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A NEXT GENERATION MULTI-BEAM FOCAL PLANE ARRAY RECEIVER OF TRAO FOR 86-115 GHZ BAND

Moon-Hee Chung[1]†, Vladimir B. Khaikin[2], Hyo-Ryoung Kim[1], Changhoon Lee[1], Kwang-Dong Kim[1], and Kiwon Park[1]
[1]TRAO, KASI, 61-1, Hwaam-dong, Yusong-gu, Taejon 305-348, Korea
[2]The Special Astrophysical Observatory of RAS, 194021 St. Petersburg, Russia
E-mail: mhchung@trao.re.kr

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ABSTRACT

The noise temperature of existing millimeter-wave receivers is already within two or three times quantum noise limit. One of practical ways to increase the observation speed of single dish radio telescope without longer integration time is use of multi-beam focal plane array receiver as demonstrated in several large single dish radio telescopes. In this context the TRAO (Taeduk Radio Astronomy Observatory), which operates a 14 m Cassegrain radio telescope, is planning to develop a 4 x 4 beams focal plane array SIS receiver system for 86-115 GHz band. Even though millimeter-wave HEMT LNA-based receivers approach the noise temperature comparable to the SIS receiver at W-band, it is believed that the receiver based on SIS mixer seems to offer a bit more advantages. The critical part of the multi-beam array receiver will be sideband separating SIS mixers. Employing such a type of SIS mixer makes it possible to simplify the quasi-optics of receiver. Otherwise, an SSB filter should be used in front of the mixer or some sophisticated post-processing of observation data is needed. In this paper we will present a preliminary design concept and components needed for the development of a new 3 mm band multi-beam focal plane array receiver.

Keywords: multi-beam feed, sideband-separating SIS mixer, focal plane array receiver

1. INTRODUCTION

The TRAO (Taeduk Radio Astronomy Observatory) 14 m radio telescope is located at about 110 meters above sea level. Because of the low altitude of the observatory site and lossy radome enclosing the radio telescope, the observation frequency band of the TRAO 14 m telescope is restricted to lower than 200 GHz. In general the noise temperature contributed by the atmosphere and the antenna itself is greater than around 300 K across the operation band. The noise contribution of the system except the receiver portion is far higher than the noise temperature of SIS mixer-based receivers for 3 mm and 2 mm bands. This implies that decreasing the single-beam receiver's noise temperature does not greatly benefit the observation efficiency in terms of mapping speed when performing the observation of large extended sources like molecular clouds or galactic plane.

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† corresponding author

Table 1. Cassegrain antenna parameters of the TRAO radio telescope.

Antenna Parameter	Specification
Diameter of the main dish	1371.6 cm
Diameter of the secondary mirror	108.6 cm
Prime focal distance	508 cm
Interfocal distance	462.3 cm
Illumination semi-angle	7.02 deg
Feed taper	–13/-10 dB

Since many millimeter and submillimeter-wave observatories faced the same problem, over the last two decades several multi-beam focal plane array receivers at millimeter and submillimeter wavelengths have been constructed and proved the promising performances compared to the single-beam receivers (Payne 1988, Erickson et al. 1992, 1999, Güsten et al. 1995, Groopi et al. 2003, Schuster et al. 2004). The multi-beam focal plane array receiver became a radio astronomical instrument of choice for the single dish millimeter and submillimeter-wave telescope (Goldsmith et al. 1993). One of the main rationales of developing the multi-beam focal plane array receiver is to dramatically improve the mapping speed. In addition to this advantage, another benefit is to make possible the cancellation of the atmospheric fluctuations in continuum observations. In this context, the TRAO is planning to develop a new multi-beam focal plane array receiver for 3mm band.

The image rejection or sideband separation in the spectral line observations is imperative to eliminate the atmospheric noise or unwanted signal noise from the image band. Earlier multi-beam receivers based on Schottky or SIS mixers utilized quasi-optical devices for the single sideband diplexing (Erickson et al. 1992, Güsten et al. 1995, Groopi et al. 2003) or a technique of backshort adjustment of the SIS mixer for achieving the image rejection (Schuster et al. 2004). A cryogenic HEMT LNA-based multi-beam array receiver for 3 mm band employed a technique of choosing very wide IF frequencies to ease sideband separation problems (Erickson et al. 1999). In conjunction with the advance of millimeter-wave waveguide design and fabrication techniques, the sideband-separating SIS mixers using waveguide structure for 3 mm and 1 mm bands have been rapidly progressed during the past few years. These waveguide type sideband-separating SIS mixers have been developed by several groups (Claude 2003, Asayama et al. 2003b, Kerr et al. 2004) and the laboratory demonstrations and a test observation (Asayama et al. 2003a) indicated that the sideband-separating SIS mixer technology is mature enough to be applied to multi-beam array receivers. Employing such a sideband separating SIS mixer enables the optics of multi-beam array receiver to be simpler than quasi-optical scheme-based receivers for the image rejection and the operation of multi-beam focal plane array receiver can be easier. On the other hand, as shown in Erickson et al. (1999), recent progress of millimeter-wave HEMT LNA also provides another option for multi-beam array receiver developments.

The detailed technical designs for components needed in the multi-beam focal plane array SIS receiver are now under way. In this paper we describe our design philosophy concerning the input optics, sideband separating SIS mixer, LO system and IF amplifier.

2. ANTENNA MODELING

The radio telescope of the TRAO is a classical Cassegrain type and the secondary focus is located just before the vertex of the primary reflector. The Cassegrain F/D is 4.074. Table 1 shows

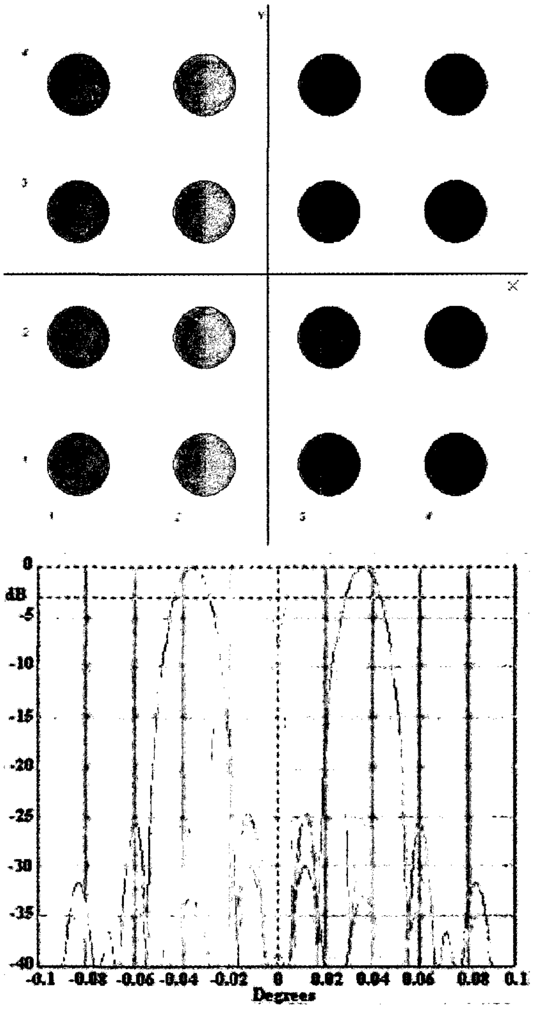

Figure 1. Position of array feeds (top) and beam patterns of the array at 100 GHz (bottom).

the antenna parameters of the TRAO radio telescope.

For the simulation of the multi-beam radiation pattern of the 14 m telescope and calculation of some other antenna characteristics (illumination, aperture, spillover, sidelobe efficiencies, beam overlapping level, etc.), FOPAS (Focal Plane Array Simulation) program has been applied (Khaikin 2005). FOPAS uses GO+PO approach and takes into account the geometry of dual reflector radio telescope, expected aperture distribution or beam pattern of ideal broadband feed, the feed removal from the focus and off-axis aberrations. Some results of the simulation are given in Figures 1-3. The long focal length of TRAO Cassegrain type telescope with m = (e+1)/(e-1) = 1-1 gives negligible aberrations for off-axis beams. Given the telescope optics, the minimum feed spacing in the secondary focus is 25 $\sim$ 27 mm which provides beam separation larger than 100 arcsec and beam overlapping level $-12 \sim -11$ dB. With closer feed spacing, spillover/sidelobe efficiency falls while

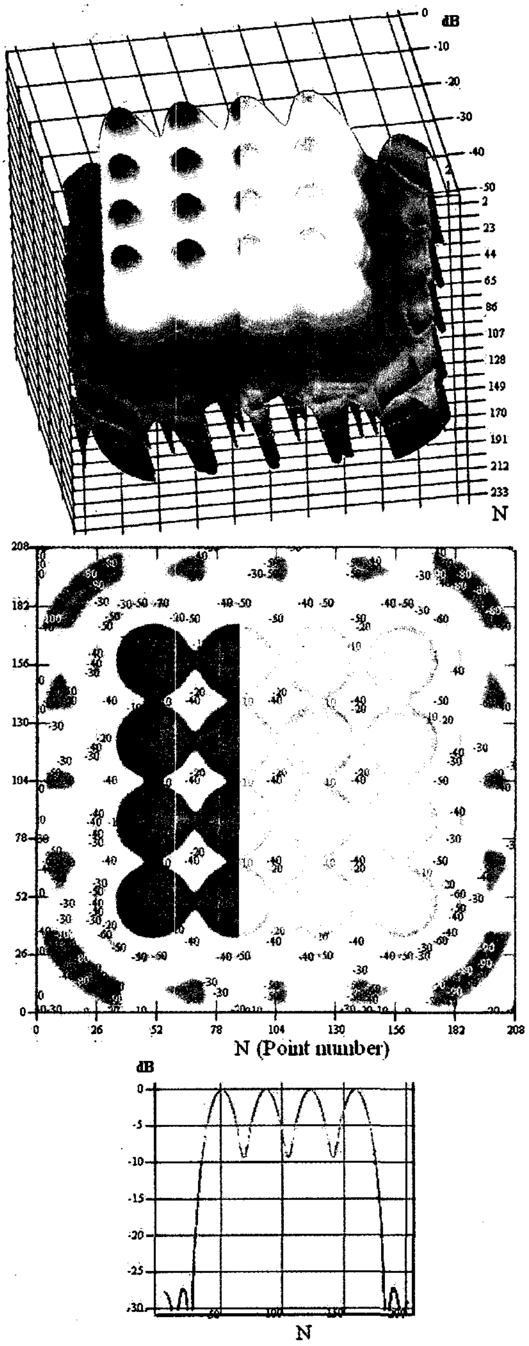

Figure 2. 3D 4 x 4 beam pattern of TRAO 14 m telescope at 100 GHz (top) with -10 dB feed taper, isolines (middle), and cut view (bottom).

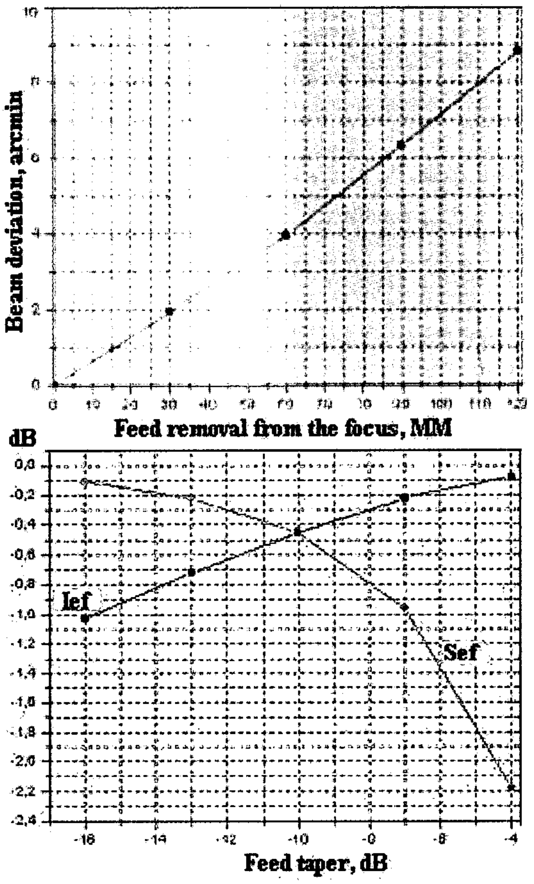

Figure 3. Beam deviation dependence on the feed removal from the focus (top), illumination and spillover efficiencies as a function of feed taper (bottom).

the antenna temperature increases. Therefore an additional input optics is needed in a multi-beam mode to reduce beam separation, beam overlapping level, antenna temperature and cross-talk effect as well. In the multi-beam simulation we used the feed spacing 23.5 mm which must be provided by the additional input optics with an ellipsoidal mirror. For more accurate simulation PO+GO+GTD approach must be used to take into account all the mirrors and diffraction effect in the input optics.

3. INPUT OPTICS

Considering the fact that the main goal of multi-beam focal plane array receiver is to increase the mapping speed, how to configure the input optics of multi-beam array receiver is one of the most important design issues. To make the sampling on the sky as close as possible, it seems better to pack the mixer and feedhorn modules as closely as possible. But some spacing constraints arise from the physical dimensions of the sideband-separating mixer block which is relatively larger compared with a single DSB mixer block and the cross-talk among the adjacent feedhorns. One method to

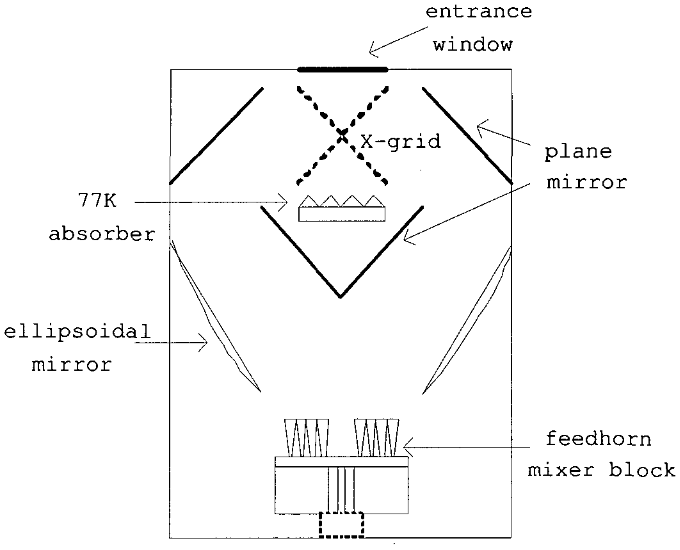

Figure 4. Layout of optical scheme.

avoid the above problem is to interleave the opposite polarizations of the two sub-arrays, which was already used by other groups (Erickson et al. 1992, Güsten et al. 1995). In the current design we make use of the similar approach to deploy the feedhorn-mixer modules of the array, that is, 16 beams are divided into two groups: horizontal and vertical polarization groups each containing 8 feedhorn-mixer modules. Another issue in designing of the input optics of multi-beam array receiver is concerned with the image rotation. Recently the OTF technique has been widely used for mapping observation. If such an OTF observation technique is employed, it's not needed to have an image rotator in the multi-beam array receiver. The combination of multi-beam array receiver and OTF observation technique will offer a powerful observation capability for the mapping of large extended sources.

The overall layout of the input optics of multi-beam focal plane array receiver is depicted in Figure 4. The main function of the optics is to perform the polarization interleaving on the sky and match the beams from the feedhorns to the required beam waist for the optimum illumination on the subreflector. The input beam is divided into two orthogonal polarizations via an X-grid through which the infrared radiation falls on 77 K absorber. Without this scheme a huge thermal load caused by the infrared would impinge on the cold stage. The optics has a symmetric structure for both polarizations. The sub-array for each polarization consists of 8 feedhorn-mixer blocks. The diameter of feedhorn is around 22 mm and corrugated circular horns will be used for its well-known properties and performance. The maximum field of view of multi-beam focal plane array receiver can be determined by the allowable antenna gain degradation due to the lateral displacement of the feed at Cassegrain focal plane. The spacing between the adjacent beams and the entrance window located near the Cassegrain focus are decided to be 23.5 mm and about 100 mm diameter, respectively. The antenna gain decrease due to the off-axis displacement in the 4 x 4 beams configuration is practically negligible and the main constraint of the field of view is rather the physical dimensions of multi-beam array receiver. The plate scale of the TRAO 14 m telescope is 3.69 arcsec/mm and

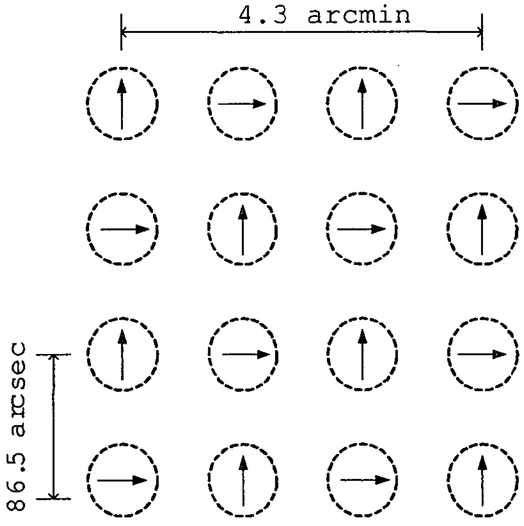

Figure 5. Beam footprint on the sky of the multi-beam focal plane array receiver at 100 GHz.

Table 2. Design goal of the SSB SIS mixer.

Mixer Parameter	Specification
RF band	86 – 115 GHz
Noise temperature(SSB)	< 60 K
IF band	4 – 8 GHz
Image rejection ratio	> 10 dB

the spacing of beams on the sky is 86.5 arcsec as shown in Figure 5. The beam spacing is about 1.73 x FWHM at 100 GHz. The most critical part of the input optics is to design a single large off-axis ellipsoidal mirror as shown in Figure 4. The requirement of maintaining good image qualities over the field of view leads to take a different mirror design approach compared to the traditional single-beam mirror optics. The design technique involves modifying the basic ellipsoidal mirror's geometric foci while keeping other properties fixed in order to improve the off-axis imaging across the field of view at the expense of a slight degradation of the on-axis image as explained in Serabyn (1997). So, the modified ellipsoidal mirror has a larger size and more axisymmetric section than the original basic ellipsoidal mirror. Optimizing the geometry of ellipsoidal mirror is being carried out by using commercially available software such as Zemax to calculate the Strehl ratios across the field of view.

4. SIDEBAND-SEPARATING SIS MIXER

In the spectral line observation the sideband separation or image rejection is necessary to practically suppress the unwanted noise from the image band. Until recently the methods of sideband

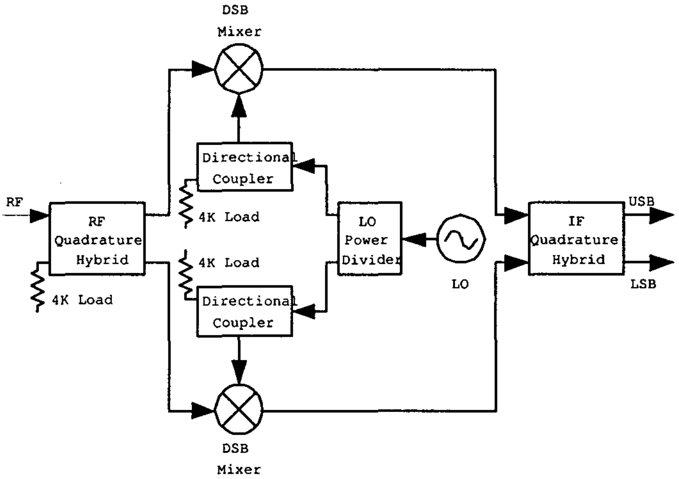

Figure 6. Schematic diagram of the sideband separation mixer.

separating at millimeter and submillimeter wavelengths were use of quasi-optical devices or relying on sophisticated software. But over the past few years several groups have developed sideband-separating SIS mixers for 100 GHz and 230 GHz bands using waveguide technology and demonstrated very encouraging performances (Claude 2003, Asayama et al. 2003a,b, Kerr et al. 2004). So, it was decided to employ sideband-separating SIS mixers in the multi-beam focal plane array receiver. As shown in Figure 6, a sideband separating mixer module comprises two quadrature hybrids for RF and IF, directional couplers, in-phase power divider, and two DSB mixers. The DSB mixer is a tunerless SIS mixer which has no need of using mechanical tuner. We can fabricate the RF quadrature hybrid, directional couplers, in-phase power divider, and DSB mixers in a single E-plane split-block component of which two halves have a symmetric structure. The RF quadrature hybrid and directional couplers are an E-plane branch-line coupler type. Considering the integration of 16 mixer modules in a limited space, the physical size of the mixer module is a critical issue and now the sideband separating mixer block is being optimized to have a compact size which enables ease of assembling and maintaining the sub-array unit. The design goal of single sideband separating SIS mixer is described in Table 2.

5. LO, IF AMPLIFIER AND OTHER PARTS

In the summary below we briefly mention other parts needed for the multi-beam focal plane array receiver. The LO signal generation for simultaneously pumping the 16 SSB SIS mixers (or 32 DSB SIS mixers) at 3mm band doesn't appear to be a greatly difficult task thanks to the very small LO power requirement of SIS mixer itself and the advancement of the millimeter-wave solid-state MMIC technology (Morgan et al. 2002). What makes LO power problem sophisticated is rather how to distribute and adjust the LO power for each SIS mixer which is supposed to demand different LO power level. An encouraging experience of shared LO power adjustment for a waveguide type array SIS receiver was reported by Schuster et al. (2004) and a further work for this LO adjustment problem is required. The IF amplifier scheme must be as simple and compact as possible due to

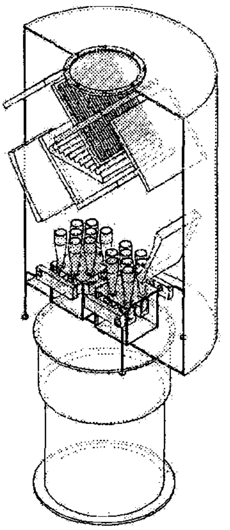

Figure 7. 3D drawing of the proposed multi-beam focal plane array receiver.

a large number of mixer elements in the array receiver. One of the candidates for such a goal is to integrate MMIC amplifier like WBA13 chip into the mixer module(Engargiola et al. 2004), so that the cryogenic isolator is not necessary between mixer and IF amplifier and assembling of the IF amplifiers into the mixer modules can be very simplified. As reported in the literature, WBA13 is a very low noise and ultra wideband cryogenic MMIC amplifier which seems appropriate for the IF amplifier across 4-8 GHz. If the thermal isolation between the SIS mixer and IF amplifier chip is made for the power dissipation of amplifier not to influence the physical temperature of the SIS junctions, such a scheme can make assembling of the mixer and IF amplifier module very simpler. Another issue is concerned with cooling system. We have used a Daikin CG308SC cryocooler since several years and its cooling capacity is about 3W at 4 K which is believed to be sufficient for cooling the whole SIS mixers to 4K.

6. CONCLUDING REMARKS AND FUTURE WORKS

Figure 7 illustrates a 3D drawing of the proposed receiver system in this paper. This is a preliminary design concept and there remain many technical works to be done. The development project of the multi-beam focal plane array SIS receiver is now in the phase of detailed designs. Because of the relatively wide field of view, the proposed multi-beam focal plane array receiver may be suitable for survey observation programs. In addition to the above plan, a multi-beam array receiver employing cooled HEMT LNA is being proposed in parallel for the TRAO 14 m telescope (Khaikin et al. 2005). Both multi-beam focal plane array receivers can be used for mapping in continuum and spectral line observations which also include a search for Spectral Spatial Fluctuations (SSF) of Cosmic Microwave Background (CMB). SSF of the CMB temperature must be a result of an interaction of primordial molecules (LiH, H2D+, HeH) with CMB and proto-objects moving with peculiar velocities relative to the CMB (Dubrovich 1977, 1997, Khaikin et al. 2005). SSF detection will lead to the discovery of the cosmological molecules which can help us to explore Dark Ages epoch of the early universe ($10 < z < 300$) and physical properties of Dark Matter and Dark Energy.

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