level (De Petris et al. 1996). The very easy access and good atmospheric conditions (in winter precipitable water vapour can be as low as 0.3 mm) make it a perfect site to test the receiver and to start measurements of galactic molecular lines. The atmospheric transmission in Figure 3 has been calculated considering MITO characteristics at 1 and 4 mm precipitable water vapour (Liebe 1985). Extremely good atmospheric conditions can be found on the Antarctic Plateau. The results obtained by the *AST/RO* telescope (Stark et al. 2001) at the Amundsen–Scott base at the South Pole is an example of the potentiality of the Antarctic site even with small aperture (1.7 m) dishes. An even better site will be Dome C, due to its higher elevation (3233 m above sea level) and intrinsic atmospheric stability (for a discussion see Valenziano & dall'Oglio 1999 and Hidas et al. 2000). Proposals for a 2–4 m class millimetre and submillimetre telescope to be installed at Dome C are under evaluation.

5 Optical Coupling

5.1 Introduction

To increase optical efficiency and spatial resolution, the receiver must be coupled to a large telescope, usually with Cassegrain or Gregorian configuration. Careful study of the coupling is very important. At millimetre and submillimetre wavelengths we have beams and optical elements whose dimensions are close to these wavelengths, therefore the rules of geometrical optics do not apply and diffraction phenomena are important. However, pure electromagnetic analysis is extremely complex and time consuming. We used therefore Gaussian beam analysis which gives wavelength dependent corrections to geometrical optics and reduces to it in the case when the wavelength goes to zero. In Gaussian beam analysis, a propagating beam is thus characterised by the waist radius w (the distance from the propagation axis at which the electric field drops to $1/e$ of its maximum) and by the equiphase surface of curvature radius R. In our analysis we took advantage of the reciprocity theorem and we used both backward and forward propagation.

5.2 Beam Transformation and Coupling Efficiency Test

The coupling of the emission of the LO and loads with the input feed horn has been performed by following the method presented in Goldsmith (1998). The field power coupling has been studied by the coefficient

$$K = 4\left[\left(\frac{w_b}{w_a} + \frac{w_a}{w_b}\right)^2 + \left(\frac{\pi w_a w_b}{\lambda}\right)^2 \left(\frac{1}{R_b} - \frac{1}{R_a}\right)^2\right]^{-1}$$

(1)

where w_a, w_b, R_a, and R_b are the waist radii and the curvature radii of the two propagating beams in forward and backward directions.

To couple the receiver's input and the telescope, assuming a Cassegrain configuration like MITOs, we have propagated the beam originating at the receiver to the antenna and imposed its curvature radius, over the subreflector, to be equal to the distance between the mirror
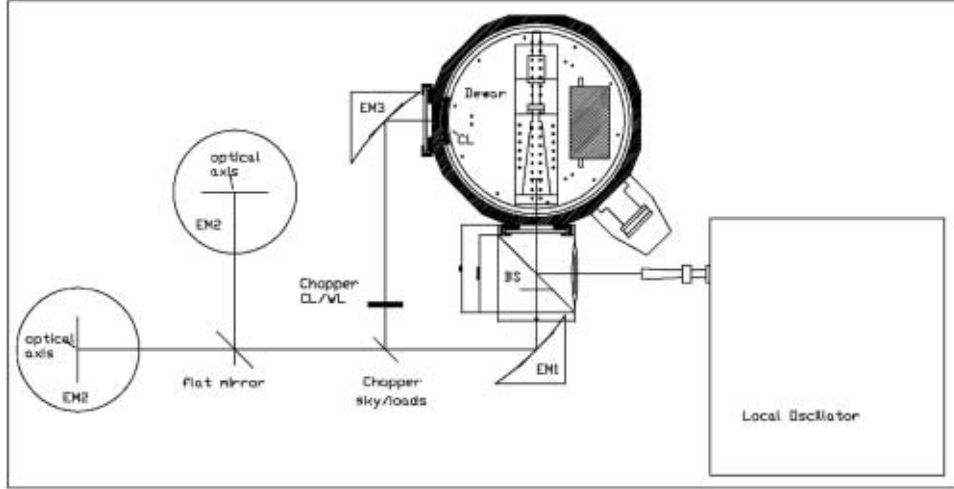
Figure 4 Layout of the optical configuration of the 94 GHz receiver prototype for MASTER. The LO is injected into the horn by means of a beam splitter and a lens placed in the same structure as the beam splitter. The radiation from the sky reaches the horn via ellipsoidal mirrors EM1 and EM2 (which can be placed in two different positions). The radiation from the loads (cold/warm) gets to the horn via ellipsoidal mirrors EM1 and EM3. The cold load is anchored to the 77 K shield of the dewar and the warm load is placed on a chopper wheel. A second chopper wheel allow us to switch or chop between the sky and the loads.

and the Cassegrain focus. The system aperture efficiency $\epsilon_a = \epsilon_t \epsilon_s \epsilon_{bl}$ which combines the taper efficiency ϵ_t (fractional coupling over the antenna), the spillover efficiency ϵ_s (fraction of feed power intercepted by the antenna), and the blockage efficiency ϵ_{bl} (efficiency reduction due to central obstruction) is

$$\epsilon_a = 2\alpha^{-1}[\exp(-f_b^2\alpha) - \exp(-\alpha)]^2 \qquad (2)$$

where $\alpha = R_s/w_s$ is the ratio of the subreflector radius and the waist radius, and $f_b = d_2/d_1$ is the primary mirror diameter to secondary mirror diameter ratio, i.e. the fraction of the primary mirror obscured by the secondary mirror in a Cassegrain configured telescope.

Couplings evaluated in this way are wavelength dependent.

5.3 Frequency Independence

Among the infinite possible solutions, a frequency independent coupling between two beams is always possible (from the mathematical point of view) if one uses a focusing element (for instance a lens or an ellipsoidal mirror). This can be obtained by following the method presented in Chu (1983) and solving the system of equations

$$\begin{cases} \frac{l_1}{w_a} = \frac{l_2}{w_b} \\ \frac{1}{R_b} = \left[1 + \frac{l_1}{l_2}(1 + \frac{l_1}{R_a})\right]\frac{1}{l_2} \\ \frac{1}{f} = \frac{1}{l_1} + \frac{1}{l_2} \end{cases} \qquad (3)$$

where w_a and R_a are the waist radius and the curvature radius of the beam that we have on one side of the lens, w_b and R_b are the waist radius and the curvature radius of the beam we want to get on the other side of the lens, and l_1, l_2, and f, unknown quantities, are the distance from the waist radius w_a and the lens, the distance from the waist radius w_b and the lens, and the focal length of the lens.

5.4 94 GHz Receiver's Optical Configuration

5.4.1 94 GHz Receiver Coupling to the MITO Telescope

We have studied a frequency independent configuration for the coupling between the 94 GHz receiver and the MITO telescope in the Italian Alps. The MITO telescope is a 2.6 m Cassegrain configuration antenna (De Petris et al. 1996), with a secondary wobbling mirror.

We used ellipsoidal mirrors instead of lenses because they do not absorb and are optically equivalent considering their focusing properties. Taking into account the physical sizes of the cryostat containing the receiver, we set l_2, the distance between the Cassegrain focus and the mirror, to 1800 mm. This constraint forced us to use two mirrors instead of one in order to recover one degree of freedom in the optical design.

Moreover, we set the curvature radius ($R_s = 1480$ mm) of the beam over the subreflector and the waist radius ($w_s = 170.29$ mm). This last condition corresponds to a taper of $T[dB] = 8.686(R_s/w_s)^2 = 9.9\,dB$ (i.e. the value at which the efficiency ϵ_a has the maximum value of 0.7). The optical layout is shown in Figure 4.

When deep integrations on celestial sources are performed, the sky/loads chopper is stopped, while synchronous detection is allowed through the wobbling secondary.

5.4.2 94 GHz Receiver Coupling to Calibrators and Local Oscillator

We realised a calibration system using cold and warm loads, to evaluate the performance of both the receiver and the sky signal. The cold load is anchored to the 77 K shield of the dewar and is illuminated by a flat folding mirror located between the first and second ellipsoidal mirror. A third ellipsoidal mirror refocuses the beam.

The warm load (at room temperature) is placed on a second chopper wheel in the position where the beam waist will fall.

In coupling loads emission with the receivers, we assumed, in the position where the loads are, that the Gaussian beam has infinite curvature radius and waist equal to the disc (loads) radius.

The two choppers can be used simultaneously with two (very) different chopping frequencies.

A lens couples the system horn and the LO horn. The beam splitter is at 45 mm from both the input receiver's window and the lens in front of the LO (see Figure 4).

For room problems, we couldn't arrange the components to get a frequency independent configuration when coupling the LO and the input horn. As a matter of fact, the field power coupling coefficient K for the coupling between the loads and the input feed horn is 0.999 at 84 GHz, 1 at 94 GHz, and 0.999 at 104 GHz, while for the coupling between the LO and the input feed horn K is 0.989 at 84 GHz, 1 at 94 GHz, and 0.991 at 104 GHz.

6 Astrophysical Observations

The main scientific goal of MASTER will be the observation of emission lines associated with molecular and atomic hyperfine transitions in the millimetre and submillimetre domain. An extensive database of lines of astrophysical interest can be found in the literature (e.g. the Cologne Database for Molecular Spectroscopy[1] or the JPL Molecular Spectroscopy group[2]). We will begin studying lines from CO, the second most abundant molecule in the Universe which can be used as a tracer of H_2: the rotational transition $J : 2 \to 1$ is at 230.538 GHz, while the transition $J : 3 \to 2$ is at 345.805 GHz. There are also lines of SO_2 at 221.965 GHz and CS at 92.500 GHz. These are just examples from the huge number of lines which can be studied in nearby molecular clouds like Orion and DR 21. Their analysis can give precious information about the chemical evolution of matter in our Galaxy.

When very large collecting areas are available, another possibility for MASTER is the measurement of the cosmic microwave background (CMB) temperature at redshift $z > 0$ (i.e. $2 \le z \le 3$), carried out by evaluating the excitation temperature of elements like CI in galaxies with $2 \le z \le 3$. By measuring the relative abundance of two excited states of CI it is possible to work out the temperature of the electromagnetic field responsible for the populations (CMB). Dependence of T_{CMB} with redshift z of the form $T(z) = T(0)(1 + z)$ can be confirmed.

Even if the relative narrowness of the instantaneous bandwidth doesn't make MASTER an optimal receiver for continuum observations, this triple heterodyne receiver could also be used to study the Sunyaev–Zeldovich (S–Z) effect (Sunyaev & Zeldovich 1972). Inverse Compton scattering between a hot electron gas in a cluster of galaxies and CMB photons decreases CMB intensity in the Rayleigh–Jeans spectral region (below $\sim$220 GHz) and increases it in Wien's, while the effect is null around 218 GHz. The three frequencies of MASTER, being centred on the negative, null, and positive regions of the S–Z effect, enable us to try to detect it. Studies of the S–Z effect in large clusters like Coma will be possible when MASTER is attached to the MITO telescope.

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