TECHNIQUES FOR HETERODYNE ARRAY RECEIVERS

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ABSTRACT

We present current and possibly future techniques for spatially multiplexed heterodyne receivers. The presentation comprises various ways of multiplexing LO power, dense arrangement of mixer elements in a cryogenic focal plane, manufacturing techniques of integrated optics units for reduction of optical adjustment effort, and describes an automated procedure for tuning a large number of mixer elements in short time.

INTRODUCTION

Millimeter and submillimeter observations generally require appropriate weather conditions, mainly a very low water vapor content which occurs at a very cold atmosphere such that the absolute humidity is low, at certain epochs when the evaporation from the ground is low or at high altitudes where the absolute airmass is low. Since the far–IR– and Submm–absorbing water vapor content is one of the most variable quantities of our atmosphere in space and in time, all of these occasions of good observing weather are transient phenomena resulting in limited time windows for a particular site. To improve the efficiency of ground based or airborne telescope observing time it is conceivable to perform multiple observations at the same time, requiring arrayed receivers in the focal plane of telescopes.

In order to design, build and use array receivers for millimeter and submillimeter radiation we present current techniques for various aspects of the receiver system: In Section we review ways to distribute local oscillator (LO) power to the mixers, Section covers an integrated focal plane population concept that facilitates easy–to–use concepts with respect to manufacturing, assembly and operation. In Section the integrated optics design approach is discussed with similar premises as for the focal planes. Finally Section describes our approach at KOSMA for an automated tuning algorithm for mixer elements.

LOCAL OSCILLATOR MULTIPLEXERS

Various ways exist for multiplexing local oscillator power to a number of mixers in a focal plane simultaneously. Currently implemented designs are reviewed briefly in the following. Main design constraints common to all local oscillator multiplexing techniques is the power distribution efficiency. Goal is to distribute power to the desired number of beams without much loss: In beam splitters losses show up mainly in absorption and reflection of a few percent due to finite refraction indices, in gratings lost power is scattered away statistically or appears in higher unwanted orders.

Beam splitter

Traditionally the use of beam splitters for local oscillator multiplexing is especially attractive for small arrays. As demonstrated by *Pole STAR*[1] (2×2 810 GHz array) the total efficiency of the 2×2 beam splitter can reach up to 72%. For small arrays as 2×2 the efficiency of reflective Fourier gratings is comparable to that of beam splitters (see also discussion in Section).

Wave guide couplers

Operating large arrays at lower frequency allows supply of LO power by wave guide couplers directly to the mixers in the focal plane. This approach has been implemented by the 230 GHz array receiver HERA[2] at IRAM. At higher frequencies wave guide structures become ever smaller and thus more difficult to manufacture with sufficient surface accuracy, increasing losses substantially. An approach to overcome these losses is to supply the focal plane with low frequency LO power and multiply it immediately at the focal plane mixer elements.[3]

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Dammann gratings – Multilevel phase gratings

Dammann gratings[4] are binary phase gratings which introduce a phase shift of 0 or $\lambda/2$ throughout the whole grating surface. Multilevel phase gratings offer more flexibility for multiplexing LO power into several beams since more degrees of freedom are available. Depending on frequency, material and geometrical constraints within the instruments, step level gratings can be layed out as transmissive or reflective gratings. CHAMP of the Max–Planck–Institute for Radioastronomy (MPIfR) makes use of transmissive multilevel gratings[5] to split the LO source into 8 beams.

These gratings are usually manufactured using conventional milling techniques. Gratings for 2D–dispersion require a chess board like design with some of the facets (e.g. the white ones) recessed. Direct milling of their sharp concave corners is impossible though with a finite size end mill. In practice often two 1D–grating elements which crossed dispersion directions are employed.

Fourier gratings

Increasing the number of levels in multilevel gratings eventually converges into a grating with smooth structure, a Fourier grating.[6] The effort of calculating the grating pattern becomes small[7] if the Fourier–transform formalism is applied and the surface structure is approximated by a finite number of Fourier components. Resulting smooth structures can be used in off–axis configuration and are easily machined on a numerically controlled mill with a spherical end mill.

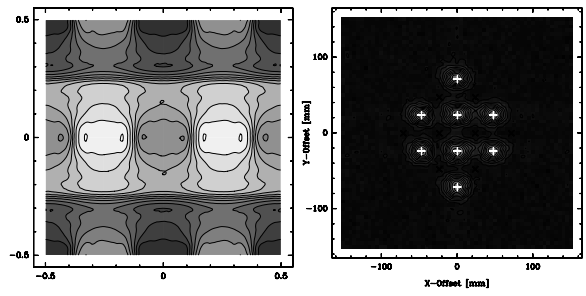

Figure 1: *For STAR[6]: Grating structure of the unit cell (left) and the measured 2–4–2 diffraction pattern (right).*

As mixer development advances to ever higher frequencies, LO power becomes scarce and grating efficiency becomes an issue. Above that focal planes will be populated two–dimensionally with mixers which implies splitting of LO power in both focal plane dimensions. Therefore the approach for LO power multiplexing involves several design constraints that are discussed in the following:

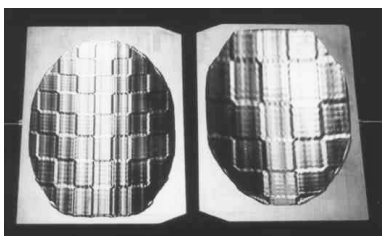

Figure 2: *SMART's collimating Fourier grating for 810 (left) and 490 GHz (right).*

To maximize the efficiency multilevel phase gratings or Fourier gratings in reflection are required. Since there is no way of using a reflection grating in normal incidence[8] without application of a beam splitter, the grating has to be designed in off–axis geometry. Shadowing of multilevel gratings in off–axis geometry and machineability issues naturally favor Fourier gratings.

Since our integrated optics approach intends to manufacture as many components as possible in one machining cycle to reduce complexity, one might as well combine a Fourier grating structure and a collimating parabola[9] (see Fig. 2).

The efficiency of multiplexing LO power into an array of LO beams scales with the number of degrees of freedom for shifting the phase of the radiation. The degrees of freedom though depend on the number of beams to split into. Therefore at larger beam numbers the efficiency of Fourier gratings exceeds the one for step level gratings. Measurements show[6,9] that efficiencies $> 90\%$ can be achieved.

POPULATING FOCAL PLANES

Since heterodyne detection systems are not background limited they do not Nyquist–sample focal planes. Instead, precautions are taken to focus the radiation of a point source entirely into one mixer to minimize integration time. The goal is to maximize the overlap integral of the two radiation patterns in the focal plane: The one of the telescope optics and the one of the mixer horn. Also to reduce losses we lay out the optics as purely reflective.

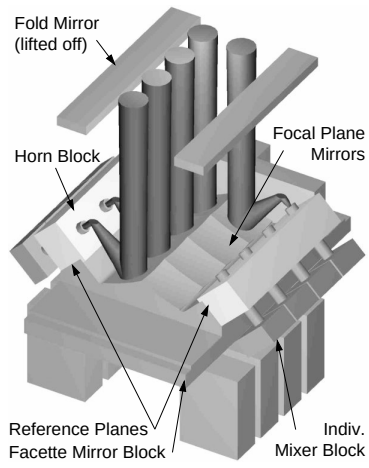

Figure 3: *Focal plane design of SMART*

The accurate arrangement of mixer elements in a focal plane is crucial for the alignment of the submm beams on the sky. The mixer horns have to be aligned with respect to both the optical axis and the focus of the system. To avoid adjustment effort for a larger number of elements we have made use of our CNC machining capabilities and milled the whole focal plane unit from one piece. Figure 3 shows the unit with all the reference planes. The actual focal plane is sampled by facet mirrors that are milled into a facet mirror block. The brightly drawn blocks capture the mixer horns in high–precision machined bores, and these blocks are mounted against reference planes on the facette mirror block.

Another integrated mixer concept is proposed by Walker et al..[10] There, corrugated feedhorn structures are readily arrayed etched in silicon and the beam matching is achieved by a lenslet array in front of the horns.

OPTICS

Common setups comprise a stiff bench where the optical elements are bolted down. Each of the elements then has to be adjusted with translation or tip/tilt stages for correct optical alignment.

At KOSMA we developed a way to manufacture the analogon to the optical bench as mirror–symmetric plates with reference surfaces directly milled onto it. The achievable accuracy is $\sim 2\mu m$ and is governed by the accuracy of repeatedly accessing a certain coordinate on our CNC milling machine. In the case of SMART[11] the optical elements are sandwiched between these plates and need no further adjustment. The result of this design effort is that assembly and mounting at the telescope requires hardly more effort than that of a single pixel receiver. Figure 4 shows the good alignment of the beams on the sky for the two frequencies for SMART.

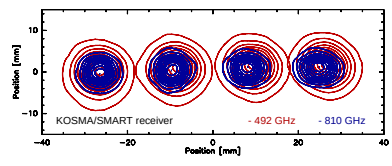

Figure 4: *Focal plane map of SMART at 810 GHz (solid) and 490 GHz (grey). Shown are contours from 5 to 95 % in 10% increments.*

AUTOMATIC TUNING OF MIXERS

Tuning a millimeter or submillimeter heterodyne mixer element requires several parameters to be ascertained and set, depending on the mixer type: bias voltage, LO power and frequency, magnetic field (for SIS mixers), and the intermediate frequency (IF) attenuator setting.

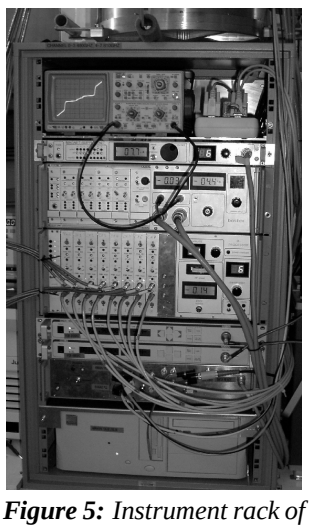

Figure 5: *Instrument rack of SMART*

For array receivers the hardware electronics like bias– and magnet power supply, IF processor, backends (acousto–optical spectrometers or auto–correlators), scale linearly with the number of focal plane elements as does the tuning effort for the mixers.

However, employing a computer controllable system for addressing the control circuits of the parameters makes tuning life much easier and fast. At KOSMA, we have put considerable effort into streamlining and automating the tuning of mixer elements.[12]

The computer can measure system characteristics like I/V– and conversion curves and then sets the tuning parameters to the optimum values. For some parameters (e.g. bias voltage) look–up tables are sufficient to set the values. In the case of the magnetic field however, the optimum value has to be determined from the actual measurements, using a special algorithm (Fig. 6). In a coarse–tune routine it evaluates the I/V–curve and finds the minima in Josephson current across the mixer junction. The positions of these minima are not reproducible due to hysteretic behavior of the junctions. After storing the positions of these minima a fine–tune algorithm looks for well suited local minima in the conversion curve and applies the parameters found.

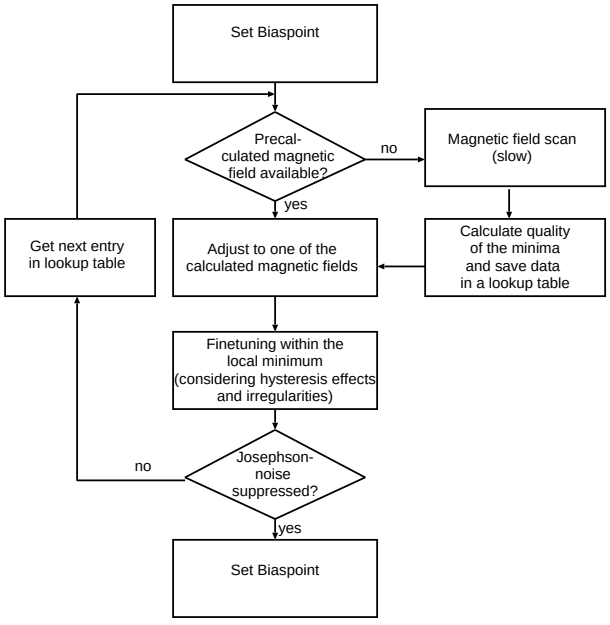

Figure 6: *Algorithm for automatic tuning of mixer elements*

The system can also be tuned manually, if desired, to keep a certain parameter fixed. For reliability issues manual and computer input just increment or decrement an internal counter which stores the parameter setting locally. A two-channel oscilloscope displays the selected I/V– and conversion curve simultaneously.

Since September 2001 the SMART receiver is operational at KOSMA's 3m–telescope on Gornergrat, Switzerland.

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