Development of ALMA Band 8 (385-500 GHz) Cartridge

Y. Sekimoto[1,2,*], Y. Iizuka[1], N. Satou[1], T. Ito[1], K. Kumagai[1], M. Kamikura[1,2], M. Naruse[1,2], and W. L. Shan[3]

[1]*National Astronomical Observatory of Japan, Tokyo 181-8588, Japan*

[2]*University of Tokyo, Department of Astronomy, Japan*

[3]*Purple Mountain Observatory, China*

* Contact: Sekimoto.Yutaro@naoj.ac.jp, phone +81-422-34-3982

***Abstract*—We have developed a cartridge-type receiver covering from 385 to 500 GHz for pre-production of ALMA Band 8. It receives two orthogonal polarizations and down-converts the sideband-separated signals to intermediate frequencies (IF) between 4 and 8 GHz. The cartridge-type receiver consists of a cold optics, a feed horn, an OMT, two sideband-separating SIS mixers, cryogenic multipliers of local oscillator (LO). These components were individually tested and then the cartridge was integrated and tested as a complete assembly. We have also developed equipment to test both components and the integrated receiver. The single sideband (SSB) noise temperature of this receiver is 130 K at the band center and 180 K at the band edges. The beam pattern and cross-polarization pattern are consistent with physical optical calculation. These results are promising for receiver production to the Atacama Large Millimeter/submillimeter Array (ALMA).**

I. Introduction

The Atacama Large Millimeter/submillimeter Array (ALMA) is an international astronomy facility, built by Europe, North America, and Japan in cooperation with the Republic of Chile. ALMA, consisting of 64 12-meter diameter antennas and 16 Atacama Compact Array (ACA) antennas, is located in northern Chile at an elevation of 5000 meters. Atmospheric windows from 30 GHz to 950 GHz are covered by 10 frequency bands with relatively wide bandwidth of 20 – 30 % [1][2][3]. Each frequency band is observed with a cartridge-type receiver receiving two orthogonal polarization. The cryogenic interface of the receiver cartridges for the ALMA was proposed by the Rutherford Appleton Laboratory (RAL) in UK[4]. The cartridges are installed in a cryostat at the Cassegrain focus of the antennas with some offset. Each cartridge contains cryogenic receiver optics or warm optics outside of the cryostat toward the sub-reflector. ALMA front end does not employ a mechanical tuner except for calibration device because of operational reliability.

The cartridge-type receiver contains optics, mixers, amplifiers and local oscillators to achieve a modular concept. ALMA cartridges use a cartridge body provided by RAL and two cryogenic multipliers and a warm cartridge assembly provided by NRAO, which includes a YIG oscillator, an active multiplier chain, a bias module, and a controller.

II. Design

A Cartridge

The ALMA Band 8 cartridge receives frequencies from 385 GHz to 500 GHz, which corresponds to 26 % bandwidth with a center frequency of 442.5 GHz. Band 8 cartridge adopted sideband-separating (2SB) mixer of IF 4 - 8 GHz instead of double sideband (DSB) mixer of IF 4 - 12 GHz because the atmosphere in the 400 GHz band has several deep absorptions by H_2O and O_2[5]. To escape from these dips, a sideband-separating mixer is desirable for the Band 8 cartridge [6][7].

We have developed an ALMA Band 8 cartridge pre-production model as shown in Figure 1 based on experience of development of the qualification model [8]. The main difference from the qualification model is a waveguide OMT [8] as a polarization splitter. It has a few advantages:

1. A receiver optics at 4 K stage can be quite simple and compact. An ellipsoidal mirror, a corrugated horn, and a wire grid can be reduced from the cryogenic optics
2. There is no beam squint between two polarizations.
3. A concern on thermal cycle of a wire grid can be resolved.

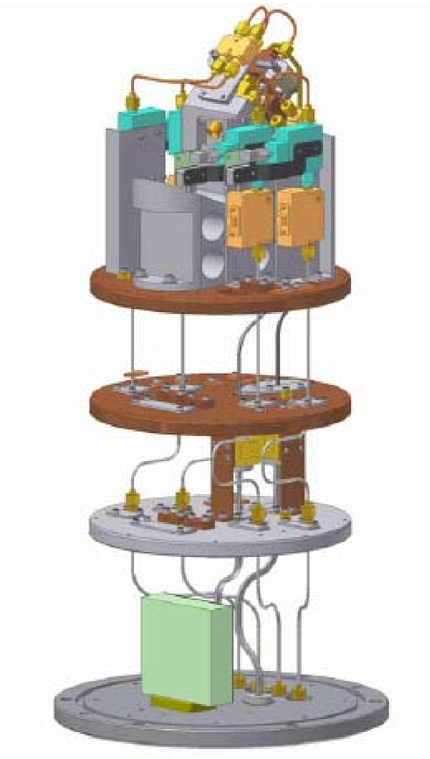

Fig.1 ALMA Band 8 pre-production model cartridge receiver.

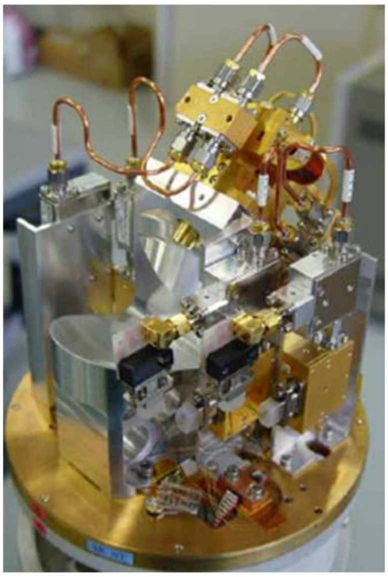

Fig.2 The 4 K stage of ALMA Band 8 pre-production model cartridge receiver.

B Optics

The receiver optics of the ALMA 12 m antenna is described [10]. A physical optics calculation of the ALMA receiver optics was made [11] [12]. They use commercial software, GRASP8 (TICRA Co.). We have repeated their calculation with an updated version of GRASP9.

A cryogenic optics of this receiver adopts a single mirror to couple a feed horn in front of an SIS mixer block and the sub-reflector. An advantage of a single mirror over two mirrors is that it is relatively easy to align optical components of horns, mirrors and a wire grid. A disadvantage is that it is less free of mechanical design of the receiver. A reflection angle at the mirror is 22.5 degrees. The optical parameters were chosen as independent at both the feed horn and the sub-reflector in the frequencies of between 385 and 500 GHz. The receiver optics is inclined 1.006 degrees toward the subreflector.

The optics block was carefully designed mechanically to achieve optical parameters at 4 K.

1. to include cryogenic deformation of optics block at 4 K.
2. to allow mechanical measurements easily, several reference positions on the optics block are added.
3. to reduce weight to 590 grams, holes were drilled in optics block.
4. to reduce standing wave between the subreflector and the horn, an area around the horn aperture was hollowed out.

The optical block and mirrors were made of 6061 aluminium (Fig.). The alignment to the 4 K stage of cartridge body is determined by two 2 mm dowel pins. The block was measured with a coordinated machine, Mitsutoyo LEGEX910 and was consistent with designed values within typically 20 μm.

A corrugated horn for this receiver was designed by [13][14]. The design parameters are horn diameter of 7.99 mm, horn axial length of 24.1 mm, and horn slant length of 24.43 mm. The width and separation of corrugation are 90 μm. The round taper with 675 μm length connects the throat of the corrugation with a diameter of 680 μm and a circular waveguide with a diameter of 568 μm, which is in turn smoothly connected with a length of 1.375 mm to a rectangular waveguide with 556 μm x 278 μm (WR2.2). This was fabricated by electroforming by Oshima Prototype Engineering, Co.

C OMT and Sideband Separating Mixer (2SB)

We have developed an ortho-mode transducer (OMT)[8] and a sideband-separating (2SB) mixer [15]. To reduce waveguide transmission loss, an OMT and two RF quadrature hybrid / LO -17 dB couplers are combined in a waveguide block as shown in Fig. 3.

The Band 8 prototype OMT was a scaled model of Band 4 OMT [16], which has a Boifot junction and a double ridge for polarization separation. It was optimized for mechanical robust design of inner waveguide structure. It has low loss of -0.4 dB at 4 K and good polarization isolation of larger than 25 dB [8].

The sideband separation scheme is based on the design developed for the ALMA Band 4 cartridge[17]. The Band 8 sideband separation (2SB) mixers have been developed with waveguide quadrature hybrid [15]. The cartridge receives both upper and lower sidebands as IF frequencies from 4 to 8 GHz. It employs an RF quadrature hybrid and two single-ended DSB mixers followed by an IF quadrature hybrid as shown in Fig.. We have chosen to adopt a modular approach, which was originally proposed by [18] in which the DSB mixers and RF/LO coupler are independent. This allows the individual components to be tested separately prior to integration. In the modular scheme, it is essential to establish good interfaces to integrate these components.

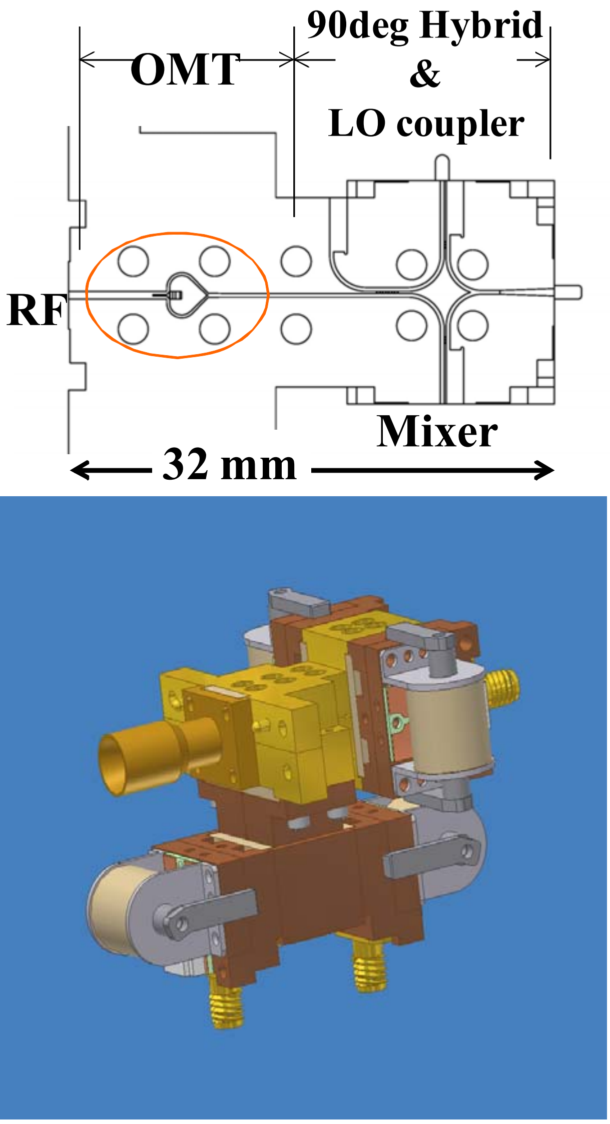

Fig. 3 Upper panel shows waveguide path of an OMT /RF quadrature hybrid / LO -17 dB assembly. Lower panels shows outlook of ALMA Band 8 pre-production model horn, OMT, 2SB mixers assembly.

The DSB mixer of this receiver has been developed by [19]. The SIS junction is made of Nb and AlOx on a quartz substrate of 60 μm thickness. It uses parallelly connected twin junction (PCTJ) which has been developed by [20] and [21]. The SIS junctions have a current density of 10 kA cm^2 or ωRC = 5 with a diameter of 1.2 μm. The input of a waveguide DSB mixer with 558 μm 229 μm (WR2.2) is reduced to a half of 508 μm x 127 μm at the SIS chip. This smaller size was chosen to cover the RF frequency between 385 and 500 GHz with cutoff frequency for the fundamental mode of around 300 GHz close to the lower RF frequency limit, in order to minimize the problem caused by unwanted lower-order harmonics in the LO signal. Typical noise temperature of ALMA Band 8 DSB mixers is shown in Fig. .

A superconducting magnet was used for a DSB mixer to suppress the Josephson effect. It consists of iron yokes and superconducting wires (Cu-cladding NbTi ϕ0.07 mm) with 3500 turns. It has 300 gauss with 10 mA current.

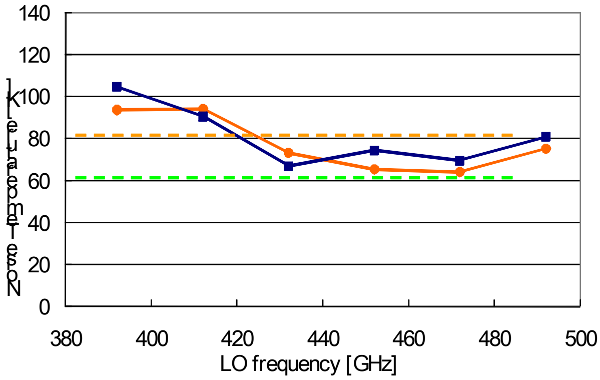

Fig. 4 Noise temperature of ALMA Band 8 DSB mixers.

D Intermediate Frequency (IF)

The Band 8 cartridge uses 4 cryogenic low noise amplifiers (CLNAs) to amplify the IF signal between 4 and 8 GHz from two 2SB mixers. It also uses 4 cryogenic IF isolators (CISO) at the input of the CLNAs. The CLNA made by Nitsuki uses GaAs HEMT chip and is operated with power consumption of 8 mW at 4 K. The noise temperature was 6 – 8 K with gain of 30 dB.

Two IF quadrature hybrids made by Nitsuki are mounted between the 2SB mixer and the CISO. Coaxial cables between the mixer and the CLNA use phase-matched one made of copper, while others are made of stainless steel (the central conductor is a silver-plated cupronickel). The phase difference of the pair cable is less than 3 degree.

To compensate frequency-dependent loss of thermally-isolated coaxial cables between 4 K and 300 K, warm IF amplifiers made by AML have an gain slope of 4 dB from 4 GHz to 8 GHz. The gain is 38 dB and NF is less than 1.5.

E Local Oscillator (LO)

Local oscillator for Band 8 cartridge has been developed and is provided by National Astronomy Radio Observatory (NRAO) in USA. It consists of cryogenic multiplier (x 6) operated at 100 K and warm cartridge assembly (eg. [22]). The output of the multiplier is transmitted with an oversize waveguide (WR6.3) to the OMT/2SB assembly. The LO signal is coupled to RF signal at the -17 dB coupler and terminated with wedge-type MF116 load. The load design is based on [23].

III. Receiver Performance

A Noise Temperature

Noise temperature of a Band 8 pre-production prototype cartridge was measured with standard Y-factor method.

These tests have been performed with a cartridge test cryostat [24].

Noise temperature was measured with cryogenic fifth times multipliers because of its availability. The outline is the same as sixth times multiplier. The multipliers are pumped with a Gunn oscillator and a W-band power amplifier covering frequency 80 – 99 GHz. A chopper which changes hot and cold loads moves at 4 Hz. Fig. shows single sideband (SSB) noise temperature of the Band 8 pre-production cartridge.

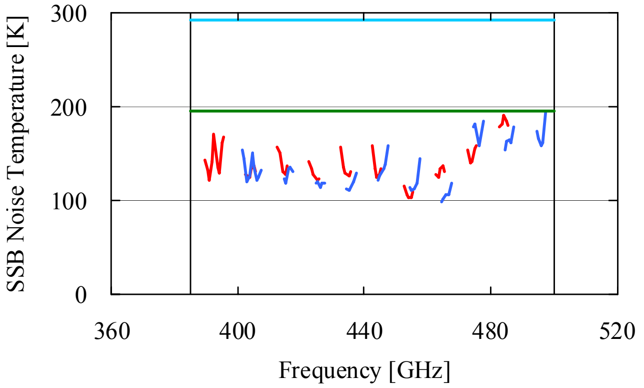

Fig. 5 SSB noise temperature of ALMA Band 8 pre-production cartridge. In ALMA specification, SSB noise temperature is less than 196 K over 80 % of the frequency range and less than 292 K at any frequency from 385 to 500 GHz.

B. *Image rejection ratio (IRR)*

Image rejection ratio (IRR) was measured with a method using an external signal source [25]. The RF signal from the source is coupled quasi-optically to hot and cold loads. Optics for both Y-factor and a signal source was designed with 5 times of Gaussian beam radius. They are frequency-independent at the horns.

The IRR was larger than 10 dB as shown in **Fig.** .

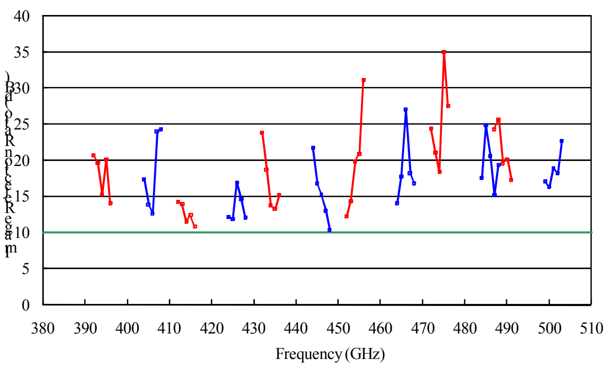

Fig. 6 Image rejection ratio of ALMA band 8 pre-production cartridge. The ALMA specification of IRR is larger than 10 dB.

C. *IF spectra*

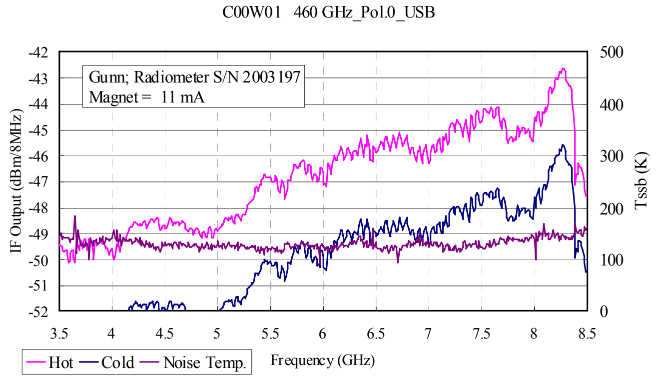

Fig. 7 Typical IF spectrum of ALMA Band 8 Pre-production cartridge at the LO frequency of 460 GHz.

A typical spectrum of the IF output is shown in Fig. . This is measured with a spectrum analyzer. The output power in the IF spectra has a gain slope because warm IF amplifier has a positive gain slope of 4 dB from 4 GHz to 8 GHz. The ALMA specification of gain variations in any 2 GHz is less than 4 dB. Band 8 pre-production cartridge can comply it in most of frequencies, but there are some frequencies which has larger variation than this specification.

D. *Beam measurements*

Beam pattern and Cross polarization pattern of Band 8 pre-production cartridge optics have been presented by [26]. The measure beam patterns are consistent with physical optics simulations at 385, 442, and 500 GHz. The cross polarization levels at 385, 442, and 500 GHz, are less than -23 dB. The main source of cross polarization was the OMT.

E. *Other performance*

Other performance such as gain compression, amplitude stability, and phase stability was measured with Band 8 QM cartridge [8]. Gain compression was less than 10 dB. The amplitude stability was around $3x10^{4}$ in 1 sec. The phase stability was less than 2.0 degrees on a timescale from 0.1 sec to 10 minutes.

F. Conclusions

We have developed a prototype of ALMA Band 8 cartridge receiver as well as its test equipment. The cartridge-type receiver includes cold optics, a feed horn, an OMT, two 2SB mixers, cryogenic multipliers, cryogenic and warm IF amplifiers. These components were individually tested and then the cartridge was integrated and tested as a complete assembly. We have also developed equipment to test both components and the integrated receiver.

The single sideband (SSB) noise temperature of this receiver is 130 K at the band center and 180 K at the band edges. The beam pattern and cross-polarization pattern are consistent with physical optical calculation. These results are promising for receiver production to the Atacama Large Millimeter/submillimeter Array.

ACKNOWLEDGMENT

We thank ALMA front end IPT lead by Gie Han Tan, John Webber. The authors also thank Takashi Noguchi, Tomonori Tamura, Shi-Cai Shi, Junji Inatani, Genshiro Fujii, Shin'ichiro Asayama, Yoshi Uzawa, Masahiro Sugimoto. This work was partially supported by Grant-in-Aid of JSPS No. 17530058.

REFERENCES

[1] Brown, R. L., Wild, W., and Cunningham, C. 2004 Advances in Space Research 24, 555
[2] R. Hills "Submillimeter interferometers: new standards for future instrumentation", Proc. Of 19th Int. Symp. on Space Terahertz Tech., 2008
[3] G. H. Tan "The ALMA front ends : an overview" Proc. Of 19th Int. Symp. on Space Terahertz Tech., 2008
[4] Orlowska, A., Harman, M., and Ellison, B. ALMA Project Book, chapter 6, 2002
[5] S. Matsushita, H. Matsuo, J. R. Pardo, S. Radford, "FTS Measurements of Submillimeter-Wave Atmospheric Opacity at Pampa la Bola II : Supra-Terahertz Windows and Model Fitting" PASJ, 51, 603, 1999
[6] Guilloteau, S. ALMA memo 393 "DSB versus SSB and Bandwidth/Sensitivity tradeoff" , 2002
[7] Iguchi, S. PASJ 57, 643, "Radio Interferometer Sensitivities for Three Types of Receiving Systems: DSB, SSB, and 2SB Systems", 2005
[8] N. Satou, Y. Sekimoto, Y. Iizuka, T. Ito, W. Shan, T. Kamba, K. Kumagai, M. Kamikura, Y. Tomimura, Y. Serizawa, S. Asayama, M. Sugimoto, "A Submillimeter Cartridge-Type Receiver: ALMA Band 8 (385 - 500 GHz) qualification model", Publication of Astronomical Society of Japan in press 2008
[9] M. Kamikura, M. Naruse, S. Asayama, N. Satou, W. Shan, Y. Sekimoto "Development of a 385 – 500 GHz Orthomode Transducer (OMT)", Proc. Of 19th Int. Symp. on Space Terahertz Tech., 2008
[10] Carter, M. C. et al. 2004 SPIE, 5489, 1074, "ALMA front end optics"
[11] Tham, C. Y., Withington, S. 2003, "Receiver Optics Design Electromagnetic Analysis, Second Report (Bands 3, 6, 7 and 9)"
[12] Tham, C. Y., Withington, S. 2003, "Receiver Optics Design Electromagnetic Analysis, Third Report (Bands 4, 8 and 10)"
[13] Matsunaga, M., Sekimoto, Y., Matsunaga, T., Sakai, T. 2003 PASJ 55, 1051 "An Experimental Study of Submillimeter-Wave Horn Antennae for a Submillimeter-Wave Astronomy"
[14] Matsunaga, M., Matsunaga, T., Sekimoto, Y. 2004 Proceedings of the SPIE, Vol. 5445, 446 "Analysis of submillimeter-wave horn antennas for submillimeter-wave telescope"
[15] M. Kamikura, Y. Tomimura, Y. Sekimoto, S. Asayama, W. L. Shan, N. Satou, Y. Iizuka, T. Ito, T. Kamba, Y. Serizawa, T. Noguchi "A 385 - 500 GHz Sideband-Separating (2SB) SIS Mixer Based on a Waveguide Split-block Coupler" International Journal of Infrared and Millimeter-Wave 27 (1), 37, 2006
[16] S. Asayama, S. Kawashima, H. Iwashita, T. Takahashi, M. Inata, Y. Obuchi, T. Suzuki, and T. Wada "Design and Development of ALMA Band 4 Cartridge Receiver", Proc. Of 19th Int. Symp. on Space Terahertz Tech., 2008
[17] Asayama, S., Ogawa, H., Noguchi, T., Suzuki, K., Andoh, H., Mizuno, A. ALMA memo 453, 2003
[18] Claude, S. M. X., Cunningham, C. T., Kerr, A. R., and Pan, S.-K. 2000, ALMA memo 316 "Design of a Sideband-Separating Balanced SIS Mixer Based on Waveguide Hybrids"
[19] Shan, W. L., Shi, S. C., Noguchi, T., Sekimoto, Y. 2005 IEEE trans. Applied Superconductivity 15, 503 Design and Development of SIS Mixers for ALMA Band 8"
[20] Noguchi, T., Shi, S. C., and Inatani, J. 1995, IEEE applied superconductivity, 5, 2228 "An SIS mixer using two junctions connected in parallel"
[21] Shi, S. C., Noguchi, T., Inatani, J. 1997 IEEE Trans. on Applied Superconductivity, 7, 2587 "Development of a 500-GHz band SIS mixer"
[22] E. Bryerton, J. Hesler "Sideband noise screening of multiplier-based sub-millimeter LO chains using a WR-10 Schottky mixer", Proc. Of 19th Int. Symp. on Space Terahertz Tech., 2008
[23] F. P. Mena, A. M. Baryshev, "Design and Simulation of a Waveguide Load for ALMA-band 9", ALMA memo 513, 2005
[24] Sekimoto, Y. et al. 2003 ALMA memo 455 "Cartridge Test Cryostats for ALMA Front End"
[25] Kerr, A.R., Pan, S.-K., and Effland, J.E. 2001, ALMA Memo 357, "Sideband Calibration of Millimeter-Wave Receivers"
[26] M. Naruse, M. Kamikura, Y. Sekimoto, T. Ito, M. Sugimoto, Y. Iizuka, N. Satou, K. Kumagai "Near field beam and cross-polarization pattern measurements of ALMA band 8 cartridges", Proc. Of 19th Int. Symp. on Space Terahertz Tech., 2008