MMA Memo 242:
Suggestion on LSA/MMA Front-end Optical Layout

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Abstract

Frontend Optical layout for MMA has been discussed in MMA Memos [1, 2]. We present here more detailed discussion for one of the previously suggested layouts, which employs a rotating beam director. However, we suggest to use warm optics and mechanics for such beam director. Regarding that we analyze possible mirror reflection loss. The optical design is discussed from the point of view of redundancy requirements, SIS mixer cooling and operation modes.

Introduction

The design of LSA/MMA front-end receiver is one of the key components of the future LSA/MMA instrument. Its design depends not only on technical problems of building multifrequency, multichannel and dual polarization receiver with the state-of-art sensitivity but also on considerations which form redundancy philosophy and instrument maintenance and running requirements.

Let us to illustrate this by discussing redundancy of the LSA/MMA frontend. Using dual polarization receiver itself protects the latter against complete loosing of a frequency channel due to a single mixer failure. However, we will loose Ö 2 of sensitivity in that case. Should we replace the broken mixer immediately, or the entire instrument performance will not degrade significantly if some percentage of broken pixels has occurred? The joint LSA/MMA project has become reality and the number of the antennas will rise up to 64. With realistic model for the receiver failure statistic we have to consider a number of mixers, frequency channels and may be even pixels being out of functioning at a time. Loosing a frequency channel (both mixers) should be considered as a signal for immediate action to replace the receiver, while loosing a mixer, perhaps, should wait for a regular maintenance. This approach to the redundancy allows us to avoid use of "hot replaceable" receiver modules to be plugged into the common dewar. Such modular approach will require very complicated dewar with a set of complex sensitive cryogenic, RF, IF and low-frequency interfaces for each plugged module. Presumably, such complexity can only increase statistics of failures. Instead, we choose a compact integrated design for the front-end that can be optimized in the sense of EMI/EMC, cryogenics and optics. Such a receiver can be replaced as an entire unit in the case of a failure with later maintenance held in laboratory conditions. Assuming altitude of above 5000 m at the LSA/MMA site this work looks easier than replacing a SIS receiver module with required high precision, accuracy and delicate interfaces.

Cryogenics

It seems reasonable to split HEMT amplifiers and SIS mixers between two separate dewars. HEMT amplifiers require only 10-20 K ambient temperature and can dissipate substantial amount of power. Requirements for cooling power can be fulfilled by employing a two stage cooler. Large area of the input windows (for frequencies below 100 GHz) adds up thermal load of the cooler and, therefore, splitting the front-ends into HEMT and SIS simplify cryogenic design for HEMT and eliminate thermal extra-load on the low-temperature cooler for SIS mixers. Further discussion is devoted to the SIS mixer front-end.

Nb-based SIS mixers for frequencies up to about 400 GHz operate at about 4 K, while above 400 GHz mixers, which demonstrate state-of-art performance, are further cooled down below 2 K. This fact needs further detailed research efforts. Generally speaking, an extra cooling improves "superconducting" properties of the Nb films. The lower ambient temperature decreases the level of thermal excitations around the tunnel barrier and leads to decreasing of the subgap current which is responsible for the SIS junction noise. This improvement is more pronounced at frequencies closer to the Nb gap frequency (gap frequency is about 650 GHz for practical Nb films with critical current density of about 8-10 kA/cm^2). This, perhaps, because high energy quanta delivered by powerful LO source may contribute to creating of extra quasiparticles in Nb electrodes that weaken superconductivity. By lowing the ambient temperature we decrease the energy of the thermal excitation on top of which the energy of quanta creates the quasiparticle. As the result, the cryocooler design will become even more complex and SIS mixers should be split into the two groups according to the required operating ambient temperature 4 and 2 K.

We mentioned above the extra thermal load through the input windows to inject LO/signal. The number of windows and their total area is of importance especially for 2 K section of the SIS mixer front-end where we can not expect excessive cooling power. Idle windows should be blinded to avoid unnecessary thermal load.. The cryogenic design should be compact to minimize length of the cold busses providing the mixers? cooling. More close placement of the mixers decreases the cold volume and the area of the first and the second thermal shields which consequently decreases the average flux of the thermal radiation launched towards the cold stage, finally yielding lower cooling power requirements.

Compact integrated design has the advantage of possible using of common IF amplifiers along with IF multiplexer with minimum length of IF cabling, especially in the case if the mixers will be equipped with a built-in IF pre-amplifier. Cold relays can be employed to switch the mixers bias, magnetic field supply wires and temperature sensors to avoid excessive wiring which typically brings EMI/EMC problems and is a source of additional heat.

SIS Mixer Optics

The two types of SIS mixers have been developed for mm and submm wavelength regions. The waveguide (WG) mixers consist of the mixer block where SIS chip mounted across the waveguide channel or a WG probe is employed. The WG mixer is typically equipped with a back-short and, sometimes, E-plane tuner with attached corrugated horn or, possibly, diagonal horn for frequencies above 500 GHz. WG mixers are traditionally used for radio astronomy and can be precisely tuned for optimum performance at the desirable frequency.

The open structure or quasioptical (QO) mixers consist of a mixer chip with integrated tuning circuitry integrated with a planar antenna and an immersion lens made from the same material as the substrate of the mixer chip. QO mixers are inherently fixed-tuned. There is a number of differences and advantages of using both of the two types of SIS mixer; the list of features WG vs. QO is presented in *Appendix 1*. LSA/MMA specifications require fixed-tuned mixers that may equalize chances of using both WG and QO type, the latter especially towards THz frequencies. Therefore, optics for both WG and QO type of SIS mixer should be considered.

Corrugated horn has excellent gaussivity of 0.98 [3], while the diagonal horn has it slightly lower, 0.84 [3], with noticeably higher cross-polarization level. Both horns launch fast beam of about F/3 that require a short focus mirror or lens placed close to the mixer to keep beam size reasonable. The lens can be a problem for dual polarization because of difficulties with the matching layer (grooved matching layer does not work well for both polarization [4]).

QO mixers use half-spherical, hyper-hemispherical and elliptical lenses. The half-spherical lens in combination with a planar antenna creates a beam very similar to that of the horn antennas. The beam launched by the hyper-hemispherical and elliptical lenses is slow, diffraction limited beam of about F/10. The gaussivity for the QO mixers is 0.89 [2]. The Si lens requires anti-reflection coating from a compound material [5]; the crystal quartz lens is matched by Teflon but may cause an enhanced back-hemisphere radiation loss.

For multi-frequency, multi-channel receiver it is natural to use individual optics to avoid difficulties in the mirrors design for wide frequency range [6], preferably by employing the Gaussian Telescope that provides *frequency independent* waist position and antenna-to-mixer beam coupling.

Metal Mirror Reflectivity for 100-1000 GHz

One of the previously mentioned optical layouts suggested a rotating beam director. This layout has an advantage of bringing the beams of all multiple mixers to the optical axis of the antenna. That allows to keep undistorted polarization and easier observation using sequence switching of frequencies / mixers without re-pointing the antenna. Using a cold optics is a natural way to reduce the noise contribution of the optic dissipation loss to the overall receiver performance. However, for a multi-channel receiver with the beam director this requirement directs to a cold mechanics. The beam director is a single failure point causing loss of the whole pixel of the array instrument. Therefore, willing to use a beam director should be complimented with a robust mechanics to control it. Removing the beam switch from the cryogenic temperature and using a step motor (known as a reliable electromechanical component) solves the problem of the reliability. However, we have to analyze possible contribution of the warm mirror to the receiver performance.

In our analysis of the mirror reflection we followed the method suggested in [2]. *Figure 1, 2* depict reflectivity of the mirrors made from different metals vs. frequency.

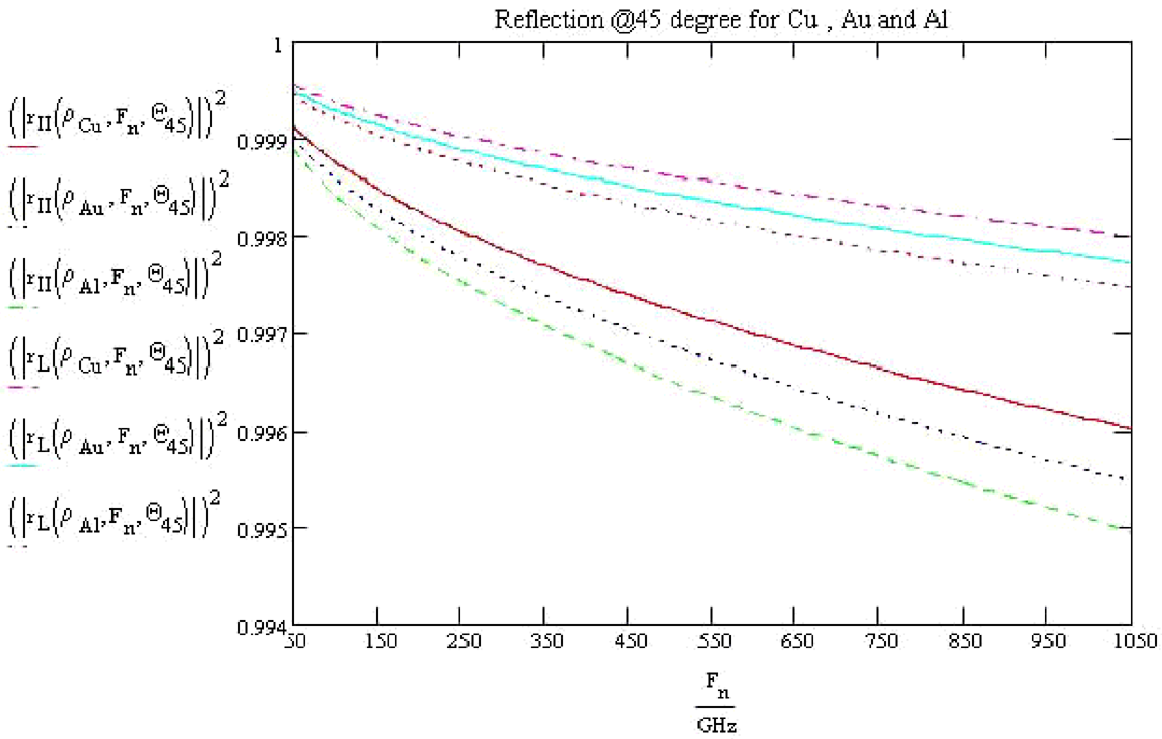

Figure 1 Reflection of the metal mirror made from aluminum, copper and gold. RF radiation comes at the angle of incidence 45^{o}, the two families of the curves present the reflection for the metals for parallel (II) (lower curves family) and the normal (L) polarization. Curves color cording is according to the legend to the left.

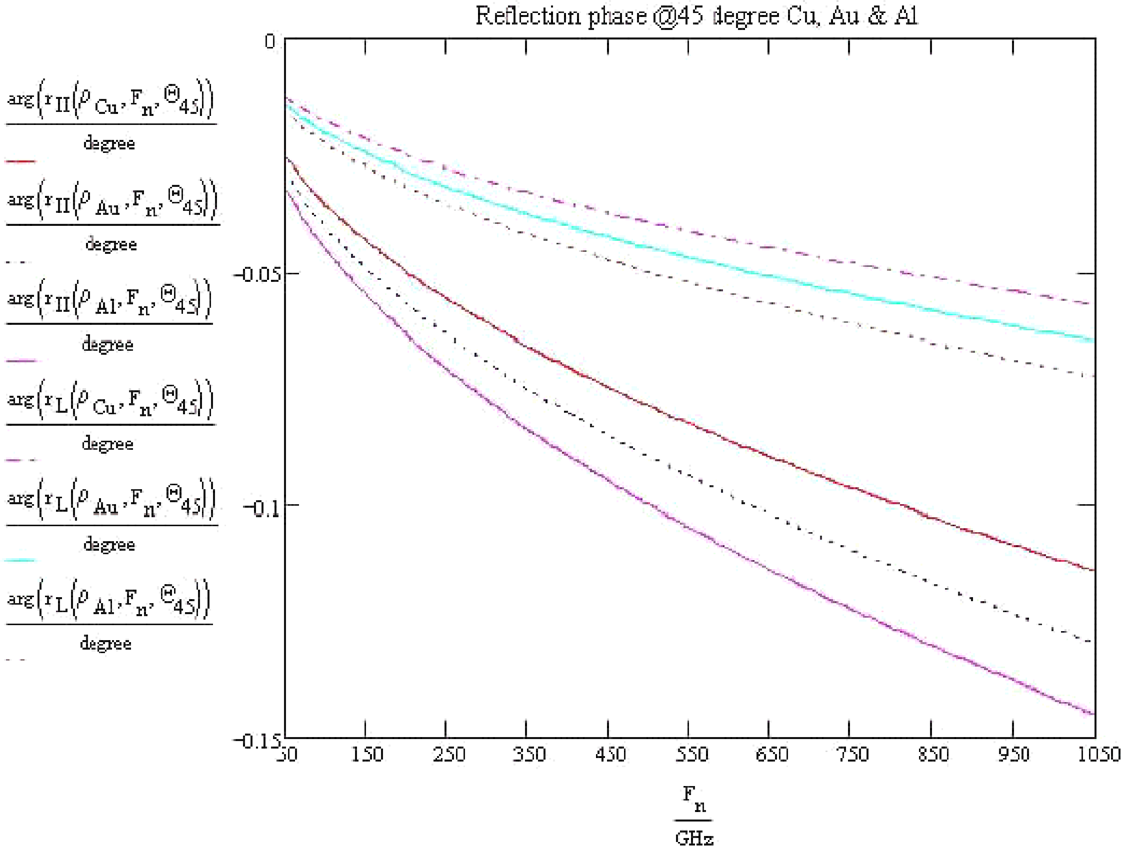

Figure 2 Phase of the reflection coefficient, angle degrees, for the metal mirror made from aluminum, copper and gold. RF radiation comes at the angle of incidence 45^{o}, the two families of the curves present the reflection phase for the metals for *parallel* (lower curves family) and the *normal* polarization. Curves color cording is according to the legend to the left.

Figures 3, 4 below present calculations for the two frequencies 100 and 1000 GHz as a function of the angle of incidence.

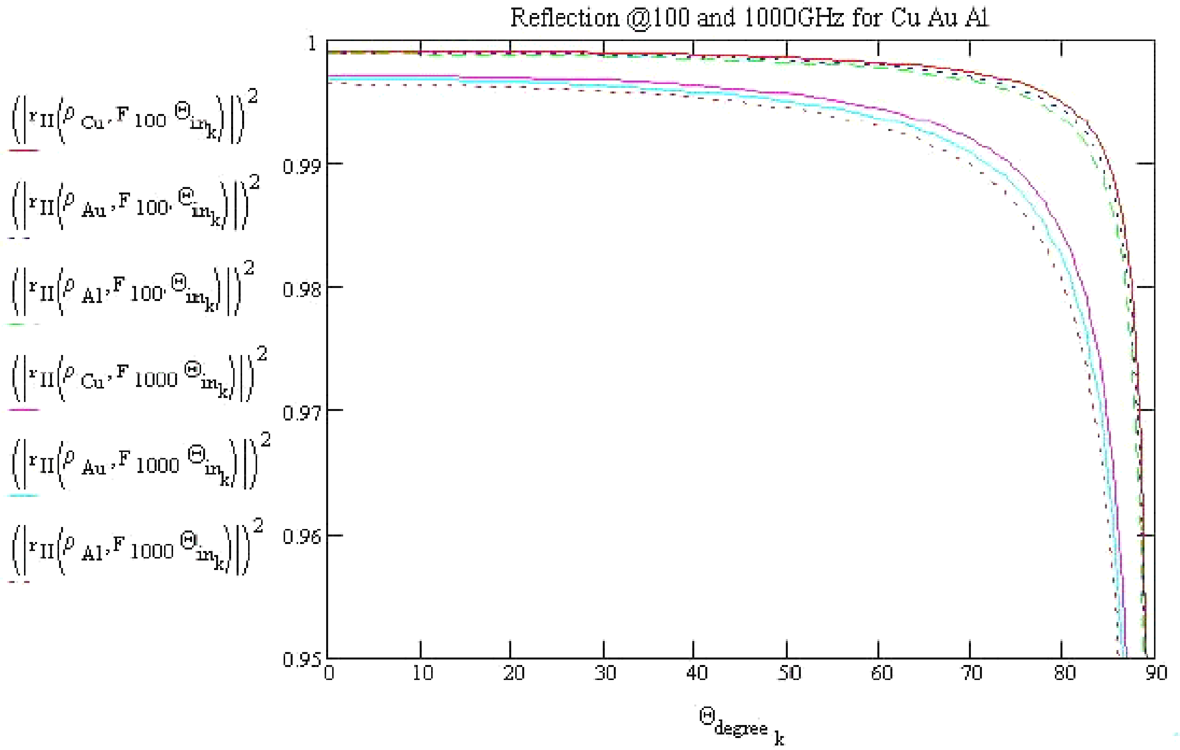

Figure 3 The reflection coefficient, for the metal mirror made from aluminum, copper and gold vs. angle of incidence. The calculation made for the two frequencies, 100 and 1000 GHz. The two families of the curves present the reflection for *parallel* polarization, the lower curves? family for 1000 GHz.

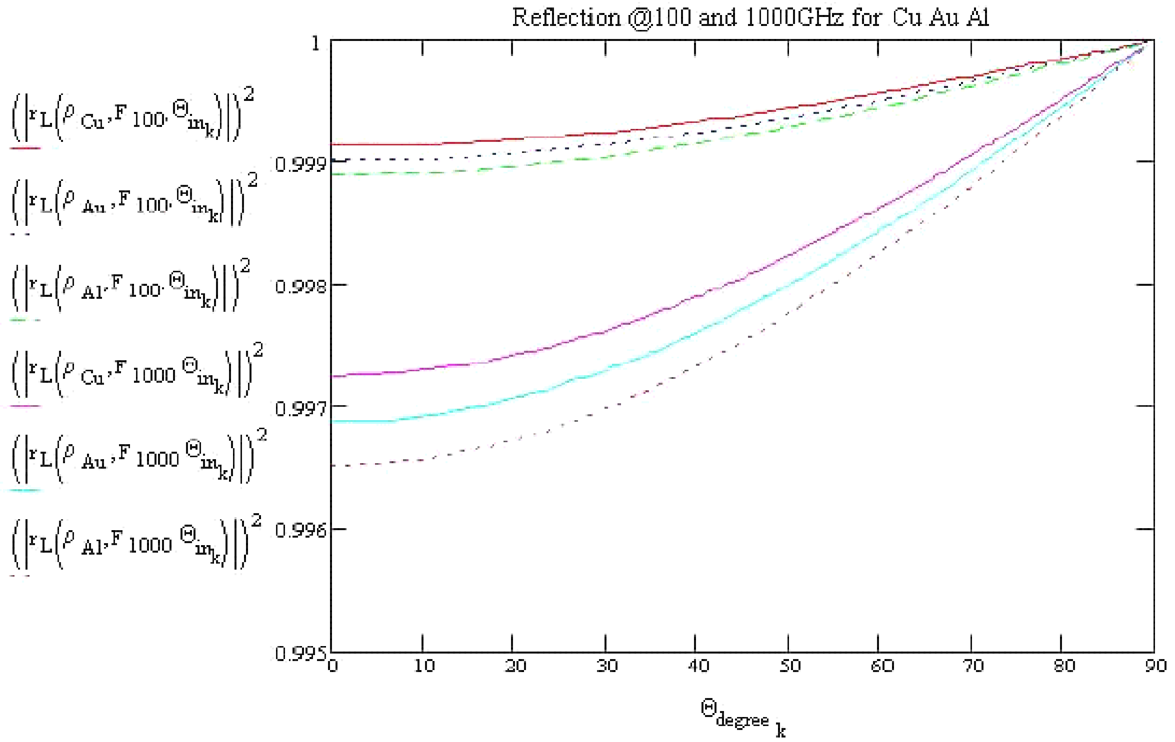

Figure 4 The reflection coefficient, for the metal mirror made from aluminum, copper and gold vs. angle of incidence. The calculation made for the two frequencies, 100 and 1000 GHz. The two families of the curves present the reflection for *normal* polarization, the lower curves? family for 1000 GHz.

In the calculation above we assumed that the mirror surface finish was better than 0.01 l_{min} . The latter requires for frequency 1000 GHz the *rms* surface accuracy of better 3 mm. One of possible technologies to produce flat mirrors for the beam director is to use an optically polished substrate made from glass, or a similar material, and to employ thin film deposition technique (sputtering, evaporation, etc.). This will ensure that the thin film reassemble flatness of the substrate and the film metal properties are well under control (typically the films may demonstrate higher resistivity than that of bulk metals). Additional advantage of using the vacuum deposition technique is a possibility to passivate *in situ* the surface of the mirror with, e.g., SiO_2 to prevent oxidation or the surface damage.

The plot (*Figure 5*) shows the skin depth for the metals considered above for the mirrors as a function of frequency. Assuming 5 times skin depth thick film we will get the required film thickness of 1.5 m>m (Cu film, for the lowest operating frequency 50 GHz). The protection layer of gold and/or SiO_2 can be of the order of 0.2 mm.

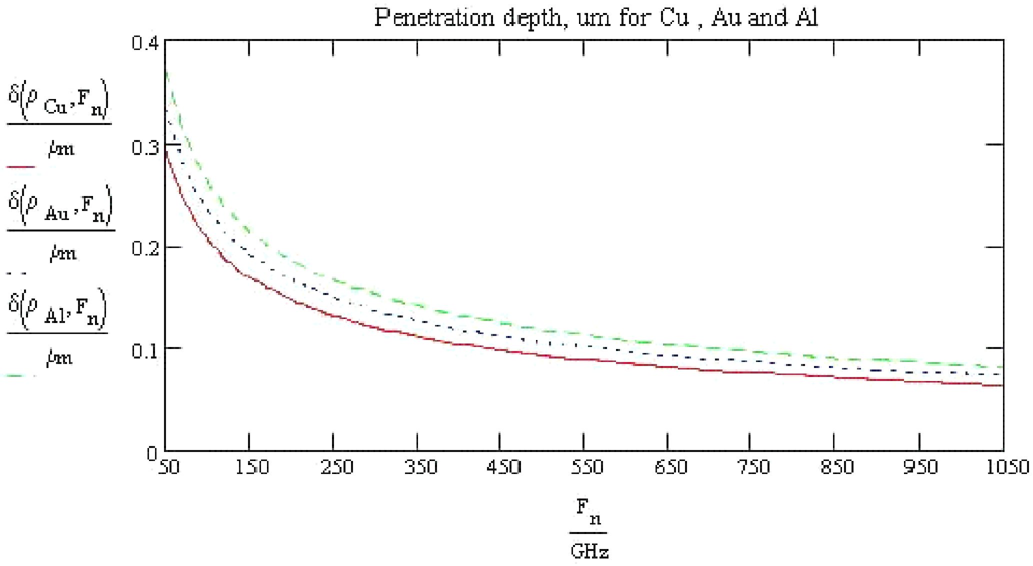

Figure 5 Penetration depth [mm] for copper (red), aluminum (blue) and gold (green) as a function of frequency.

Meshed / perforated surfaces can be a subject of interest as frequency separating filters to provide multifrequency operation or for filtering out the signal and pass through IR [7]. The reflectivity of such a surface can be modeled as a reflectivity of a solid metal surface with the *equivalent metal resistivity* that is a product of the actual metal resistivity and the ratio of the perforated/metal areas per unit of area. More complicated approach should take into account the increasing of the perforated metal resistivity due to extended length of the RF current flow onto such surfaces (we assume that the perforation size is much less than a wavelength of the radiation and DC current flow line approximation is applicable).

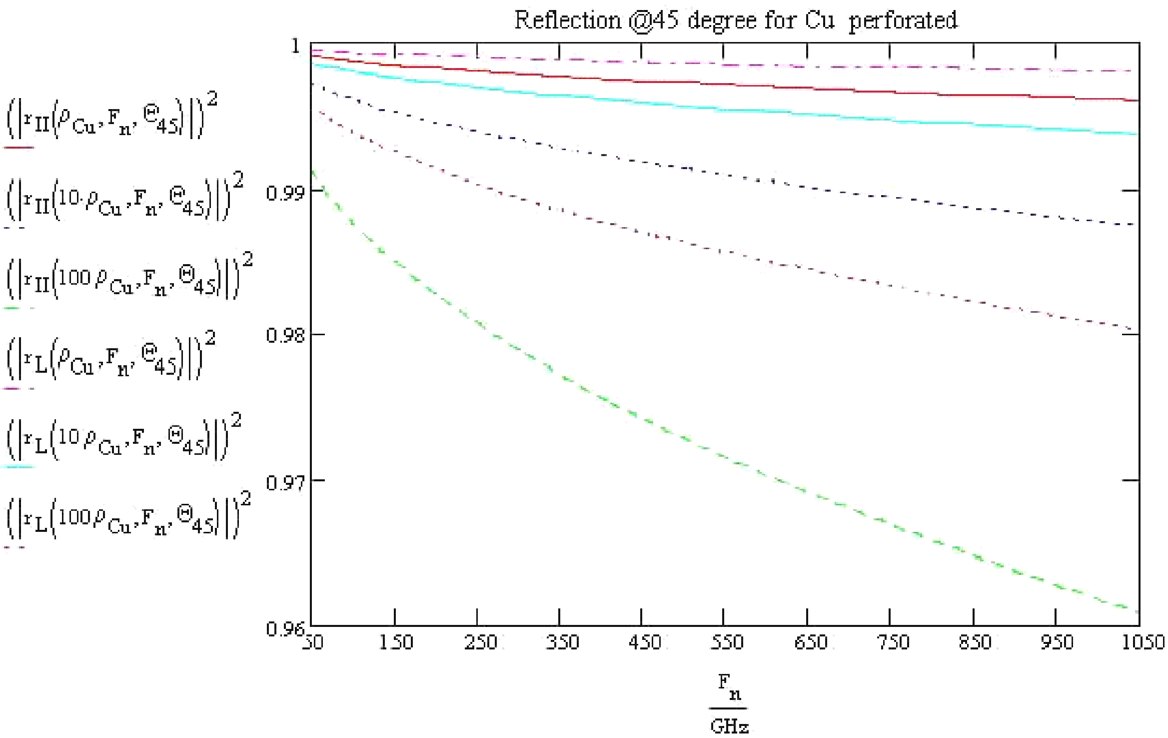

Figure 6 Modeled reflectivity of the Cu perforated surface. The solid red curve and the dash-dot magenta curve present reflectivity of the solid Cu metal surface for parallel (II, the even curves, from the top to the bottom) and normal polarization (L). Incidence angle is 45°, the ratios of the of the perforated/metal areas per unit of the reflector area are 10 and 100 (color coding at the left).

To summarize the results of our calculations, we can conclude that at ***the 50-1050 GHz frequency band the reflection of the metals, such as aluminum, copper and gold is > 99,5% for the incidence angle of 45°*** and even better for the lower angles of incidence. The requirements to the surface flatness, rms and the *metal thickness* allow using, e.g., the vacuum deposition technique to fabricate flat mirrors for the beam director. However, this technology hardly can be extended to produce focusing mirrors unless the film deposition technique would allow homogenous film thickness deposited on a curved surface or the mirror surface curvature is not very high. Reflectivity of the perforated surface can be noticeably lower at higher frequencies depending on the ratios of the of the perforated/metal areas per unit of the reflector area.

Receiver Optical Layout

Figure 7 below presents schematically the design of the beam director with room temperature optic and the dewar design. The two flat mirrors forming the beam director are used also to switch the receiver beam towards the calibration loads. The importance of the calibration was discussed in [8], therefore we consider that as additional advantage to have the built-in calibration loads. The plate of the director is rotated by a step motor to select a channel. The idle channels are blinded by the plate to prevent unwanted thermal load on the cryocooler. We assumed that we are able to place all focusing elements individually for each mixer inside the dewar.

For the suggested layout the input window of the cold calibration load must be transparent for all operating frequencies. The alternative is to calibrate the window loss vs. frequency to correct for the effective calibration load temperature at every frequency. This also requires monitoring of the window ambient temperature for accurate calibration.

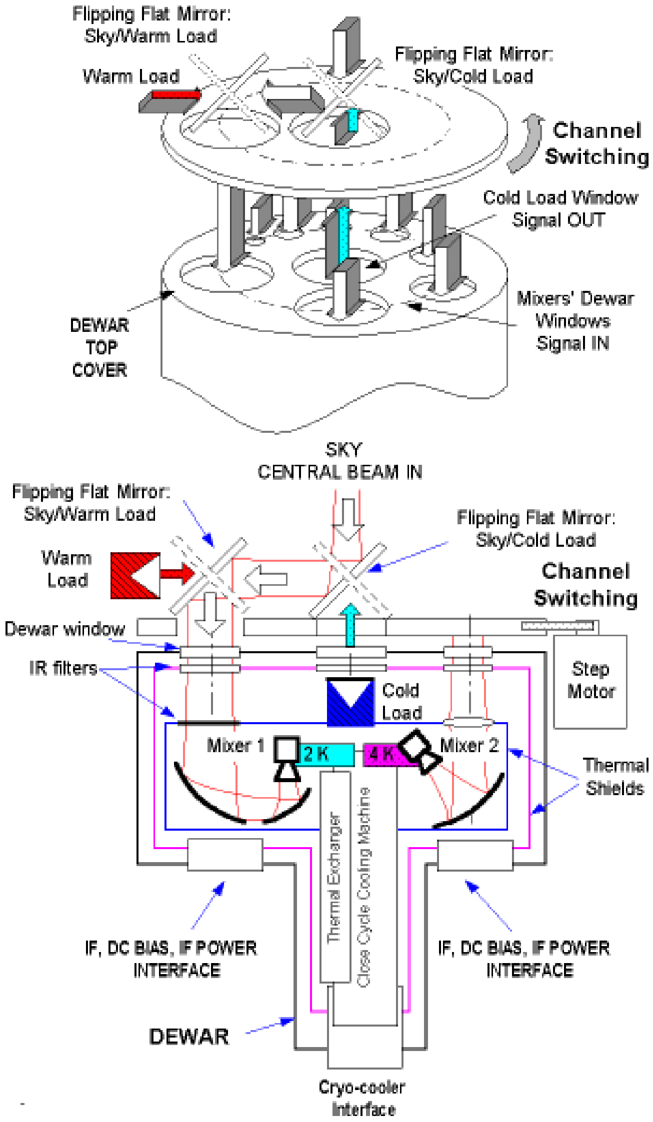

Figure 7 Suggested LSA/MMA receiver layout. Each mixer in the drawing represents dual-polarization mixer unit.

Only one mixer (dual polarization frequency channel) is available at a time to be operated for the suggested receiver layout. Note, however, that the scheme provides easy and quick changing of the observation frequency by rotating the director plate *without re-pointing the antenna* (64 antennas must be re-pointed for the entire instrument otherwise!). The receiver employing the suggested layout *can not be operated in a multifrequency observation mode*. However, the *off-axis* feed *can not* provide multifrequency operation either due to pointing of the channels on the different sky positions unless very unlikely event of pointing two channels at the two different objects of interest.

If the multifrequency observation is of a high priority, this can be realized by introducing a polarization splitting grid in front of the receiver at 45^{o} to the beam direction. The receivers with the layout presented at *Figure 7* made as *a single polarization receiver* should be connected to each port of the polarization splitter (grid). The multifrequency operation will be provided by the *two receivers* for *any combination of the frequencies* via the split polarization and at the expense of Ö 2 loss in the sensitivity compare to the dual polarization observation.

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Appendix 1

WG mixer vs. Quasi Optical mixer*

WG	QO
Corrugated or diagonal horn attached to a waveguide mixer block with backshort or fixed tuned	Planar type antenna (antenna array) integrated with a SIS mixer onto immersion lens. Fixed tuned
Traditional design, well known technology	Relatively new, used for radioastronomy observations only at submm wavelengths
Allow tuning for best matching	Fixed tuned
Gaussian Beam Coupling **0.98**/0.84	Gaussian Beam Coupling 0.89 (DS<->DD)
Fast beam ~F/3	Slow beam ~F/10 (with hyperhemispherical or elliptical lens)
Difficult scaling with frequency, but technology does exist. Could cause problems with the SIS mixer embedding impedance (interconnection) above 400 GHz.	Easy scaling with frequency (matching layer on the Si lens could be an issue). SIS structure directly connected to the antenna output.
WG-band (25% max?)	Typically 25% or more
Excellent EMI/EMC protection (multi-frequency frontend). Problem with ground loops.	Less shielded against EMI/EMC. Easy to avoid ground loops using suspended IF ground.
Magnetic field guiding and IF circuitry may interfere with RF design	Magnetic field guiding and IF circuitry easy to integrate into RF design
Difficult and expensive in series production (using standard way of doing it via milling process). Requires unique experience at frequencies above 500 GHz	All accurate operations are made via photolithography; the only "critical" operation is the sample mounting onto the lens. Lens is fabricated by a commercial company.

* The list of the comparison above is not complete and suggests continuation of the discussion.