ALMA MEMO #299

A Martin-Puplett Interferometer Side-Band Separation Module for 600 – 720 GHz.

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Abstract

A side-band separation receiver module for the 600 to 720 GHz ALMA band is proposed. The design is based on a cold Martin-Puplett Interferometer (MPI) with reflective optics. The operation principle and design parameters of the module are presented. The MPI SSB module performance with lossless optical components is compared with a DSB module using the same mixer and taking into account an atmospheric model for the 600 to 720 GHz band.

Atmosphere influence in 600 GHz-720 GHz band

The atmospheric transmission and radiation temperature for 0.5 and 1 mm precipitible water vapor (pwv) are shown in Fig. 1. The atmosphere in this band is already very opaque and may result in significant rise of the system noise temperature. Let us consider the narrow spectral line observation. The DSB receiver accepts the atmosphere noise signal with a spectral density of at least 75 K both from the signal and image sidebands. For slightly worse atmospheric conditions this noise level can go up to 130 K. As a consequence a sideband rejection/separation scheme which couples the image sideband of a mixer to a cold blackbody load with temperature lower than 75 K has lower system temperature than a DSB receiver if the loss for the SSB scheme can be kept low.

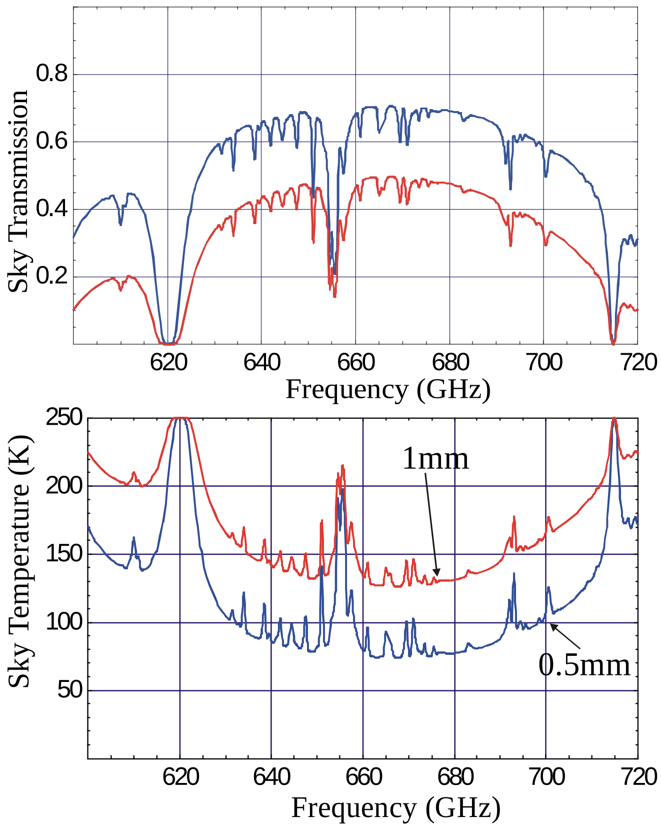

Fig. 1 Atmospheric transmission and radiation temperature for 1 mm and 0.5 mm pwv and 250 K atmosphere temperature

Receiver Module Description

The proposed receiver module is shown in Fig. 2. It consists of two blocks to receive both linear polarizations of the input signal. The grid G1 and additional elliptical mirror M6 are used to split the input signal between the blocks. Each receiver block is shown to have its own LO, however the scheme can be easily modified for a single LO per frequency band.

The receiver block utilizes the classical side-band separation scheme based on a Martin-Puplett Interferometer (MPI). The input signal comes through the polarization separation grid G1 to the elliptical mirror M1 and passes through the MPI input grid G2. The interferometer is formed by two rooftop mirrors M2, M3 and a grid G3. The rooftop mirror M3 is movable and allows to tune the MPI for SSB operation over the whole frequency band. The beam coming to the MPI must have a high F-ratio in order to avoid high loss in the MPI. The signal from the MPI goes to the output grid G4 where upper and lower side bands are separated. The following elliptical mirrors M4, M5 allow to couple the signal to the fixed tuned DSB waveguide mixers.

The Local Oscillator is injected into the MPI via wire grid G2. No additional interferometer is considered to perform the LO injection. A cold attenuator consisting of wire grid G5 and cold absorbers must be used in this scheme in the LO path because the noise from the LO chain is directly connected to the image side band of both USB and LSB mixer. An attenuation factor ≥ 4 is required to give an image termination temperature < 75 K for the LO at ambient temperature.

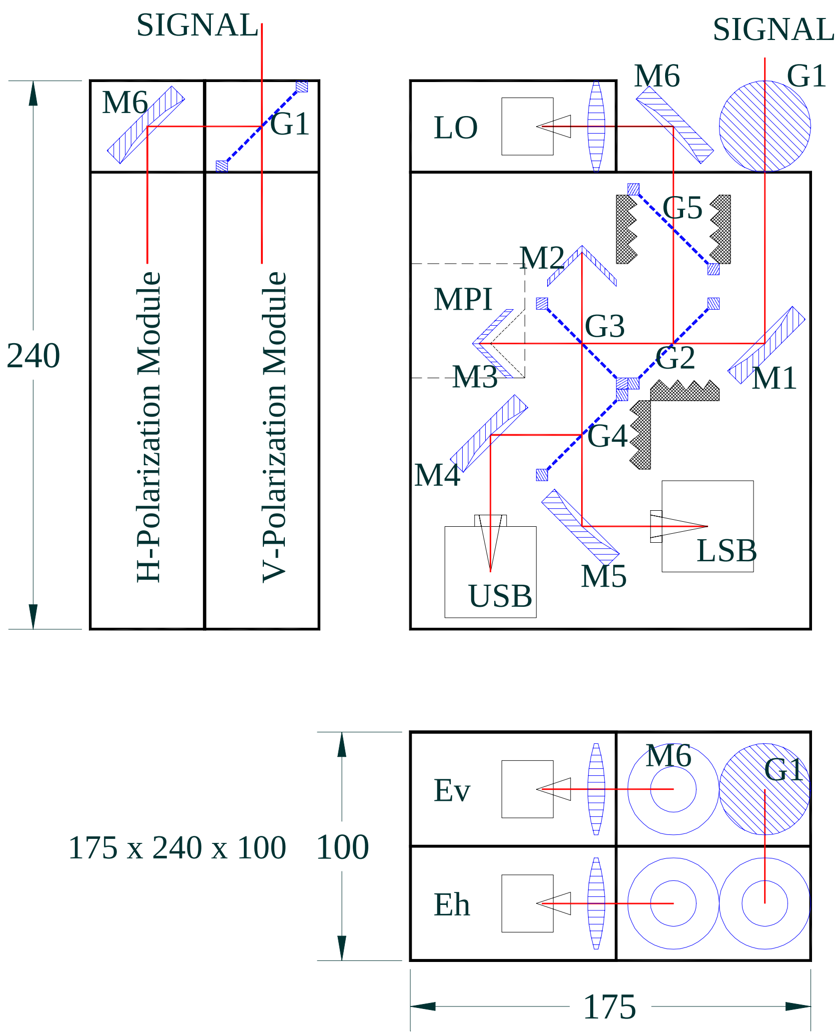

Fig. 2: SSB receiver module layout. Dimensions are in mm.

Optical elements at a temperature of <10 K are used in this scheme. This allows to reduce the absorption losses in grids and mirrors and decrease the noise contribution due to lower temperature. The optical elements are chosen in such a way that the clear aperture size is 5 Gaussian beam radii. This allows to minimize the scattering losses in the system.

Operation Principle and Performance

The MPI has a well-known sinusoidal frequency response. It is presented in Fig. 3. No optical loss is taken into account in this calculation. The LO in this case is injected at 630 GHz. As it is seen from Fig. 1 the LO power splits equally between the USB and LSB mixers. The output of the MPI at the LO frequency is circular polarized. The LO power balance between the LSB and USB mixers can be fine tuned by changing the path length difference of the MPI without a significant change in the sideband separation ratio. An MPI mirror moving range of 0.3 mm is sufficient to cover the whole 600-720 GHz band with only one mixer (for SSB operation). There is no requirement that the LSB and USB mixer should be nearly identical to achieve good image suppression. Differences in the mixer noise temperatures do not reflect in the side-band separation ratio. Furthermore one mixer and corresponding IF amplifier can be omitted without affecting the SSB performance. No additional IF processing circuits such as a 90° hybrid is needed for the receiver module operation.

The maximum IF bandwidth for this arrangement is 7.5 GHz per side band at 8 GHz IF central frequency and with 10 dB side-band separation ratio as specified for ALMA. From Fig. 3 it follows that the upper side band of the LSB mixer and the lower side band of the USB mixer is coupled to the LO port. This means that noise appearing at the LO port is received at the image side band of the corresponding mixer. In order to reduce this noise a cold attenuator or beam splitter must be used in the LO injection path to terminate the image side bands at a temperature lower than the LO physical temperature. The LO insertion loss, however, does not lead to a signal loss. This allows to choose a higher LO coupling coefficient for this scheme

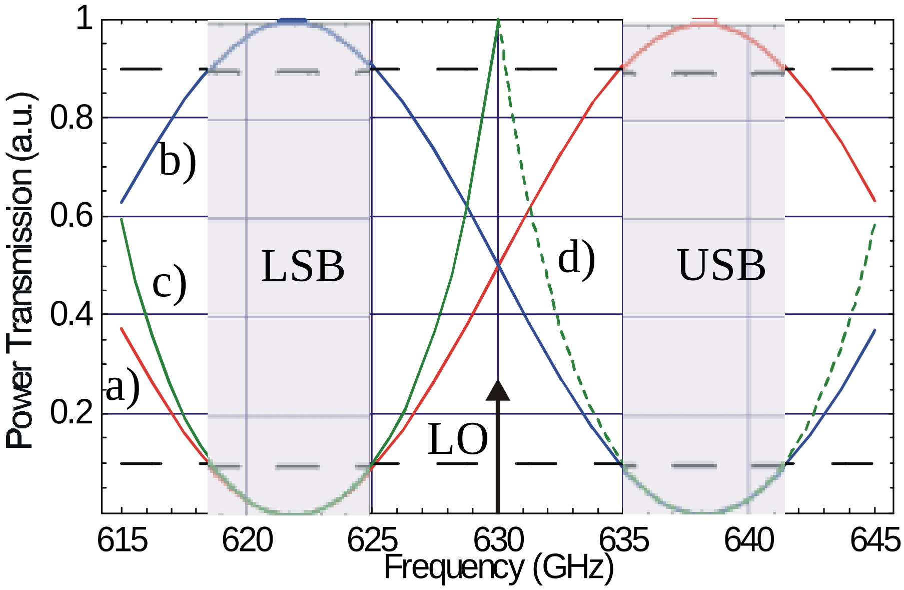

Fig. 3 Power Transmission coefficients and USB/LSB ratio of MPI set to 9.16 mm path length difference. a) Signal-USB and LO-LSB port transmission, b) Signal-LSB and LO-USB port transmission, c) USB/LSB ratio, d) LSB/USB ratio

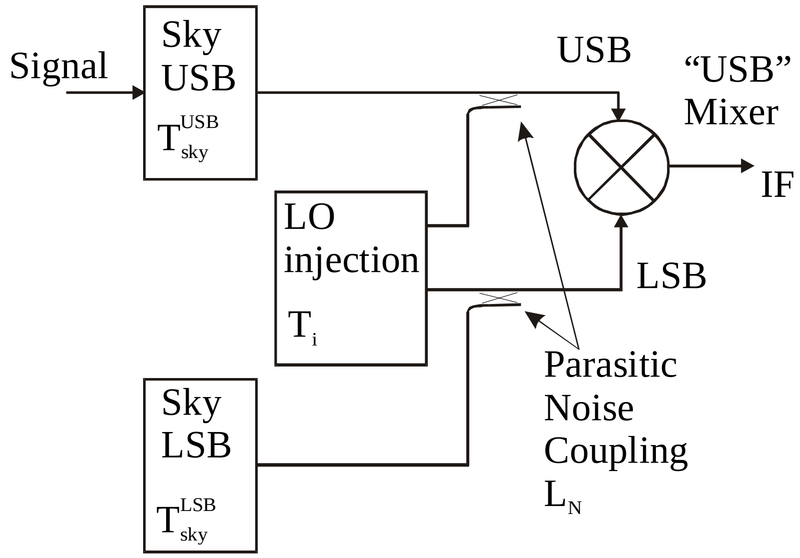

Fig. 4 Noise/Signal diagram of proposed receiver module. Only the USB mixer is shown.

compared to standard DSB beam splitter LO injection for the same degradation of noise properties.

We will now compare the performance of the SSB module (assuming lossless optical components) with a DSB module.

The signal diagram for the receiver module is shown in Fig. 4 for the case of narrow spectral line observations. The signal connections are identical for both the USB and LSB mixer. We consider for example the USB mixer. Since the "USB" mixer itself is intrinsically a double side-band mixer, both USB and LSB contributions are considered. The input signal with the spectral density T_{in} comes through the atmosphere with transmission L_{sky}^{USB} and output noise spectral density T_{sky}^{USB}. From now on we will quote noise spectral density expressed in degrees K as noise temperature. We assume Planck correction for the radiation temperature of a black body at physical temperature T:

$$T^{Planck} = T\left(\frac{hf/k_bT}{\exp(hf/k_bT)-1}\right), \qquad (1)$$

where f is the radiation frequency, h is the Planck constant, and k_b is Boltzman constant. We assume that the mixer noise temperature is measured using the standard black body method where radiation temperatures are corrected using the Planck formula (1).

If the IF frequency differs form central IF frequency additional loss appears in the USB signal chain and additional noise is coupled to it from the direction of LO. This is represented by "Parasitic noise coupling" in Fig. 4 and it is characterized by the coupling coefficient L_N. The noise temperature which is attributed to LO injection T_i is dependent on LO coupling coefficient L_{LO}, LO radiation temperature T_{LO} and image dump radiation temperature T_{dump} in the following way:

$$T_i = T_{LO}L_{LO} + T_{dump}(1 - L_{LO}). \qquad (2)$$

Symmetrically the LSB of the considered mixer will receive noise from the LO T_i and the noise from atmosphere T_{sky}^{LSB}. The output signal of this mixer T_{out} is expressed in the following equation:

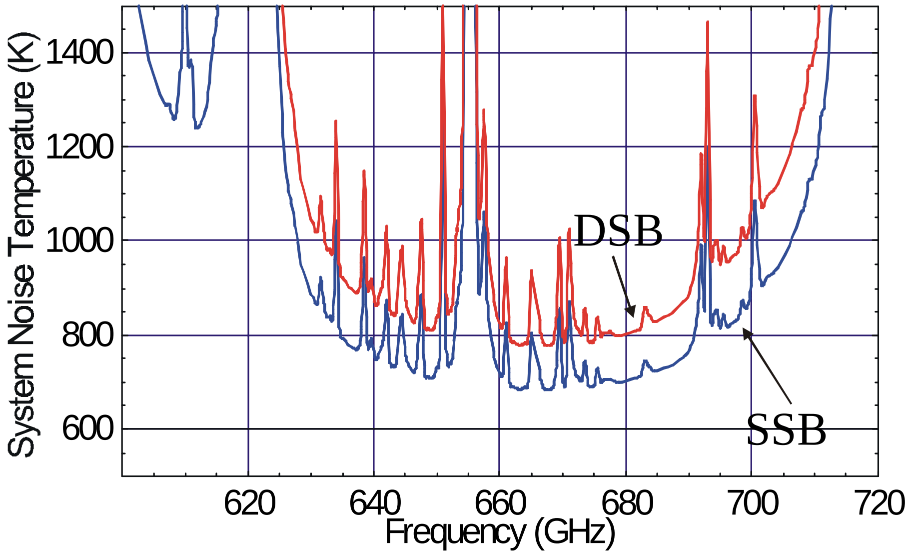

Fig. 5 The system noise temperature of a DSB receiver with mixer noise T_{SSB} = 300 K and -10 dB LO coupling at 300 K compared with SSB receiver with mixer noise T_{SSB} = 300 K, side-band separation of -10 dB, an -10 dB LO coupling and 60 K image dump black body temperature, 0.5 mm relative humidity.

$$T_{out} = \left(\left(T_{in} L_{sky}^{USB} + T_{sky}^{USB}\right)\left(1 - L_N\right) + T_i L_N + T_i\left(1 - L_N\right) + T_{sky}^{LSB} L_N + T_{mix}^{SSB}\right) G_{mix}^{SSB}, \quad (3)$$

where T_{mix}^{SSB} and G_{mix}^{SSB} are mixer SSB noise temperature and gain. Side-band separation ratio USB/LSB can be expressed as:

$$USB/LSB = L_N / \left(1 - L_N\right). \quad (4)$$

The expression for SSB system noise temperature follows from (3):

$$T_{sys}^{DSB} = T_{sky}^{USB} / L_{sky}^{USB} + \left(T_i + T_{sky}^{LSB} L_N + T_{mix}^{SSB}\right) / \left(L_{sky}^{USB}\left(1 - L_N\right)\right), \quad (5)$$

where T_i can be calculated from (2) if the physical temperature of the LO chain and the LO injection coefficient is known.

In the DSB case the noise temperature is expressed as:

$$T_{sys}^{DSB} = \left(T_{sky}^{USB} + T_{sky}^{LSB}\right) / L_{sky}^{USB} + \left(T_i + T_{mix}^{SSB}\right) / \left(L_{sky}^{USB}\left(1 - L_{LO}\right)\right). \quad (6)$$

The results of calculation of system noise temperature for SSB and DSB receivers having the same mixer noise temperature T_{SSB} = 300 K are presented in Fig. 5. Note that the LO injection coefficient for DSB mixer should be 3 dB lower to achieve the same LO coupling as SSB receiver because the LO power is split between two mixers in SSB receiver. The system noise has been calculated for 0.5 mm pwv and L_N = 10 dB noise coupling coefficient. The improvement of system noise temperature is about 12% in the SSB case. The difference increases further in favor of the SSB module if the atmospheric conditions worsen.

Discussion

Decreasing the physical temperature of the last stage of the LO multiplier chain results in a decrease of the receiver noise temperature as shown in Fig 6. This suggests the LO at 80 K as a major improvement both for multiplier efficiency and receiver sensitivity. The proposed SSB scheme allows to achieve lower noise temperature for higher LO coupling coefficient.

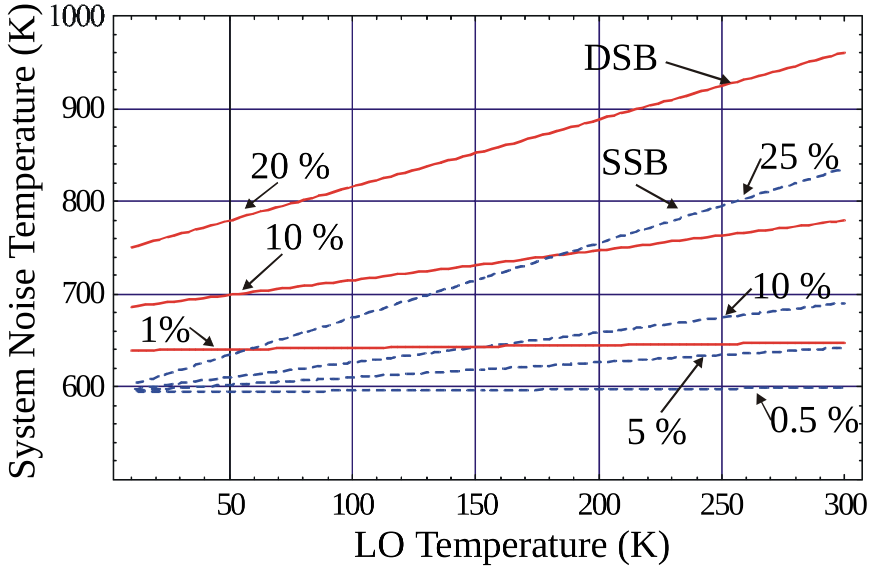

Fig. 6 System noise temperature vs. LO physical temperature calculated for different LO coupling level. DSB mixer noise is shown in solid line, SSB mixer noise is shown in dashed line. LO coupling level is shown in presents. The mixer parameters are the same as in Fig. 5.

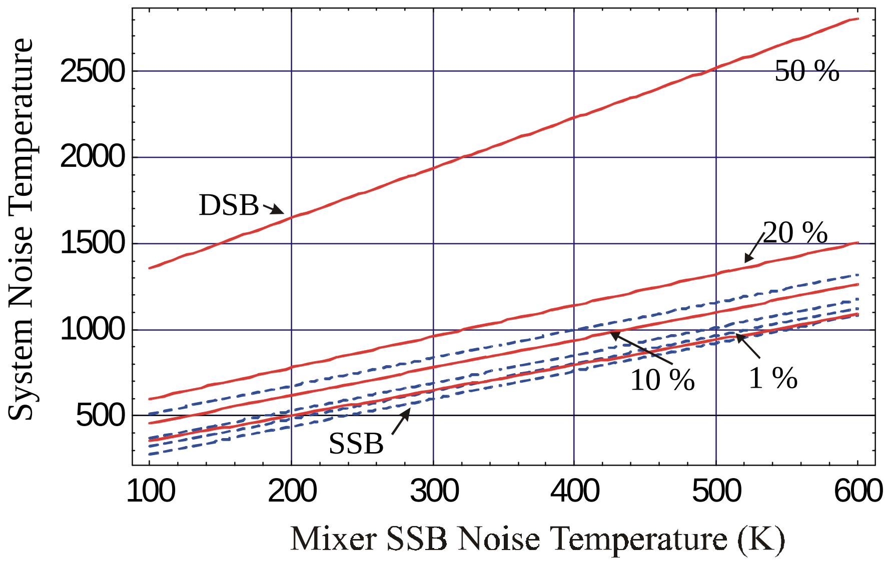

Fig. 7 System noise temperature vs. mixer SSB noise temperature calculated for different LO coupling level. DSB mixer noise is shown in solid line, SSB mixer noise is shown in dashed line. LO coupling level is shown in presents. T_{SSB} is 300 K and LO is at 300 K temperature for these calculations.

The dependence of the system noise temperature on mixer SSB noise temperature for DSB and SSB receivers is presented in Fig. 7 for different coupling coefficients. It is seen once more that the SSB module has less requirement to the LO coupling. The difference between SSB and DSB receivers increases as the mixer noise improves. That means that SSB separation is necessary to realize fully the state of art performance of the mixer.

The proposed SSB module can be used also for continuum DSB observations if both USB and LSB mixers are switched on at the same time. In this regime this scheme is still better than an equivalent DSB beam splitter injection scheme because it does not introduce the loss in the signal chain. However if continuum observations is not the first priority one of the mixers-IF amplifier combinations (USB or LSB) can be removed from the system without affecting the SSB performance.

Remarks about simplifying the module

The proposed module for 600 to 720 GHz satisfies the requirement of SSB operation using mostly available technology. It can certainly be built within the tight ALMA schedule. However, a fairly large number of optical components and moving parts in the cold are needed in each module. In view of the large number of receivers for ALMA and the associated fabrication, alignment and testing effort, a less complex frequency module seems attractive. Recent new calculations about the advantage of SSB vs. DSB operation taking optical losses into account (J. Lamb, priv. comm.) show that the SSB advantage may not be sufficient to justify the effort of SSB modules at high frequencies. Our proposed module would simplify significantly, if DSB operation would be acceptable for ALMA. Instead of 8 grids, 2 movable mirrors and 4 mixers per receiver (for SBS), a DSB module would require 3 grids, no movable mirrors and 2 mixers.

Conclusions

A sideband separating receiver module for the 600 – 720 GHz ALMA band has been proposed. The module is based on a Martin-Puplett interferometer. The preliminary calculations taking into account the ideal optical elements and typical atmosphere showed that the SSB receiver has better noise temperature than the DSB receiver using the same mixers and LO coupling coefficients.

The main module parameters are:

- Size: .... 125 mm $\times$ 240 mm $\times$100 mm
- max IF bandwidth .... 7.5 GHz per sideband
- IF central frequency .... 8 GHz
- Polarization .... Horizontal and Vertical
- RF band .... 600-720 GHz
- USB/LSB ratio .... >10 dB
- Temperature of optics .... 10 K
- Cold diplexer

This module does not require two mixers and amplifiers as well as it does not require any IF processing for SSB operation. This is an advantage over a hybrid SSB scheme. The decrease in the physical temperature of the LO leads to a significant improvement of the system noise temperature with the same LO coupling coefficient.