Design of a Dual Polarization SIS Sideband Separating Receiver based on waveguide OMT for the 275-370 GHz frequency band

A. Navarrini*, M. Carter
IRAM (Institut de Radioastronomie Millimétrique)
300, rue de la Piscine, 38406 St. Martin d'Hères Cedex – France
*Present address: Radio Astronomy Lab, University of California, Berkeley, CA, USA

Abstract

We report on the design of a wideband waveguide Orthomode Transducer (OMT) integrated with two 90^0 waveguide hybrid couplers and four 16 dB branch-guide LO directional couplers for the 275-370 GHz frequency band. The device allows the sideband separation for each of two mutually orthogonal polarizations to be achieved by employing four fixed-tuned SIS DSB mixer-units. The central part of the system is based on a Bøifot type junction OMT as realized by Wollack [1], and is similar to the design discussed by Narayanan [2]. The proposed device takes advantage of the –3 dB splitting operated over one polarization of the RF input power that is delivered in the two side arms of the Bøifot orthomode junction by a thick septum parallel to the E-field of the considered polarization; the RF signals of the split polarization are added through two 16 dB branch-guide couplers to the signals of a Local Oscillator (LO) that enter the Bøifot orthomode junction side arms with a phase difference of 90^0. The RF and LO are applied in two fixed-tuned DSB SIS mixers whose IF outputs are recombined in a 4-8 GHz IF 90^0 quadrature hybrid, so that the resulting downconverted upper (USB) and lower (LSB) sideband of the considered polarization are separated. The LO quadrature hybrid, the 16 dB waveguide couplers, and the idea of assembling these elements to get a single polarization sideband separating receiver (2SB) are adopted from the work of Claude [3]. The RF signal of the orthogonal polarization passing the septum is divided using an in-phase power divider and delivered through side arms perpendicular to the previous. The sideband separation for this second polarization is realized using the same scheme as for the first polarization.

The advantage of the device is to exploit the –3 dB splitting operated over each of two mutually orthogonal polarizations by the waveguide OMT junction and power divider, as required for sideband separation, and to avoid the problem of signals recombination of classical waveguide OMTs. Both the OMT junction and the in-phase power splitter have been optimised using a 3D electromagnetic simulator. Return loss better than 16 dB, and transmitted power to the four side arms within 0.1 dB of the reference value at –3 dB of the single polarization input excitation are expected over the RF band of design. Because of symmetry properties, the structure has not cross-polarization. Although the 3D structure looks complex, the proposed device can easily be constructed using conventional split-block techniques with reliability and cost-effectiveness.

I. Introduction

Most of cryogenically cooled millimeter and submillimiter wave receivers in radio astronomy are based on Double Side Band (DSB) SIS mixers that have noise performances approaching the quantum limit. In a DSB receiver the atmospheric noise contribution coupled in the image band during a radioastronomical measurement

degrades the system sensitivity for spectral line observation. Backshort-tuned Single Side Band (SSB) mixer that reject the image sideband, or mechanically tuned interferometer that provide image sideband filtering can be used to reduce the SSB system noise temperature, which is the figure of merit of spectroscopic observations.
An alternative to these systems is offered by the sideband separating receiver (2SB) based on fixed-tuned DSB mixers. A 2SB receiver provides at its output two separated IFs, one containing the down-converted RF signal from the Upper Side Band (USB), the other from the Lower Side Band (LSB), each with a high rejection of the respective image band. With respect to SSB mixers or tuned interferometer, a 2SB receiver offers the advantage of not having moving parts, and has twice more IF band.
To increase further the capacity and versatility during astronomical observation, dual polarization operation is often required or, in some cases, mandatory (e.g. ALMA project). The easiest way to separate linearly polarized signals with orthogonal polarizations is obtained with a quasi-optical system based on a grid consisting of free-standing parallel wires. The polarization with E-field parallel to the wires is reflected by the grid, while the perpendicular polarization is transmitted. Although the wire grid is intrinsically wideband it has important drawbacks. In fact, it is large and bulky and requires two well aligned feed-horns along the optical path of the two wave polarizations resulting from the well aligned wire grid. In a practical implementation of a receiver, the wire grid should reside inside the cryostat, which correspondingly increase the size of the required dewar.
An alternative to the wire grid is represented by the waveguide orthomode transducers (OMT). Waveguide OMTs are more compact and less sensitive to mechanical vibrations than wire grid based systems. Moreover, they require the use of only one dual-polarized broadband corrugated feedhorn, thus the optical alignment is much facilitated and the instrumental polarization offset is reduced. Therefore, waveguide OMT are the favoured solution for focal plane imaging arrays.
OMTs are classified in three different groups with increasing geometrical complexity and manufacturing difficulties, and with increased performances (see Bøifot [4]). A broadband waveguide OMT has been realized by Wollack [1] for ALMA band 3 (86-116 GHz) using a design rescaled from a lower frequency model based on the Bøifot junction. The main disadvantage of Wollack's OMT is the use of pins located at the entrance of the waveguide side arms. Pins act as capacitive posts that tune out the discontinuity of the holes created by the side arms in the common waveguide. However, the complexity of assembling the pins in the block make them unsuitable for scaling the OMT at higher frequencies. In a more recent design of Narayanan the discrete compensation pins have been replaced with capacitive steps at the side arm apertures that are easier to fabricate and allow to achieve equivalent performance as the original Wollack design.
Starting from the design published by Wollack we have carried out 3D electromagnetic simulations using the FDTD package CST Microwave Studio [5] and optimised a new type of broadband Bøifot type junction OMT based on a thick septum that resulted in a design similar to that discussed by Narayanan. With respect to that design, our junction OMT does not require the use of short capacitive steps that have been replaced by standard multistep transitions on the side arms. Finally, the polarization with E-field

parallel to the septum that is split in the Bøifot junction side arms results in low return loss over a wide band. A multi-step power divider has been optimised in the main arm of the OMT to split the linear polarization passing the septum, having E-field perpendicular to the septum itself, in two full-height waveguides perpendicular to the Bøifot junction side arms. The resulting four arms system consisting of the OMT junction with their side arms plus the main arm power divider is the central part of our dual polarization 2SB. The sideband separation for the polarization parallel to the septum is obtained by adding each of the Bøifot type junction OMT side arm to a LO provided by a 90^0 hybrid followed by a 16 dB branch-guide coupler. A similar configuration is used to achieve the sideband separation for the orthogonal polarization.

In the whole, the proposed device contains: (i) an improved Bøifot type junction OMT with a thick metallic septum; (ii) an optimised multistep power divider; (iii) four 16 dB branch guide couplers; (iv) two 90^0 hybrid couplers.

The 275-370 GHz dual polarization 2SB can be realized by using 4 fixed-tuned DSB mixers at the ends of the proposed device. The device consists of 6 mechanical blocks that can be assembled to form a compact structure together with the 4 mixers.

The present paper is organized as follows: in section II we introduce the concept of a classical single polarization 2SB in which the required circuits for combining and phasing the signal and LO power are realised in full height rectangular waveguide. In section III we discuss our design of the Bøifot orthomode junction integrated with the multistep power divider in the main waveguide arm, and present the results of electromagnetic simulations for such structure. Finally, in section IV we present the design of the whole structure of the dual polarization 2SB and discuss the construction of the mechanical blocks.

II. Single Polarization 2SB

Sideband separating receivers have been widely used at microwave frequencies for many years. The schematic of a 2SB is shown in Fig.(1). Here, a single polarization of the incoming RF signal enters an in-phase power divider and is split in two parts. Before being applied to the DSB mixers, the two signals are added through a coupler to the power of LOs with 90-degree phase difference coming from an LO quadrature hybrid. The IF outputs are combined in a IF quadrature hybrid at whose output ports the downconverted upper (USB) and lower (LSB) sidebands appear separately.

Claude [3] has realized a single polarization 2SB integrating fixed-tuned DSB SIS mixers for the 275-370 GHz band. Its receiver setup is shortly discussed here as some of its basic elements are also employed in the design of our dual polarization sideband separation receiver. This includes a waveguide power divider, a waveguide quadrature hybrid coupler providing a 3 dB power splitting with 90^0 phase shift from the two outputs, two branch-guide 16 dB LO directional couplers, two SIS mixers, and a commercial 4-8 GHz IF quadrature hybrid (in our design the quadrature hybrid is used in the LO section instead of the RF section). The two full height waveguides of the broadband LO hybrid are coupled through the broad walls and are separated by five shunt guides $\lambda_g/4$ long.

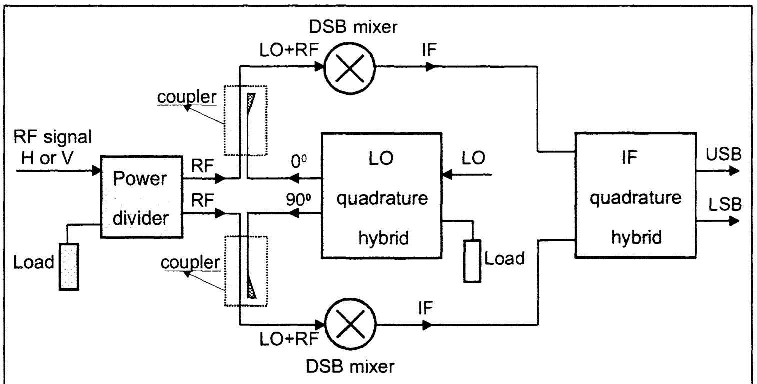

Fig.(1): Schematic diagram of a single polarization sideband separating receiver.

Two $\lambda_g/4$ long shunt guides are used in the 16 dB couplers. The couplers were realized by splitting the blocks on the E-plane; this facilitates their integration with other components. All the elements of the network were designed and tested at IRAM.

III. Bøifot type orthomode junction and in-phase power divider

III-a Design of orthomode junction

The twofold symmetric Bøifot junction was chosen as starting point for the OMT junction design investigated in this work. Different geometries were considered in turn with varying septum types and waveguide junction dimensions. The electromagnetic structures were optimised with CST Microwave Studio in the 275-370 GHz frequency to achieve the following requirements:

a) return loss < -15 dB for the two polarizations; *b)* transmitted power to the four side arms within 0.1 dB of the reference value at –3 dB of the single polarization input excitation; *c)* cross-polarization level below –40 dB. The latter specification is required in a practical implementation of a receiver because it is desirable for the cross-polarization induced by the OMT to be stable and less than the level arising from the feed assembly and telescope which a rarely below that figure. Very low cross-polarization levels are achievable with our design, with values that in principle are zero as a consequence of the symmetry of the designed structure, and that in practice depend on the amount of misalignments that are determined by specified mechanical tolerances. Although a detailed study of the influence of all possible contributions to the cross-polarizations has not been performed we point out that the typical cross-polarization levels in classical waveguide OMT are much lower than the those induced by a standard wire grid (≈-30 dB) and are also sufficiently low for most astronomical applications.

A 3D view of the final orthomode junction design is shown in Fig.(2). Further details are illustrated in Fig.(3). The square waveguide at the input (dimensions 0.76×0.76 mm^2) can support the propagation of 4 modes in the frequency band of interest: TE_{10}, TE_{01}, TE_{11} and TM_{11}, with cut-off frequencies of respectively, $\nu_{c,TE10}=\nu_{c,TE01}=197$ GHz, $\nu_{c,TE11}=\nu_{c,TM11}=279$ GHz. The excitation of the higher order modes TE_{11} and TM_{11} is excluded for symmetry reasons. In fact, the main and side-arm junctions are twofold symmetric about the horizontal and vertical guide planes, thus TE_{11} and TM_{11} excitation can be avoided in the square common arm of the junction as long as this condition is realized during fabrication and assembly. The alignment of the septum inside the

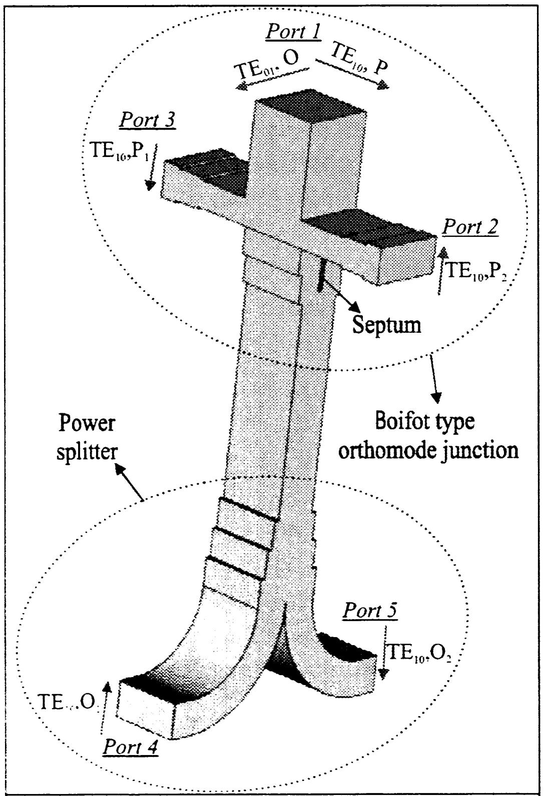

Fig.(2): Three-dimensional view of the designed Bøifot type orthomode junction with power splitter. The RF signal coming from the feed-horn enters the square waveguide from the top (Port 1). The RF power coupled at the square waveguide entrance into the TE_{10} mode (polarization P, parallel to the septum) is equally split between two side-arms (Port 2 and 3). The RF signal coupled into the TE_{01} mode (polarization O, orthogonal to the septum) is divided, after passing the septum, by a power splitter with E-plane bend side arms perpendicular to the previous (Port 4 and 5).

orthomode junction and of the input square waveguide at the interface with the flange of the circular-square waveguide transition (or the feed-horn including such transition) previous the OMT, is critical to minimize the excitation of the TE_{11} and TM_{11} modes. When proper assembly is realized only the desired fundamental modes TE_{10} and TE_{01}, with E-field excitation respectively, parallel (P) and orthogonal (O) to the septum will propagate. Referring to Fig.(2), the polarization of the RF signal at the input (Port 1) with E-field parallel to the septum will be divided on the side arms at the septum location (Port 2 and Port 3). The RF signal with input polarization perpendicular to the septum will pass the septum itself and will be divided by the power splitter in two side arms (Port 4 and Port 5). Higher order modes whose excitation is not excluded by symmetry reasons are created by the discontinuity due to the side arm apertures and septum. Although their cut-off frequencies fall outside the useful frequency band and the modes are evanescent, their reactances must be compensated by a proper choice of the septum geometry and orthomode junction dimensions. In general, the thinner the septum, the easier the structure is to compensate. Decreasing the septum thickness δt makes its realization more difficult, decreases the return loss of both input polarizations, increases the transmission through the main arm of the polarization perpendicular to the septum at values closer to –3 dB, and increases also the transmission of the polarization parallel to the septum that should not be passed (the cross-polarization level which is intrinsically very low in this structure). The adopted septum thickness of $\delta t = 50$ µm is a compromise between the bigger values required to facilitate its manufacturing from one hand, and the smaller values necessary to achieve better performances from the other hand. The ratio between septum thickness and lateral dimension of the square waveguide results in a value of $\delta t/L \cong 0.066$ (in the original Wollack design $\delta t/L \cong 0.024$). The adopted septum geometry consists of a circular tapering from full waveguide lateral size down to a narrow square section tip that properly feed the symmetric side arms allowing for wide band performances. We found using simulations that the advantage of circularly tapered septum tip over the more standard triangular type as used by Wollack is the decreasing of return loss for the parallel polarization with a corresponding improved "flatness" of the –3 dB transmitted power on the junction side arms. The short and narrow square section at the septum tip end improves further the performances, particularly by decreasing the return loss of the

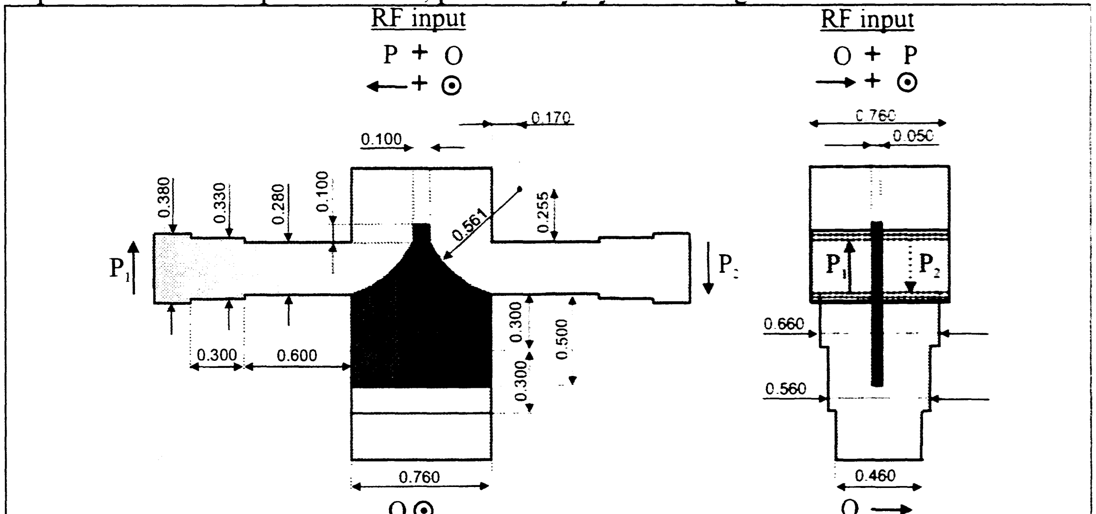

Fig.(3): Internal view of the optimized orthomode junction. P and O indicate respectively, the polarization with E-field parallel and orthogonal to the septum. All dimensions are in millimeters.

orthogonal polarization. The finite septum tip end width makes the design robust against possible off-axis misalignments parallel to the septum itself.

In the septum region next to the junction side arms, the main waveguide arm can be thought of as divided in two independent parallel waveguides separated by the metallic septum itself. Because of the reduced dimensions, the two waveguides support in the frequency band of interest, the propagation of only one mode with E-field orthogonal to the septum. The mode with E-field parallel to the septum is evanescent in such region and is quickly attenuated. Therefore, the length of the septum controls the attenuation of the evanescent modes: increasing its length, the transmission in the main arm of the mode with E-field parallel to the septum (cross-polarization) decreases, but the return loss for the orthogonal polarization increases. To keep such return loss below the –15 dB specification and reduce the transmission of the unwanted polarization we have decided to implement a symmetric multistep transition at the side arm junction from square to reduced height waveguide (dimensions 0.76×0.46 mm^2) along the main waveguide arm. This reduces drastically the transmission of the polarization with E-field parallel to the septum without degrading the return loss performances. In addition, the reduced waveguide dimension prevents the excitation of TE_{11} and TM_{11} modes within the operating frequency range due to possible misalignment. In fact, the cut-off frequency of such modes is pushed outside the upper limit of the band ($\nu_{c,TE11}=\nu_{c,TM11}\cong 381.1$ GHz).

The side arm waveguides next to the septum have dimensions 0.76 × 0.28 mm^2 and are 0.60 mm long (see Fig.(3)). To reduce the ohmic losses in these sections, their lengths have been chosen to have the shortest possible values for which the transmission of the polarization coupling to the side arms results unaffected. Decreasing the side arm waveguide heights shifts to lower frequency the useful band for the return loss of the polarization parallel to the septum, while improving its cross polarization and the return loss of the polarization orthogonal to the septum. The side arms are transformed with a multistep transition to the standard 0.76 × 0.38 mm^2 adopted for the full height waveguide dimensions of the ALMA Band 7 DSB SIS mixers [6] foreseen for integration with the proposed device.

III-b Power Splitter

The Bøifot type orthomode junction is connected through a reduced height waveguide to the power splitter as shown in Fig.(2). Such long waveguide section (2.24 mm) is required by mechanical assembly reasons of the various blocks constituting the device. A multistep transition to square waveguide is used before the power divider. The -3 dB splitting junction is characterized by two full height waveguides (0.76 × 0.38 mm^2) joined at the square waveguide section that are E-plane bended with radius of 1.5 mm. This bending radius is sufficient to decrease the amplitude of the reflection coefficient at the square waveguide input below –30 dB over the 275-370 GHz band.

III-c Predicted performances

The entire 5-port structure shown in Fig.(2) has been simulated without taking into account the effects of ohmic losses (only perfect conductors were considered). The results are illustrated in Fig.(4). Return loss below –16 dB are obtained for both polarizations over the whole RF band of interest with zero cross polarization level. The coupling amplitude between the fundamental TE_{10} mode at port 1 and the fundamental mode at one of the side arms of the Bøifot junction has a value of –3 dB and variations

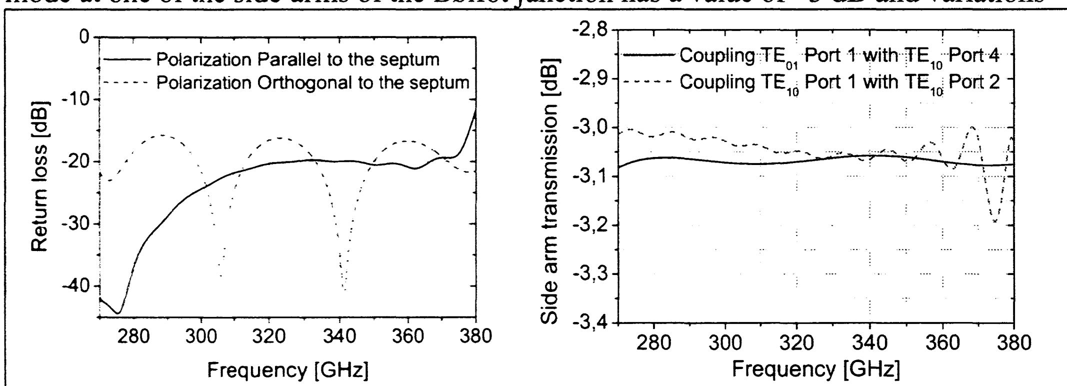

Fig.(4): Result of simulations of the 5-port device illustrated in Fig.(2). *Left):* Amplitude of reflection coefficient at the input (Port 1) for polarization parallel, and orthogonal to the septum. *Right):* Solid line: Coupling amplitude between fundamental mode at Port 1 with E-field orthogonal to the septum and fundamental mode at Port 4 (or 5). Dashed line: Coupling amplitude between fundamental mode at Port 1 with E-field parallel to the septum and fundamental mode at Port 2 (or 3).

within 0.1 dB around this optimum. A similar result is obtained for the orthogonal polarization at the input that couples to the power splitter side arms.

IV. Dual polarization 2SB

A schematic diagram of the dual polarization sideband separating receiver, based on the device illustrated in Fig.(2), is shown in Fig.(5). Here, the RF signals of the split polarization parallel to the septum (P) are added through 16 dB couplers to the signal of a

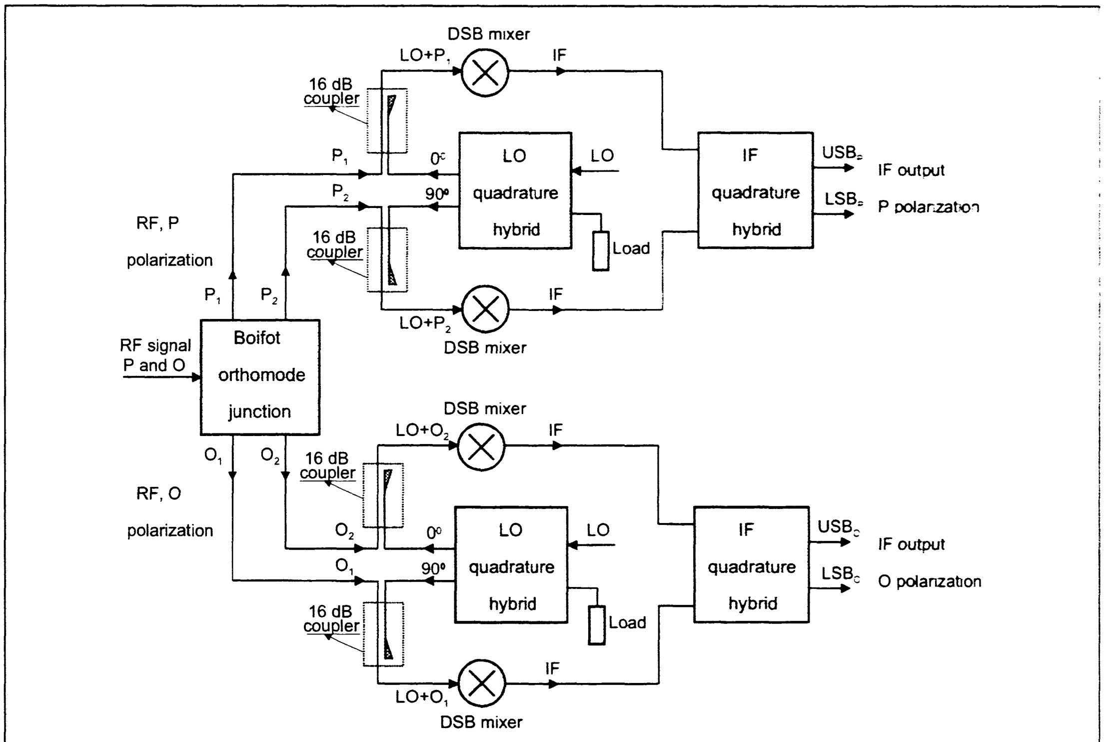

Fig.(5): Schematic diagram of dual polarization 2SB based on a Bøifot orthomode junction.

LO that enter the Bøifot orthomode junction side arms with a phase difference of 90^0. The RF and LO are applied in two fixed-tuned DSB mixers whose IF outputs are recombined in a IF 90^0 quadrature hybrid, so that the resulting downconverted upper (USB_P) and lower (LSB_P) sidebands of the considered polarization are separated. The sideband separation for the orthogonal polarization (O) passing the septum is realized using the same scheme as for the other polarization, and the downconverted upper (USB_O) and lower (LSB_O) sidebands results at the output.

IV-a Design of waveguide circuitry

The dual polarization 2SB design follows closely the schematic diagram illustrated in the above figure, and is based on two independent LO sources, each driving the two DSB mixers of each single polarization sideband separating SIS receiver. A view of the RF waveguide circuitry of the whole device is shown on the left of Fig.(6). Here, the RF input signal enters the square waveguide from the top. Each of the two orthogonal polarizations are split by the Bøifot type orthomode junction and power splitter. Two waveguide quadrature hybrid couplers and four 16 dB branch-guide directional couplers are employed to inject the LO in the RF signal paths with the proper phase. The two full height waveguide side arms at the output of the Bøifot type orthomode junction as well as the two waveguide branches following the 90^0 LO hybrid coupler must have the same electrical path length to allow a proper phase balancing at the two SIS mixer input P_1 and P_2. The two waveguides exiting the power splitter and the two waveguide branches following the second 90^0 LO hybrid coupler must also have the same electrical path length before entering the two SIS mixer input O_1 and O_2.

IV-b Design of mechanical assembly

The waveguide circuitry discussed above can be realized using 6 mechanical parts (3×2 half blocks) made of brass to allow easy machining. A view of the compact split-block mechanical assembly of the three different half blocks showing the internal waveguide circuitry is presented on the right of Fig.(6). The whole device comprises four 16 dB

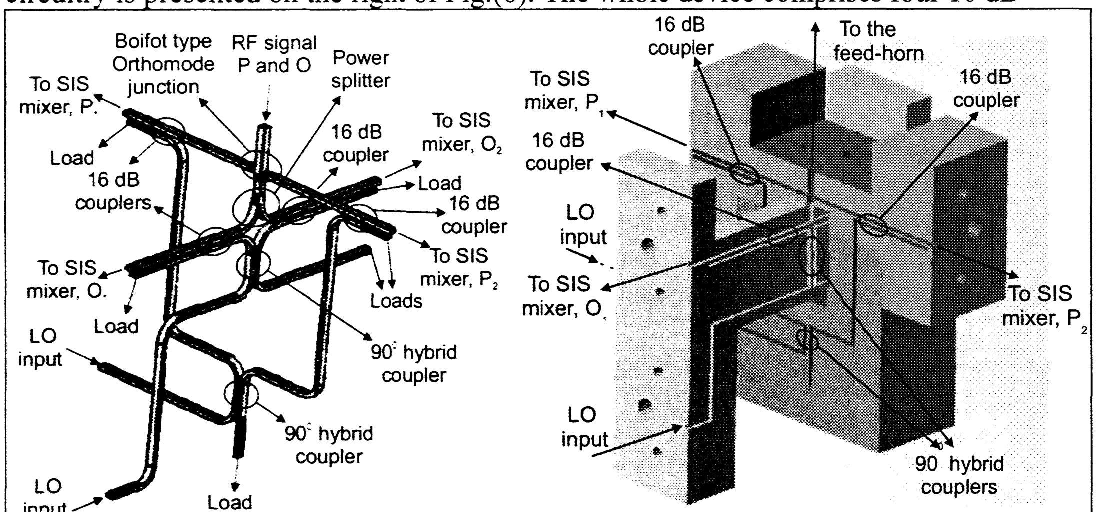

Fig.6 Left): Waveguide circuitry of the dual polarization 2SB. The RF signals with polarizations parallel (P) and orthogonal (O) to the septum are split in four waveguide arms and added to LO signals through 16 dB branch-guide couplers. Internal termination loads are also shown. *Right):* Mechanical assembly of the dual polarization 2SB. Three of the six block device have been removed to show the internal waveguide circuitry.

branch-guide couplers, two 90^0 hybrid couplers as well as the orthomode junction and power splitter. Once assembled, the device will have external dimensions 40×40×40 mm^3. A beryllium copper septum (not visible) can be positioned between hollow surfaces of two split-blocks. The blocks can be realized using a standard CNC, except for the slots of the waveguide couplers that require to use spark-erosion technique.

A view of the whole RF section of the dual polarization 2SB including the ALMA Band 7 feed-horn and SIS mixers is shown on Fig.(7). Each mixer includes its IF matching circuit and a magnetic field concentrator to suppress the Josephson currents. The dimensions of the six mechanical blocks have been chosen to allow their assembling with the ALMA feed-horn and the ALMA Band 7 mixers.

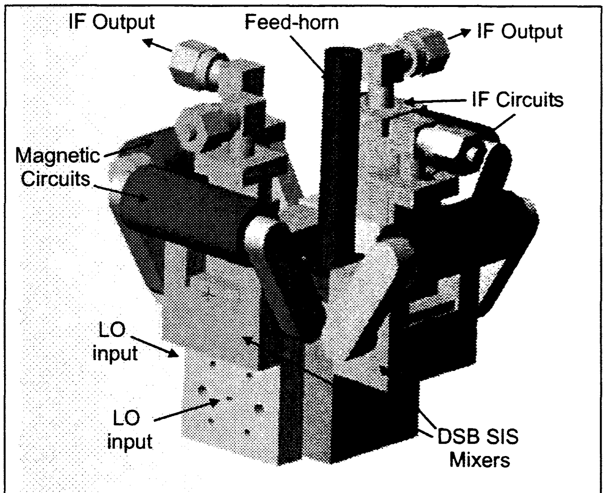

Fig. 7: View of the mechanical assembly of the dual polarization 2SB showing the feed-horn and the 4 DSB ALMA Band 7 SIS mixers including its magnetic circuits and IF outputs.

V. Conclusions

A dual polarization sideband separating receiver using a waveguide OMT has been designed for the 275-370 GHz frequency band. This is based on a Bøifot type orthomode junction that integrates a 50 μm thick septum. The RF section of the device comprises, other than the OMT, a power divider, two 90^0 LO waveguide hybrid couplers and four 16 dB branch-guide LO directional couplers. The whole system is composed of 6 mechanical blocks that are assembled to form a compact structure. Its advantage is to exploit the –3 dB splitting operated over each of two mutually orthogonal polarizations by the waveguide OMT junction and power divider, as required for sideband separation, and to avoid the problem of signals recombination of classical waveguide OMTs. The device can be constructed using conventional split-block techniques with reliability and cost-effectiveness.

Acknowledgements

We are grateful to Bernard Lazareff (IRAM) and to Renzo Nesti (Astrophysical Observatory of Arcetri, Italy) for helpful discussions. This work has been supported by IRAM (Grenoble, France).

References

[1] Wollack, E., Grammer, W., and Kingsley, J., "The Bøifot Orthomode Junction", ALMA Memo n. 425, May 2002.

[2] Narayanan, G. and Erickson, N.R., "A Novel Full Waveguide Band Orthomode Transducer", Proceedings of the 13th International Symposium on Space Terahertz Technology, Cambridge, MA, USA, March 26-28, 2002, p. 505-514.

[3] Claude, S. "Sideband Separating SIS Mixer For ALMA Band 7, 275-370 GHz", 2003, this conference, Tucson, AZ, USA.

[4] Bøifot, A. M., "Classification of Orthomode Transducers", 1991, European Transactions on Telecommunication and Related Technologies, vol. 2, n. 5, pp 503-510.

[5] CST Microwave Studio. Büdinger Str. 2 a, D-64289 Darmstadt, Germany.

[6] Navarrini, A., Lazareff, B., Billon-Pierron, D., and Peron, I., "Design and characterization of a 225-370 GHz DSB and a 250-360 GHz SSB full height waveguide SIS mixers", Proceedings of the 13th International Symposium on Space Terahertz Technology, Cambridge, MA, USA, March 26-28, 2002, p. 33-40.