LO BEAM ARRAY GENERATION AT 480 GHZ BY USE OF PHASE GRATINGS

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ABSTRACT

For the MPIfR's 480 GHz-heterodyne-array, 16 SIS mixer elements have to be driven by the local oscillator power of two LO-chains. In order to split the power of each LO into one subarray of 8 mixer elements in a conventional way a complicated beam splitting foil complex is necessary. A more elegant way to couple the LO-power is to generate the required beam array with a phase grating. Such devices have been developed at optical wavelengths and are potentially suitable for quasi optical applications.
We will report upon the design of such gratings for quasi optical systems. Theoretical considerations and first measurements of binary phase gratings at 480GHz for a 3x3 beam array will be presented, as well as calculations of more efficient multilevel gratings. The design of the grating for the array receiver will be discussed.

INTRODUCTION

To couple LO-power equally into each receiver element of a submm heterodyne array an optical power dividing system is required. There are several possible solutions for such a system. The straight-forward one is to extend the power divider for a one channel system into a dividing system for an array by splitting the LO beam with a combination of power dividing foils as described in [1,2]. As simple as this idea may be for linear arrays, for two dimensional arrays it becomes more complicated.
A more elegant way for imaging one LO beam to a mixer array is the use of a phase grating as practiced at optical wavelengths for decades and as proposed for the submillimeter range in [3,4]. It is the purpose of this paper to show our considerations of phase gratings and calculations for a grating design which generates the image of one subarray of the MPIfR's heterodyne array.

THEORY

We use a theory of phase gratings based on the scalar theory of diffraction which can be described mathematically by fourier optics [5].
The typical setup for signal array generation by a phase grating is shown in fig.[1]. The first lens of a gaussian telescope is illuminated by the gaussian beam generated by the LO feed and produces a beam waist in its focal plane, where the grating is positioned. At optical wavelengths this setup yields an uniform illumination of the grating with a plane wave. However at submillimeter wavelengths the illumination is gaussian and only at the waist position a planar phasefront can be assumed. The grating structure causes an additive phase distribution to the zero phase gaussian beam. The second lens of the gaussian telescope images the diffraction orders produced to an object plane at distance f (focal length of the lens). The intensity distribution in the output plane is given by

$$I(x,y) = \left| \int e^{-\frac{x'^2+y'^2}{\omega_0^2}} \cdot t(x',y') \cdot e^{\frac{-2\pi i(xx'+yy')}{\lambda f}} \, dx'\, dy' \right|^2 \qquad (1)$$

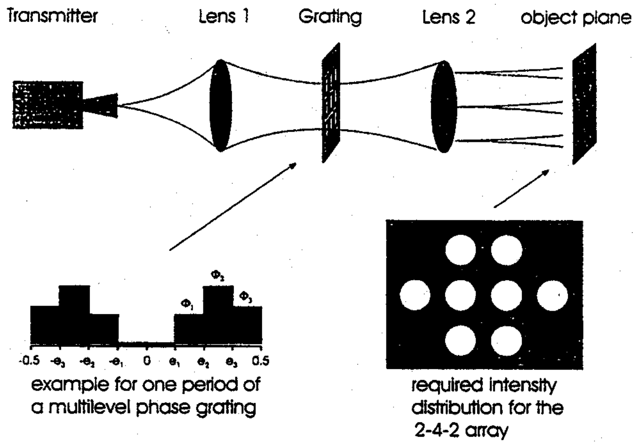

FIGURE I Typical setup for signal array generation by a phase grating. The grating is positioned in the focal plane of the two lenses, where a plane phasefront can be assumed. After diffraction by the grating the output spots can be observed in the output plane, the focal plane behind the second lens.

which is the complex fourier transform of the amplitude distribution of the incident beam with waist ω_0 and the transparency function $t(x, y)$ of the grating. The problem to solve is the determination of $t(x, y)$ under the condition to generate the required array pattern with high efficiency.
The calculations can be reduced to an one dimensional problem [6,7] if $t(x, y)$ is separable. Then $t(x, y)$ can be written as

$$t(x, y) = t_1(x)t_2(y) \tag{2}$$

If further $t_{1,2}$ is determined to be a stepped function with M transition points e_n at phase levels ϕ_n

$$t_{1,2}(z) = \sum_{n=0}^{M} e^{2\pi i\phi_n} \cdot rect\left[\frac{z - \frac{1}{2}(e_{n+1} - e_n)}{e_{n+1} - e_n}\right] \tag{3}$$

the amplitude maxima of the diffraction orders are calculated to be

$$a_0 = \sum_{n=0}^{M} 2(e_{n+1} - e_n)e^{2\pi i\phi_n} \tag{4}$$

$$a_m = \frac{1}{m\pi}\sum_{n=0}^{M} \left[sin(2\pi m e_{n+1}) - sin(2\pi m e_n)\right] e^{2\pi i\phi_n} \tag{5}$$

where a_0 is the 0^{th} and a_m the m^{th} order. One period of a grating corresponding to equation 3 is shown in figure 1. The symmetry of the structure is a further limitation on the number of solutions because only symmetric configurations of orders (a_m=a_{-m}) can be obtained. This limitation is useful if a symmetric configuration is required because the number of iterations is reduced.

RESULTS

The solutions for $t_{1,2}$ can be found by varying e_n and ϕ_n in eqn. (4) and (5). The optimized transparency function is obtained if a maximum fraction of the incident power is coupled uniformly into the required output pattern. To achieve this goal the efficiency function for a one dimensional grating η_{1D}

$$\eta_{1D} = \sum_{m=-M}^{+M} a_m^* a_m \tag{6}$$

and the error function ρ

$$\rho = \sum_{m=-M}^{+M} \left| 1 - \frac{a_m^* a_m \cdot (2M+1)}{\eta_{1D}} \right| \tag{7}$$

indicate the quality of the solutions during the iteration procedure.
For the "2-4-2" beam pattern of the MPIfR's heterodyne array (see fig.1) we first calculated the transparency function t_1 as a solution for a 3×3 array and t_2 for a 4×4 array and combine $t_1(x)\cdot t_2(y)$ to obtain a 3×4 beam array with high efficiency. Then by a second optimization process the undesirable beams in the four corners were suppressed by increasing the efficiency for the eight beams belonging to the required pattern.

Solutions for 3×3 beam arrays

For $2M + 1$ required spots M transition points have to be varied if the number of different phase levels is limited to 2 (binary grating). In this case M=1 and the phase is shifted between 0 and π. The results for maximum efficiency are shown in table I. Note that the overall efficiency η_{1D}^2 is only 44% in this case. An improvement can be achieved by use of more phase levels. For four different phase levels three transition points are necessary (M=3) and 2M+1=7 spots are generated. To suppress the 2^{nd} and 3^{rd} order only the 0^{th} and 1^{st} orders are considered in eqn. (6) and (7). Table II summarizes the parameters for two representative results. The intensity

TABLE I Solutions for a binary grating with M=1

e_1	$\|a_0\|^2$	$\|a_1\|^2$	η_{1D} [%]
0.132	0.223	0.220	66.4
0.368	0.223	0.221	66.4

TABLE II Solutions for a four level grating with M=3

e_1	e_2	e_3	ϕ_1	ϕ_2	ϕ_3	$\|a_0\|^2$	$\|a_1\|^2$	$\|a_2\|^2$	$\|a_3\|^2$	η_{1D} [%]
0.15	0.25	0.40	0.125	0.625	0.750	0.304	0.296	0.011	0.013	89.6
0.10	0.22	0.30	0.125	0.500	0.750	0.305	0.298	0.015	0.014	90.2

response of 2-dimensional gratings $(t_1 \cdot t_2)$ were then simulated using these results. In agreement with the calculated efficiencies the far-field amplitude distribution (see fig.2) generated by the four level grating the 2^{nd} order beams are largely suppressed compared with the response of the binary grating. The far-field phase distributions are also shown to be flat over the main beams. The grating structures become more complicated with increasing number of different phase levels. The binary grating (see fig.3 right) made of PTFE has been fabricated in our workshop with a numerical controlled machine. The accuracy achieved by this method is limited by the physical behavior of PTFE during the machining. The measured amplitude response (fig.3 left) indicates this fact. The nine required beams were detected but differ in intensity by up to 5dB for the corner beams on the left side. Also the beamshapes show poor features. The grating structure produces the required Bragg angle indicated by the measured distance of 22mm between two adjacent beams.

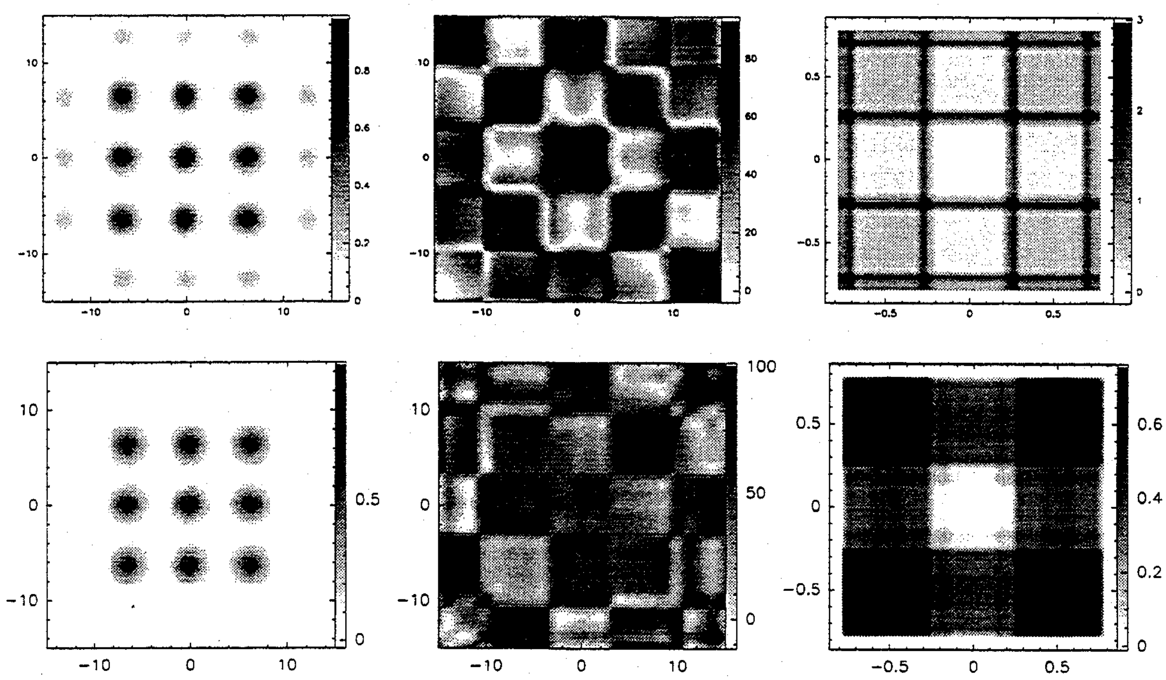

FIGURE II Far-field amplitude pattern (left), phase (middle) and grating structure for a 3 × 3 (right) binary (top) and a four level grating (bottom). The response of the binary grating shows considerable intensities in the higher orders yielding a lower efficiency. Amplitude greyscales are linear and normalized to one. The diffraction angle is in degrees, phase greyscales are in degrees and grey scales of the phase levels are 0,π and 3π for the binary and fractions of π for the four level grating. The grating period is normalized to one.

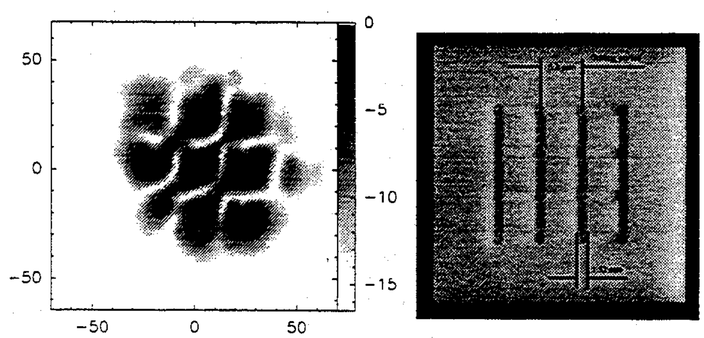

FIGURE III Very first measurement of a binary phase level grating at 460GHz for a 3×3 array. The measured intensity (left plot) is greyscaled and the coordinates in the object plane are mm. The PTFE-grating fabricated with a numeric controlled machine is shown on the photograph (right).

Solutions for 4×4 beam arrays

To generate a beam array with an even number of spots (such as 4×4) the 0^{th} diffraction order has to be suppressed and if equal distances between the beams are required only the odd numbered orders are to be maximized. We calculated binary and four level gratings once more for the case M=3 by suppressing the 0^{th} and 2^{nd} orders and put the results shown in table III into the simulation yielding the far field patterns in figure 4. The two dimensional intensity response of the four level grating is shown to be more uniform than that of the binary grating in addition to 12% efficiency improvement.

TABLE III Solution for a binary and a four level grating with M=3 and suppressed even numbered orders

	e_1	e_2	e_3	ϕ_1	ϕ_2	ϕ_3	$\|\|a_0\|\|^2$	$\|\|a_1\|\|^2$	$\|\|a_2\|\|^2$	$\|\|a_3\|\|^2$	η_{1D} [%]
binary	0.025	0.250	0.470	1	0	1	0.0004	0.174	0.0004	0.178	70.7
4 level	0.100	0.250	0.425	1.50	0.625	1.125	0.006	0.205	0.004	0.206	83.0

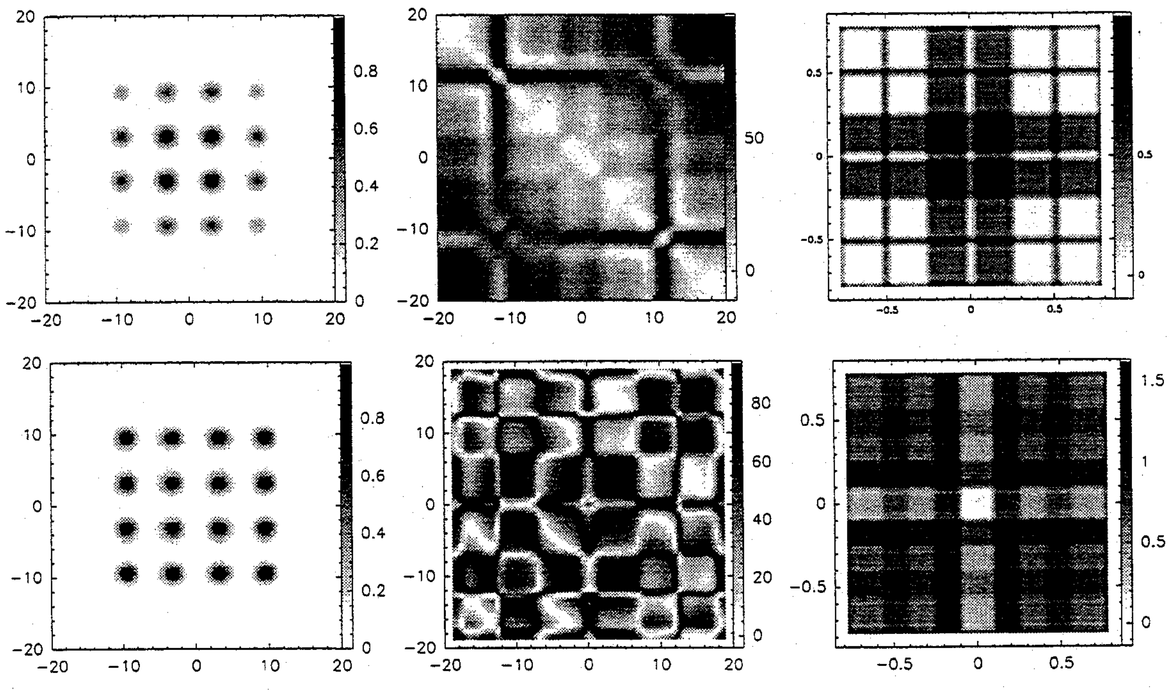

FIGURE IV Far-field amplitude (left), phase pattern (center), and grating structure (right) for a 4×4 array with a binary (top) and a four level grating (bottom)

Bandwidth

We used the four level grating calculated for a linear four beam array and center frequency ν_o=475GHz to check the bandwidth of the device. Varying the frequency means a change in phase delay (given by the phase levels) and a deviation of the transition points in the grating period caused by the wavelength dependence of the period P given by

$$P = \frac{\lambda f}{a} \quad (8)$$

with wavelength λ, distance a between two adjacent beams of the object array and the focal length f of the transforming lens. The shape of the intensity distribution in the object plane is shown in figure 5 for the range 400-540GHz. The usable bandwidth of about 60GHz (~13% of the center frequency) is mainly due to the change of the beam separation as a consequence of the wavelength dependence of the Bragg angle.

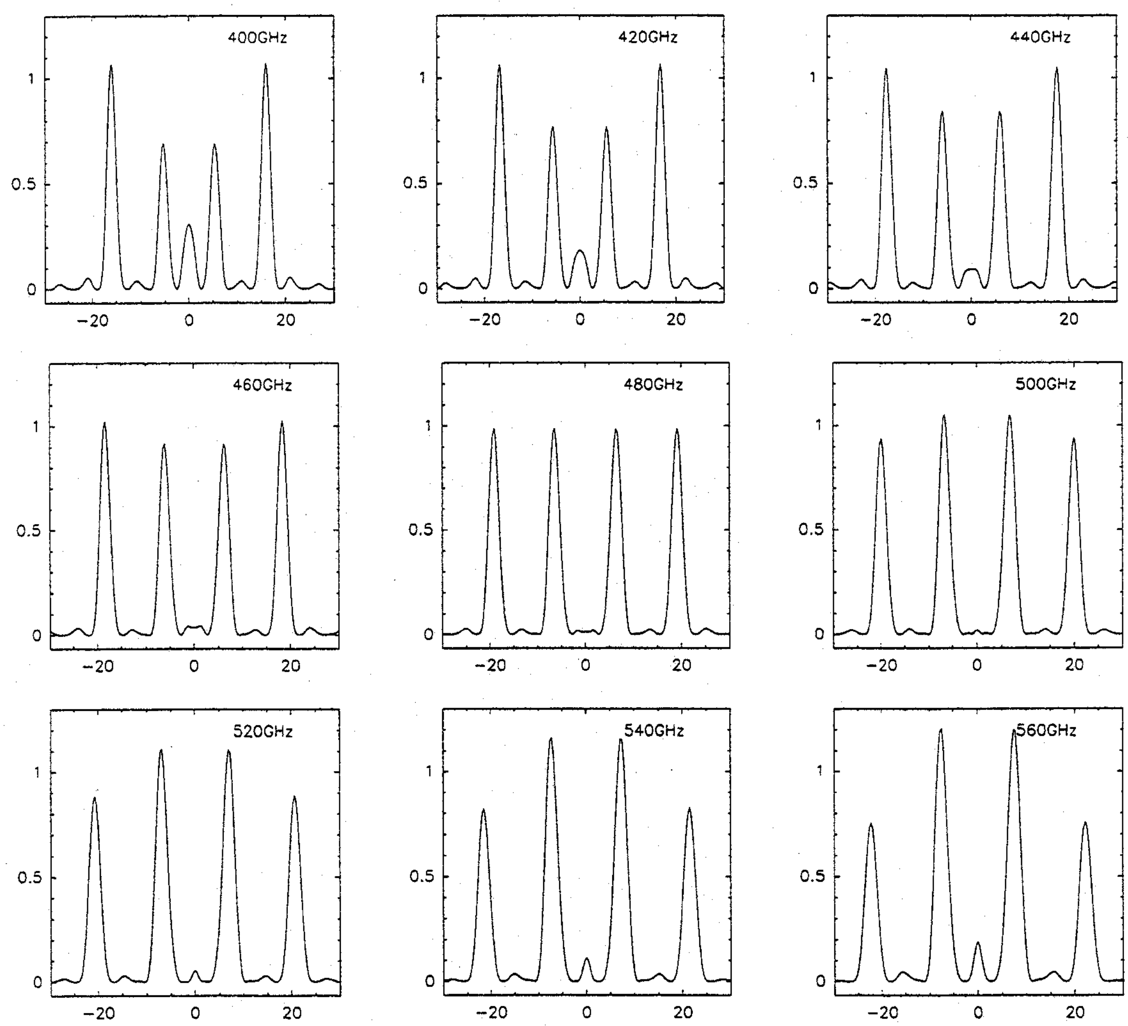

FIGURE V The calculated farfield amplitude patterns of the four spot grating at various frequencies shows the usable bandwidth of the grating is from 440GHz to 520GHz when the grating is optimized for a center frequency of 475GHz.

Solution for a 4×3 beam array

The results of the calculations for a three and a four beam linear array were combined to provide a solution for a 4×3 2-dimensional array. Because of the requirement of highest efficiency the two four level solutions were chosen.
Due to the suppression of the odd numbered orders for the four beam array the grating period has to be multiplied by a factor 2 in one dimension to obtain equally spaced beams. The resulting patterns are shown in figure 6. The combination of $t_{3beam} \cdot t_{4beam}$ yields an efficiency of 74% and is a

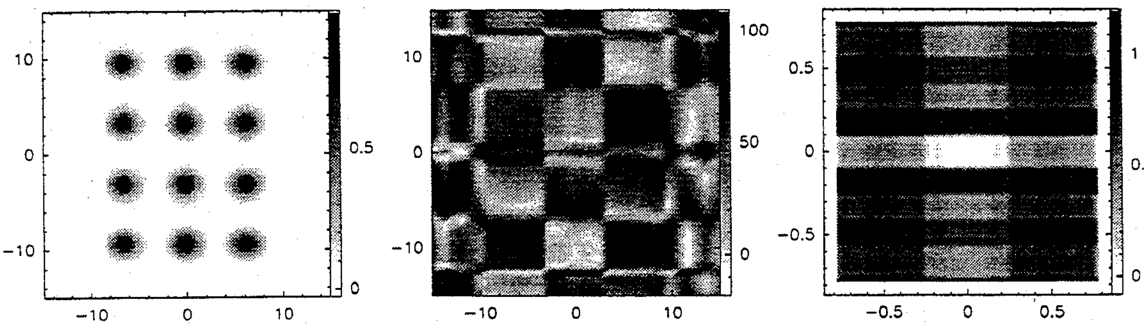

FIGURE VI Amplitude (left) and phase (center) patterns for the combined four phase level solutions (table 1 and 4). The grating structure (right side) is the result of the combined solutions. Intensity is linear greyscaled and the diffraction angle is in degrees.

potential solution for the required 2-4-2 array (figure 1). Because of the high output power available by the LO chains of the heterodyne array less than 1% of the LO power is required to drive each SIS-junction individually. If the losses in the further optics of the LO path can be assumed to be less than 6dB, sufficient power is coupled into each mixer.
In the next step we tried to optimize the grating structure for the 2-4-2 configuration (see fig.1). The resulting gratings had higher efficiencies, however they became more complicated and the size of the structures were very small (sometimes below the limit of the wavelength). This indicates that the starting function (the solution above) is too close to or is itself a local maximum in the set of solutions. Better results (fig.7), with a 15% efficiency improvement, were obtained starting the optimizing routine with the solution for the four beam linear array (tab.3) because here the routine starts at zero for the 2^{nd} dimension.

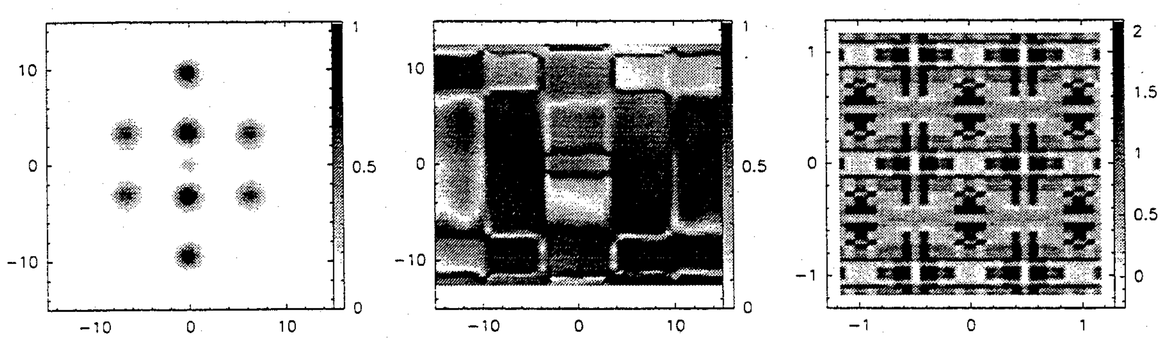

FIGURE VII Amplitude (left) and phase (center) patterns for the optimized grating structure (right). Intensity is linear greyscaled (normalized to one) vs. the diffraction angle in degrees.

CONCLUSIONS

We have presented the designs for various binary and multilevel gratings which can be used as wideband LO couplers for the MPIfR heterodyne array receiver. Measurements of a test 3×3 beam phase grating have been given, and show reasonable agreement with the theory. The final design of a grating optimized for 8 beams (2-4-2 configuration) with a high enough efficiency to supply the LO required for each mixer will be manufactured and tested in the near future.

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