Array-Receiver LO Unit using collimating Fourier-Gratings

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Abstract

The local oscillator (LO) unit in our 490/810GHz array receiver needs to transform a divergent beam coming from a horn antenna into an array of well collimated beams. Based on our development of reflective phase gratings (Fourier gratings) we designed a compact LO unit using newly developed collimating gratings.

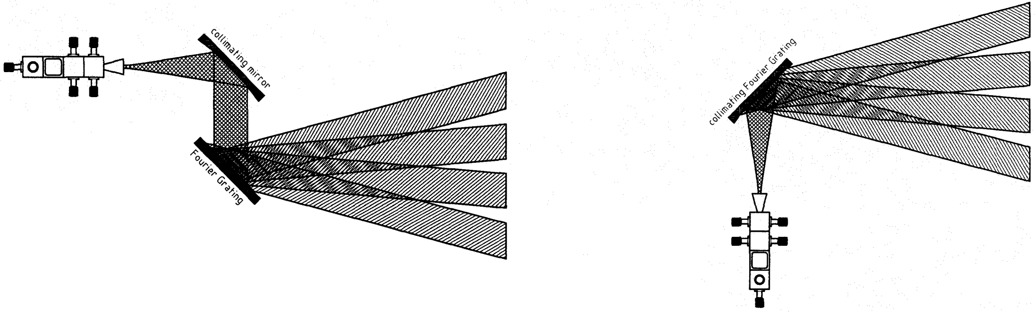

Figure 1. Old arrangement of the LO unit using a collimating mirror and a plane Fourier Grating (left hand side) and the new one with the collimating Fourier grating.

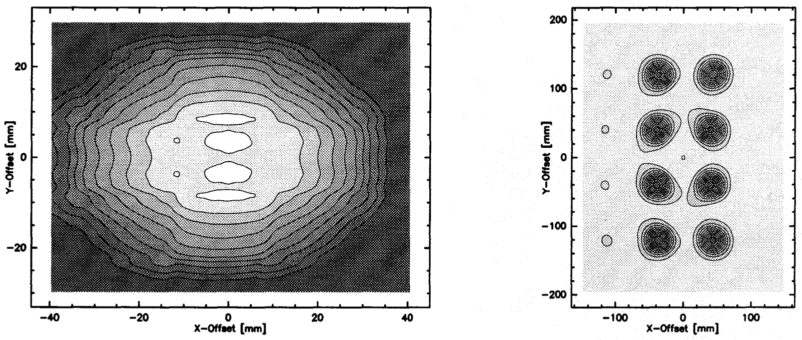

Figure 2. Example of the surface topology of a collimating grating and a computer simulation of its far field diffraction pattern. Contour levels in both plots are from 10% to 90% in steps of 10%.

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Using planar gratings, the LO source had to be reimaged to form a plane wave at the location of the grating. The new collimating Fourier grating is matched to the wave front curvature of the divergent beam and does not require an additional collimating element. Because of the smooth grating structure it is possible to produce the collimating Fourier gratings on a commercial numerically controlled milling machine.

We present the design of the grating and the entire LO unit combined with first measurements.

Keywords: phase grating, beam splitter, heterodyne array receiver, submillimeter beam multiplexer, LO unit

Introduction

One problem we had to solve while building the KOSMA Array Receiver was to distribute local oscillator (LO) power to the different mixers. It is impractical in terms of tunability and complexity of the resulting setup to use one LO for each mixer in the array. So it is necessary to use one LO for a larger number of mixers which means multiplexing the LO signal.

Waveguide splitters as they are in use at IRAM[2] work well at longer wavelengths, but are very difficult to manufacture for our frequency range (490GHz and 810GHz).

Using beam-splitters as in the AST/RO - Pole Star array[3] is efficient for a small number of mixers. But with an increasing number of mixers the optics gets more and more complex. For our array of 2 times 2×4 mixers we were looking for a more elegant way of multiplexing the LO.

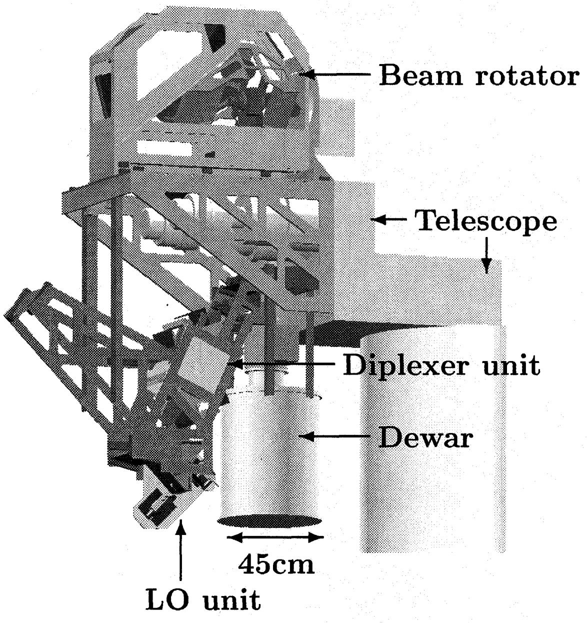

Figure 3. KOSMA Array Receiver[1]

The use of phase gratings to split the local oscillator signal into a given number of equal beams is one other possibility. Binary phase gratings also known as Dammann gratings,[4] or multilevel gratings with higher efficiency, have been used[5,6,7] as LO multiplexers. These stepped gratings are difficult to produce as reflection gratings for a 2 dimensional array of mixers. To overcome this manufacturing problem and to increase the efficiency we introduced the Fourier grating concept.[8,9]

An other important design driver was the need to reduce the number of optical elements to minimize alignment problems. In order to fit the receiver at the relatively small KOSMA telescope[10] on Gornergrat (Switzerland) we also had to shrink some components of the receiver as far as possible.

To reach these goals we combined a parabolic mirror and a Fourier grating to form one optical element. This results in a very compact and simple design of the LO unit (fig. 8).

Fourier gratings[11]

Fourier gratings, as we developed them over the last two years, have a continuous phase modulation. This results directly from the way these gratings are designed. To model the phase structure, we use a finite Fourier series (with typically 13 coefficients per spatial dimension). The coefficients are calculated by a random search followed by an optimization process.

Fourier gratings have a very high efficiency. For most one dimensional diffraction patterns the efficiency is above 90%. In two dimensions it is typically 80% or higher.

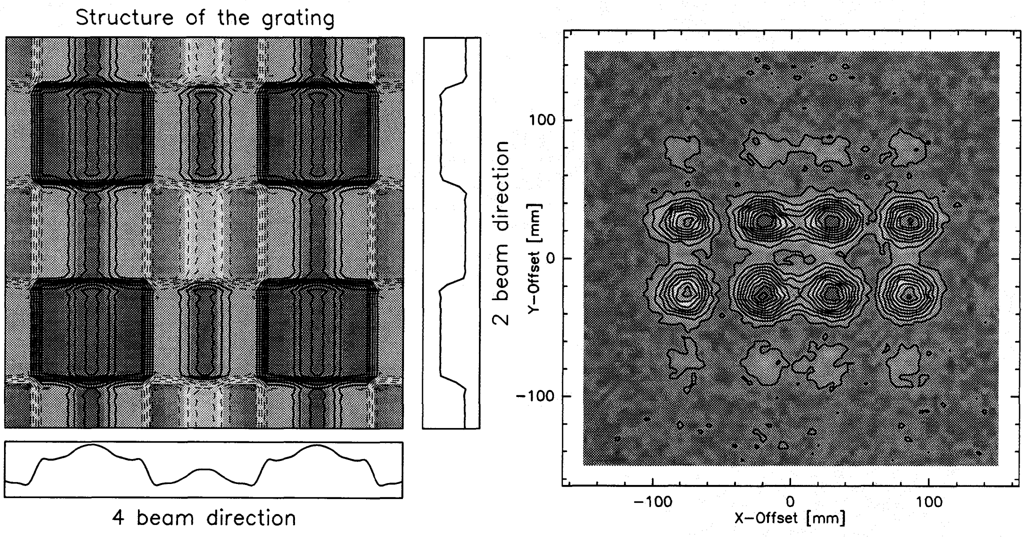

Figure 4. Surface topology of a 2×4 beam grating containing 2×2 unit cells (left hand side). Contour levels are in steps of 0.5 radians. The right hand side shows a measured diffraction pattern produced by this grating structure at 490GHz. Contour levels are from 5% to 95% in steps of 10% of the peak intensity.

Because of the continuous phase modulation, we get a smooth surface structure. This allows a 2 dimensional manufacturing with high accuracy ($\pm 3\mu m$ RMS) on a numerically controlled milling machine. With this manufacturing technique we are not limited to planar gratings, but can also produce grating structures superimposed on a curved surface.

The grating bandwidth is limited to less than ±5% of the design frequency. This range could be stretched somewhat by using a zoom optics setup. However, we considered it simpler to design exchangeable gratings. With a small number (3 to 4) of gratings we can then cover the total bandwidth of a typical astronomical receiver.

An LO unit built with such a planar Fourier grating would look similar to the arrangement shown in figure 1 (left hand side). The divergent beam coming from the horn antenna of the LO has to be reimaged to form a plane wave front at the location of the Fourier grating. This grating is finally multiplexing the signal to the various mixers.

Collimating Fourier gratings

The idea of a collimating Fourier grating is to combine the collimating mirror needed to re-image the LO beam and the grating itself into one optical component. By shrinking the distance between the grating and the collimating mirror (fig. 1 left hand side) to zero, the collimating mirror changes from an ellipsoidal to a parabolic mirror. The grating structure is then superimposed on this mirror.

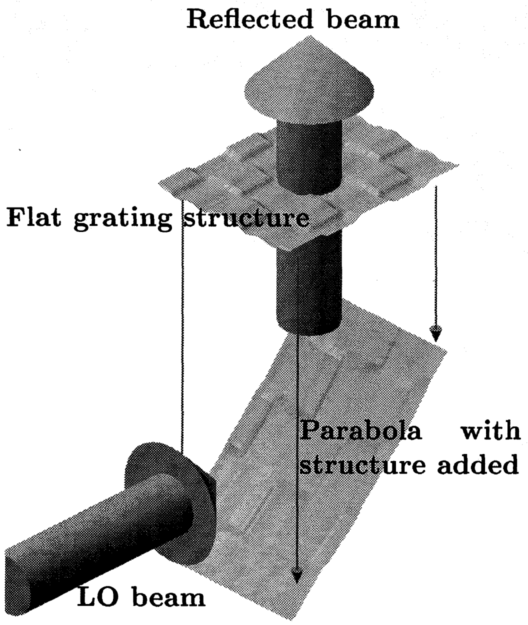

Figure 5. Calculating the grating structure

To do this, the structure of the flat grating is projected onto the parabola along the direction of the reflected LO signal as shown in figure 5. When projecting the grating structure onto the parabola the structure height changes to

$$h = \frac{h_{flat}}{\cos(\alpha)}$$

where α is the local geometrical reflection angle. This height is added along the surface normal of the parabolic mirror. The resulting structure and the theoretical diffraction pattern is shown in figure 2.

A quick and dirty measurement of such a grating is shown in figure 7. The 8 resulting beams and their correct positions are clearly shown. Because of poor alignment the power distribution between the beams is not as expected. Nonetheless, this measurement, together with the numerical simulation and our previous experience with planar Fourier gratings convinced us of the usefulness of these devices.

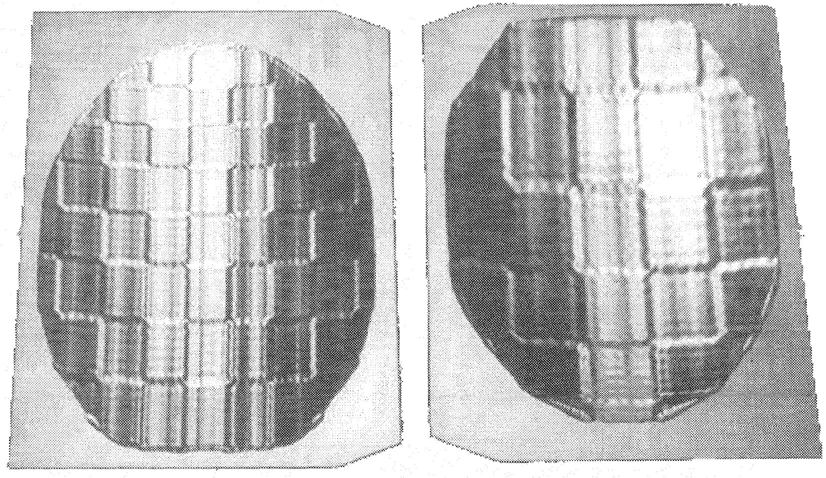

Figure 6. Photograph of the two collimating Fourier gratings for 490GHz (right hand side) and 810GHz. The reference planes around the structure are manufactured along with the grating. One unit cell contains 4 sub cells arranged in a square. The size of the unit cell changes with the design wavelength.

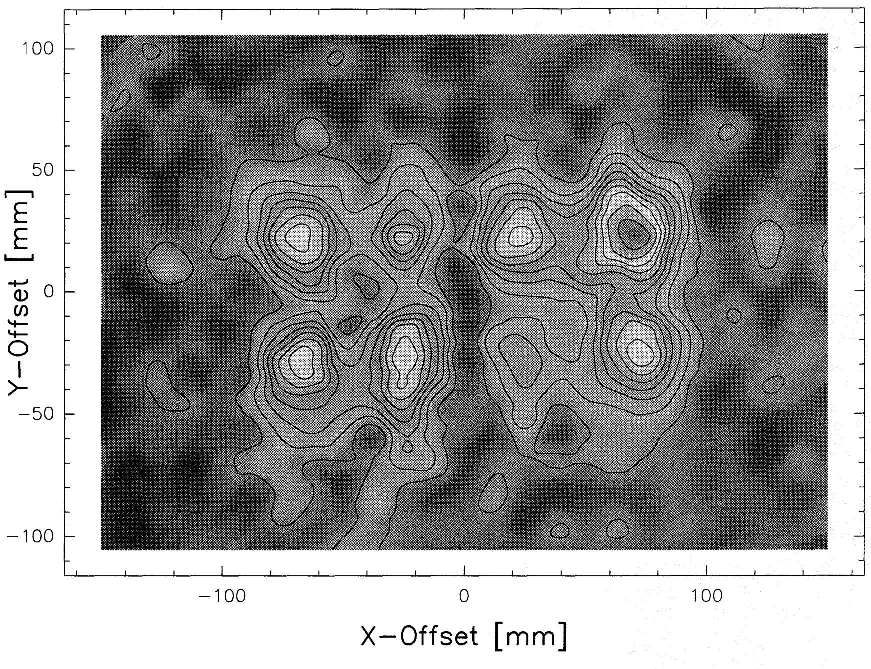

Figure 7. Intensity distribution in the diffraction pattern of a collimating Fourier grating measured at 490GHz. The variations in the intensity of the beams are due to poor alignment in the measurement setup. Contour levels are in steps of 10% of the peak intensity.

KOSMA Array Receiver LO unit

Figure 8 shows the design of the Array Receiver LO unit together with the beam-paths for the two frequencies (490GHz and 810GHz). The two frequencies are superposed onto each other by a polarizer grid.

The gratings and their holders are designed such that the grating can be easily exchanged in order to overcome bandwidth limitations. For different frequencies within the receiver band we can use different gratings to maximize the efficiency of the LO-system. Springs press the grating against three reference surfaces for accurate repositioning. The reference planes on the grating are manufactured along with the grating structure (figure 6). This gives us the position accuracy required and allows a rapid change of the grating without the need for realignment, when the observing frequency is changed.

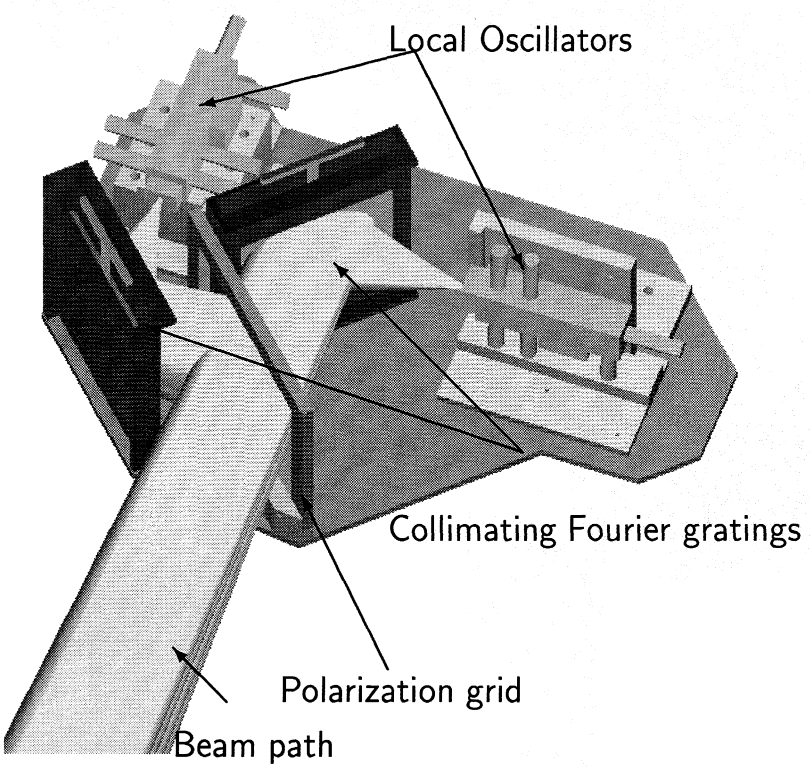

Figure 8. Overview of the LO unit

Equal pump levels were achieved on both mixers during a first test run of the system without doing any alignment work on the LO unit. In figure 9 we show the IV- and the conversion curves of both mixers. Because of the symmetry of the array receiver optics these two mixers represent one half of the array.

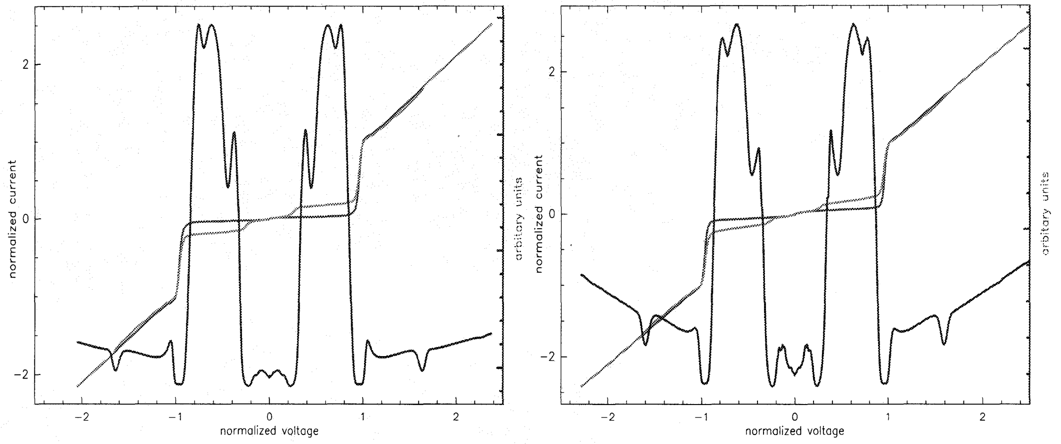

Figure 9. Pumped, un-pumped IV- and conversion curves of the two mixers in the array.

We verified that exchanging of the gratings does not affect the alignment. The pump levels and the conversion curves did not change when removing the grating and putting it back into its holder.

Conclusions

The concept of the collimating Fourier grating works well for the mixer arrangement used in our receiver as is shown by the measured diffraction pattern of the 490GHz grating. Based on earlier tests with flat grating structures for various other mixer arrangements, we are also sure that we can produce collimating Fourier gratings for other diffraction patterns.

In addition to the diffraction measurement, we got equal pump levels in the two mixers we had in the array until now. Removing and putting back the grating has no effect on the pump levels and the conversion curves, indicating that the grating repositions accurately. The additional work in changing the frequency of the array receiver, in comparison to a single pixel receiver, is, therefore, just to swap these gratings.

Simulations and measurements done with the flat Fourier gratings show the high efficiency of the LO splitting by this grating type.

With the LO unit built for the KOSMA 490/810GHz array receiver we reached a compact design which is easy to tune and which is efficient in terms of the LO power distributed to the mixers.

Acknowledgments

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