Etude d’un récepteur SIS hétérodyne multi-pixels double polarisation à 3mm de longueur d’onde pour le télescope de Pico Veleta

Study of a dual polarization SIS heterodyne receiver array for the 3mm band of the Pico Veleta telescope


*IRAM (Institut de Radio Astronomie Millimétrique), 300 rue de la piscine, 38400 Saint Martin d’Hères, France

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Abstract

A 3mm band focal plane array heterodyne receiver is being developed for Nasmyth focus of the IRAM the 30-m Pico Veleta Radio Telescope located in the Sierra Nevada Mountains, south of Spain. This receiver will comprise 25 dual linear polarization pixels operating across the 80-116GHz nominal band. Design efforts are being made to enlarge the band to cover the full 3mm atmospheric transmission window available at Pico Veleta, i.e. 70-116GHz. The instrument will be coupled to the Pico Veleta Telescope via a purely reflective low-loss optical system that includes a de-rotator. The receiver will be based on 5 x 5 cryogenically cooled dual-linear polarized feedhorns cascaded with orthomode transducers (OMT) and side band separating (2SB) SIS mixers, a technology which offers state-of-the-art performances already used in other IRAM receivers.

Introduction

In the framework of the development of a new generation of heterodyne receivers for the Pico Veleta 30-m Radio Telescope, IRAM is designing a heterodyne receiver array of 25 pixels, dual polarization, operating in the 3mm atmospheric transmission window. This new instrument will offer new science capabilities for the 30-m which will largely enhance the mapping speed of extended astronomical sources both for spectral line and continuum observations.

The main specifications of the receiver are as follow:

- Size and geometry of the array: 5 x 5 pixels per polarization, square arrangement;
- Two orthogonal linear polarizations
- Beam separation on the sky: 2 HPBW (Half Power Beam Width), corresponding to 48 arc second of separation between each pixel
- Operating RF (Radio Frequency) band: 80-116GHz nominal, with possible extension to 70-116GHz to cover the full 3mm atmospheric transmission window (see Figure 1)
- Technology: 2SB SIS mixers
- IF (Intermediate Frequency) band: 4-8GHz or 4-12GHz are possible
- SSB noise temperature goal: < 50K for each pixel
- De-rotator to track the parallactic angle
- Electronically tunable local oscillator based on YIG oscillator cascaded with active multiplier chain and millimetre power amplifiers
1. Technical study of the receiver

During the on-going design phase, the goal is to ensure optimal performances in terms of sensitivity by providing noise temperature for each pixel close that of state-of-the-art single pixel receivers. This is achieved by minimizing the optics losses and the RF signal paths through the waveguide components. Also, the design is addressing the problem of assembly and disassembly (required for repair) of the various parts. A modular design is adopted to simplify the receiver construction. The main efforts are focused on the RF, cryogenic and quasi-optical parts of the system.

The RF module arrangement optimises the local oscillator distribution, the easiness of receiver prototyping and manufacture and the system maintenance when the receiver will be in operation at the telescope.

Limited space is available in the telescope receiver cabin, because of the various instruments already installed there. This constrains the location and the design of the receiver, in particular of its room temperature optics. The electromagnetic performances of each component of the RF module (feed horn, OMT, waveguide couplers…) is optimised individually; then the full cascade of components is re-optimised to achieve best performances across 70-116GHz (close to 50% relative bandwidth)

2. Quasi-optical design

The quasi-optical design of the receiver is purely reflective. This allows to avoid the problems of reflection and transmission losses which would be inherent to the use of dielectric lenses, as well as the complexity of considering the behaviour of dielectric materials at cryogenic temperatures (contraction of the material, change in material properties…). A schematic view of the quasi-optical system of the receiver is shown on Figure 2. This optical system ensures the different functions described bellow:
At room temperature, two flat mirrors direct the beam from the sub-reflector, aligned with the telescope optical axis, along the receiver optical axis. One of those mirrors can be removed, when the receiver is not in operation, to allow the use of two other heterodyne instruments, EMIR and HERA [1].

After reflecting from the two mirrors, the 5 x 5 beams enter a de-rotator system. The de-rotator is based on a K-mirror configuration where three mirrors are assembled together and can be rotated around the main receiver optical axis. The de-rotator compensates the rotation of the pixels pattern on the sky during observation; it consists of two external flat mirrors and a central focusing mirror with elliptical profile that images the telescope aperture onto the cryostat window. This allows to limit the window size and therefore to minimize the thermal loads onto the cold stages of the cryostat. The design of the de-rotator is optimised to minimize truncation losses of the beam onto the different mirrors and use a small (38 degrees) reflection angle of the focusing elliptical mirror, to limit the optical aberrations (cross-polarization and beam distortion) due to the use of off-axis curved mirrors.

A second focusing mirror with elliptical profile is located inside the cryostat and thermalized at the physical temperature of 15K. This mirror, together with the elliptical one located at room temperature, forms a Gaussian Beam Telescope (the two mirrors are separated by the sum of their focal lengths) that transforms the beam angular spacing in the sky to an appropriate physical spacing (42mm) between the pixels of the RF module. This spacing value is a compromise between the large value that would be required to optimise the optical performance (which would increases the cryostat size and make the receiver implementation inside the cabin more difficult) and a smaller value, proper of a close packed array, which would be preferable for receiver integration but with degraded optical performance.

Inside the cryostat, a flat mirror cooled at 15K redirect the 25 beams towards the RF module and allows to keep the reflection angle from the 15K focusing mirror to a small value (40 degrees), which reduces the optical aberrations.

At last, an array of 5 x 5 individual optical elements (see Figure 4 and Figure 5) cooled at 4K is connected to the RF module. These individual elements maximize the coupling between the telescope aperture and each feed horn aperture over a broad frequency band. For each pixel, the beam is first reflected from a parabola, then from a flat mirror that redirects it into the feed horn. To allow for a compact reflective optics, double-face mirrors are used: each row of 5 pixels has an array of 5 parabola mirrors on one face and an array of 5 flat mirrors used for the adjacent row of pixels on the other face.
Figure 3: View of the cryogenic RF module. The LO distribution components and SIS mixers for polarization 0 are in blue whereas they are in magenta for polarization 1.

Figure 4: Front (left) and back (right) views of a part of the cryogenic focal plane individual optics showing the beam path for two adjacent pixels on two different rows of the array. The separation between the axis of the two feed horns is 42mm.

Figure 5: Front (left) and back (right) views of one double face mirror used for one five pixels row of the array. The width of the five-pixels row is about 210mm.
3. RF module design

Each pixel of the RF module consists of the following elements: a feed horn, an OMT, two waveguide couplers (one per polarization) to insert the local oscillator signals, and two sideband separating mixers. Only the feed horn and the OMT are discussed with some details here.

Overall, the RF module consists of 25 feed horns, 25 OMTs and 50 sideband separating mixers connected to the OMTs through 10 rows of five-pixel waveguide couplers. Two additional column couplers are also required to distribute the local oscillator power to the different rows of five-pixel couplers (Figure 3).

The electromagnetic design and optimisation of the components discussed in the following sub-sections were performed with the commercial simulation software CST Microwave Studio [2] based on the finite difference time domain (FDTD) method.

3.1. Feed horn

The optical beams propagating in free space are efficiently coupled from corrugated feed horns into circular waveguides. Step-profiled corrugated feed horns are used (see Figure 6) with varying corrugation depth and width in the throat section based on [3]. This variation in the corrugations geometry ensures broadband performances in terms of return loss with low side lobes and low cross-polarisation levels (Figure 7 and Figure 8). The profiled geometry of the horn allows to reduce the beam divergence at the horn output and consequently the truncation level onto the reflecting mirrors of the individual optics.

Figure 6: Full (left) and cut (right) views of the step-profiled corrugated feed horn. The circular waveguide output has a diameter of 2.84mm and the feed length is 72mm.

Figure 7: Simulated return loss of the feed horn.
3.2. Orthomode Transducer (OMT)

The circular waveguide output of the feed horn is connected to the circular waveguide input of OrthoMode Transducer, also called “OMT”. This component is used to diplex the two linear orthogonal polarizations of the receiver. The inner waveguide circuitry of the OMT, based on a turnstile junction design [4], is shown on Figure 9:
Each of the two input polarizations propagating into the 2.84mm diameter circular waveguide as fundamental TE11 orthogonal modes is separated into waveguide sidearms of equal amplitude and 180 degree phase by the turnstile junction. Then each polarization is recombined into a Y junction and outputs the OMT via single-mode rectangular waveguides. As the turnstile junction base, a 3-steps circular stub allows to achieve low input reflection over a broadband. The simulated performances of the OMT are presented on Figure 10. Low input returns loss below –20dB as well as a low cross-polarization level is obtained across 70-116GHz.

**Figure 10: Simulated of input return loss and cross-polarization levels of the OMT.**

Use of the OMT ensures the compactness of the system as only one RF module is required for the two polarizations unlike the case where quasi-optical diplexers are used, for which two different RF modules (one per polarization) would be required. Also, the use of the OMT allows to achieve an almost perfect alignment in the sky between the two receiver polarizations because only one feed horn per dual polarization beam is required. The OMT will be manufactured using conventional numerically controlled milling machine and fabricated in four different mechanical blocks that split along the axis of the circular waveguide input.

### 3.3. Full RF module

A 3D view of the full RF module is shown Figure 3. All the components of the module are cooled at 4K (except the cryogenic HEMT Low noise Amplifiers (LNA) that could be operated at 15K).

The RF module has two local oscillator inputs, one per polarization, that distribute the LO signals to two independent column waveguide couplers. This feature will allow simultaneous observation of an astronomical source at two different frequencies (one per polarization).

For each polarization, the local oscillator power is distributed into five rows of pixels. A column coupler is based on multi-holes broad-wall coupling. The coupling value is different in each coupling region of this component in order to distribute the same local oscillator level to each row of pixels.

The other parts of the RF module consist of identical rows of pixels to facilitate the receiver prototyping and manufacture, as the same row of five pixels is fabricated in five identical copies.

In each row, the local oscillator power is again split in five equal parts to be distributed to each pixel. The “row coupler” are based on a branch line design.

The RF signals from the OMT outputs and the LO signals from the “row couplers” enter then the side band separating SIS mixers (one mixer is used for each pixel and each polarization). Each 2SB mixer is based on DSB (Double Side Band) SIS mixer units based on the principle described in [5].
Inside the side band separating mixer unit, the RF power is split into two parts with equal amplitude and 90 degrees phase difference, while the Local Oscillator power is split into two parts of equal amplitude and 180 degrees phase difference. The RF and LO signals are mixed into one DSB SIS mixer which down convert the RF signal to an intermediate frequency (IF) that could cover 4-12GHz.

Each 2SB unit employs also a 90 degrees hybrid IF coupler that recombines the IF outputs from the two DSB SIS mixer units. At the output of the coupler, the IF signal is amplified by a cryogenically cooled low noise HEMT amplifier (LNA) and is then transported at room temperature where is further amplified and filtered, before is sent to the backends.

The RF module is designed to have all the passive waveguide components (feed horns, OMT and local oscillator couplers) bolted together. The SIS mixers and cryogenic amplifiers can be disconnected by the fixed passive parts to ensure easy swapping and repair.

4. Conclusion

The design of some of the critical parts of the 3mm heterodyne receiver array for the Pico Veleta telescope is nearly complete and the manufacture of the components is under way. The RF module arrangement ensures simplicity of the construction and maintenance of the parts, which is also important as possible upgrades of the receiver are envisaged in the future. The quasi-optical purely reflective design is innovative as it utilizes individual optics array of double face mirrors coupled to broadband corrugated feed horns, and includes a de-rotator system.

5. Bibliography

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