4th URSI AT-RASC, Gran Canaria, 19-24 May 2024

Development of a 600 GHz Phase-Grating Based Focusing Beam Divider

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Abstract

This paper presents the development of a beam divider by combining two quasi-optical elements, a phase grating and a focusing mirror, into one. A prototype of a four-pixel focusing divider working at 600 GHz has been fabricated. We describe the design, the 3D simulation and the measurement of the focusing beam divider. A good agreement between the calculation and the measurement has been found.

1. Introduction

Terahertz (THz) heterodyne receivers are widely used in spectroscopy for astronomy due to their very high frequency resolution (above 10^6) and high sensitivity. Quasi-optical systems are often used in THz range due to their low loss and the manufacturability with conventional machining tools. Heterodyne receivers are based on the use of a local oscillator (LO) to pump the mixer which performs the mixing of the THz signals coming from the sky (RF) and from the LO and then produces an intermediate frequency signal for signal processing and analysis. Recently, the trend is to develop array receivers in order to scan a larger field of view. This means increasing the number of LO sources and thus the size, the mass and power consumption of the whole receiver, which can be a potential obstacle especially for balloon borne or space missions. An option to avoid these problems is to use only one LO source to feed all mixers. In THz frequency range, Fourier phase gratings have been used as beam divider in array receivers for the LO coupling and have demonstrated interesting features. Typically, in addition of the phase grating, collimating or focusing elements are also needed to reshape the LO beam for a good coupling between the LO source and the mixers. We proposed to undertake the development of a single quasi-optical element combining the function of a phase grating and a focusing mirror. A prototype of a four-beam divider working at 600 GHz has been realized.

2. Mirror and phase-grating design

The aim of this study is to reduce the number of the quasi-optical elements in the LO coupling system using a phase grating. Previously, LERMA has developed a calculation algorithm based on Fourier grating to transform an incident Gaussian beam into multiple beams with the same Gaussian characteristics [1]. This algorithm calculates the surface structure which produces the desired far field, with the number of beams and the direction of each one set up by the user. When the grating is used for LO injection in a heterodyne receiver, it is necessary to transform the signal coming from the source and to focus it on the mixer. This could be done by two parabolic mirrors. What we propose is to superimpose the phase grating structure on an ellipsoidal focusing element and thus to have only one element instead of three. The ellipsoidal mirror has the particularity to have two focal points. In geometrical optics, a signal coming from one focal point of an ellipse is focused on the second focal point. This behavior is similar in quasi-optical consideration and it's well detailed in [2]. We use the equations in [2] to calculate the ellipsoid of revolution of the mirror on which the phase grating will be structured by taking into account the constraints on the focal distances and both the source and mixer beam characteristics.

For the prototype study, the working frequency is set around 600 GHz. The source beam provided by an amplifier-multiplier chain with a horn antenna has a divergence angle θ around 12°, which corresponds to a waist ω_0 about 0.8 mm, according to the relation between waist and divergence angle from the Gaussian beam propagation equations:

$$\omega_0 = \frac{\lambda}{\pi\theta} \quad (1).$$

The focusing mirror should be in off-axis configuration in order not to block the signal after reflection. But it is important to keep the incident angle of the input signal with the normal of the mirror as low as possible. Thus, the distortion of the beam will be kept moderate to reach an output signal with a Gaussian shape. For practical considerations, we choose an input angle of incidence of 22.5° (i.e. 45° total reflected angle) and the focal distances of 70 and 400 mm, respectively for input and output signals. The exact size of the waist in the focal plane will be evaluated by simulation and shown in the next section.

Our receiver consists of an array of four HEB mixers placed in a square form and the distance between adjacent pixels is 20 mm. The mixers are in the integrated lens-antenna configuration with an equivalent beam waist about 5 mm.

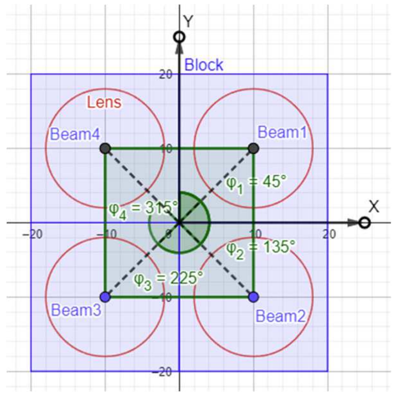

Figure 1. Expected beam distribution at the second focal plane.

Based on these features, we get the target beam distribution at the second focal plane, or the location of the mixer array, of the mirror as shown in Figure 1. and we can write the coordinates of each expected beam (Table 1).

Table 1: Coordinates of the expected 4 beams

Beam number	x coord. (mm)	y coord. (mm)	θ (degree)	φ (degree)
1	10	10	2.02	45
2	10	-10	2.02	135
3	-10	-10	2.02	225
4	-10	10	2.02	315

To meet these characteristics, we need to provide the four beams with an angle θ around 2°, from the optical axis, when the second focal distance of the ellipsoidal mirror is set at 400 mm.

$$\theta = \text{atan}\left(\frac{10 * \sqrt{2}}{400}\right) = 2.02° \quad (2).$$

These parameters (θ, φ) are used in the calculation code developed in our group to generate the phase grating's surface structure which will be projected on the surface of the ellipsoidal mirror. The profile of the phase grating is frequency dependent, the typical depth of the pattern is around λ/2, i.e. around 250 µm in our case (Figure 2).

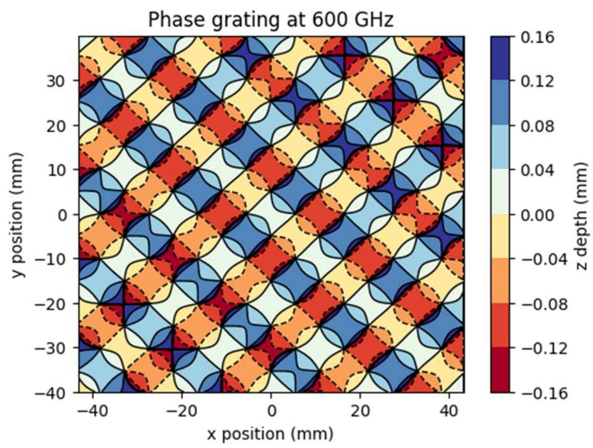

Figure 2. Calculated Phase grating surface.

3. Simulation

For the simulation we use a 3D electromagnetic software, FEKO, which is particularly adapted to simulate the propagation of focusing mirrors in free space. The mirror we designed is much larger than the wavelength of interest, so we use the Multi-Level Fast Multipole Method (MLFMM) associated with the Large-Element Physical Optics (LE-PO) in FEKO to solve the problem. First, an equivalent Gaussian source is modeled with a polarized

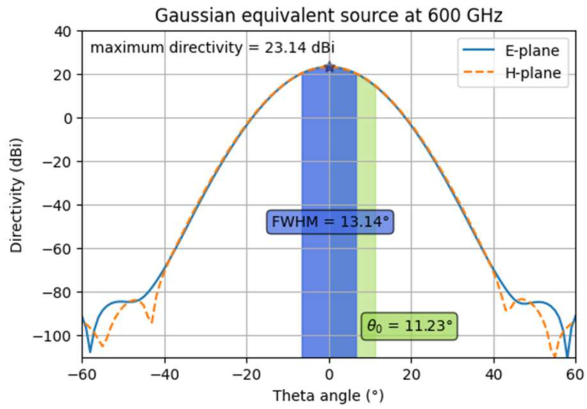

Figure 3. Simulated far field of the source at 600 GHz with spherical modes expansion.

E-field oriented along the y-axis and propagating along z-axis, according to the Ludwig-3 definition [3]. We set the far-field source with a waist $\omega_0 = 0.81$ mm (i.e. equation 1, $\theta_0 = 11.23°$). Then from this far-field, we generate a spherical mode expansion source to be used in the next simulation steps (Figure 3).

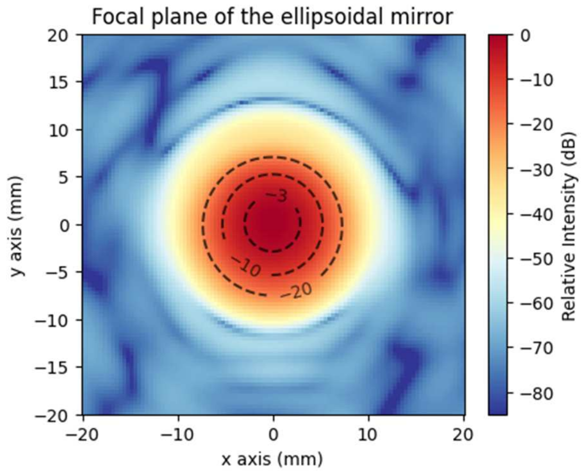

Figure 4. Simulated beam pattern of the source at the second focal plane of the ellipsoidal mirror.

With the parameters defined in the previous section, we can model the ellipsoidal mirror in 3D in FEKO. The LE-PO method allows to mesh the model with very large edges (9λ/5 instead of λ/12 with the standard MoM method), which means that we can simulate this mirror with only 20 000 triangles instead of more than 9 million with the MoM method. The modeled source is placed at the first focal point of the ellipsoid and we calculate the field distribution in the second focal plane (defined at the second focal point and perpendicular to the propagation axis). As shown in Figure 4 and Figure 5, the field follows pretty well the Gaussian distribution as expected and the size of image waist ω_{im} is 4.95 mm, which gives a magnification coefficient of $\omega_{im}/\omega_0 = 6.1$.

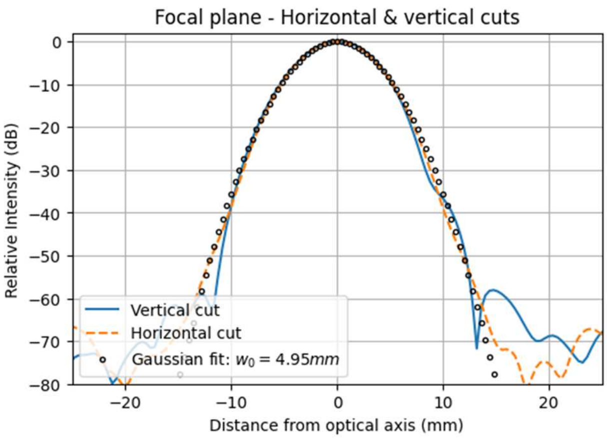

Figure 5. Simulated beam profile of the source with the Gaussian fit.

Finally, the phase grating shown in Figure 2 is superimposed on the ellipsoidal mirror surface to form the focusing beam divider and the 3D simulation is performed to get the field distribution at its second focal plane. The result is shown in Figure 6. As expected, four beams are generated in the second focal plane of the focusing divider mirror.
All beams are fitted with the Gaussian function for the characterization. Table 2 summarizes the beam characteristics.

Table 2: Characteristics of the simulated beams.

Beam number	x (mm)	y (mm)	Waist (mm)	Relative Intensity (dB)
1	10	9.5	4.92	0
2	10	-10.5	4.94	-0.28
3	-9.5	-10.5	5.15	-0.41
4	-9.5	9.5	5.15	-0.77

The four beams, located very close to the desired positions (±0.5 mm), are quite homogenous in terms of intensity, with a maximum deviation of 16% (-0.77 dB) for only one beam. If we compare the intensity of the four beams generated by the focusing divider with the intensity of the beam reflected by the ellipsoidal mirror without grating structure, we can estimate the efficiency of the system. We plot the intensity distribution of all the beams in Figure 7. The maximal intensity of the divided beams varies between 20-24% of the total power reflected by the mirror. By adding the power of the four beams, we obtain a total efficiency of 89% of the focusing divider.

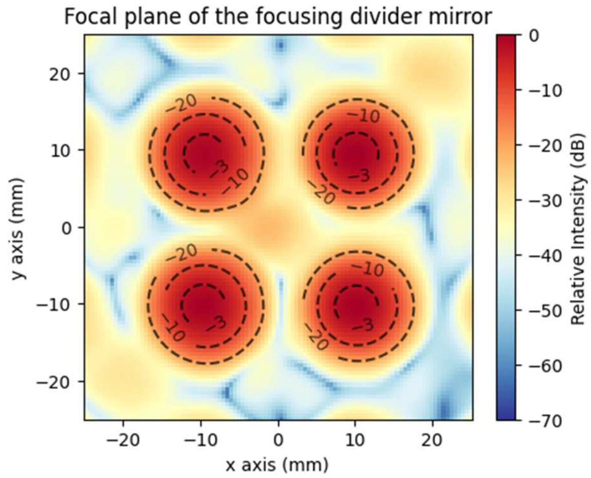

Figure 6. Simulated beam pattern at the focal plane of the focusing divider at 600 GHz.

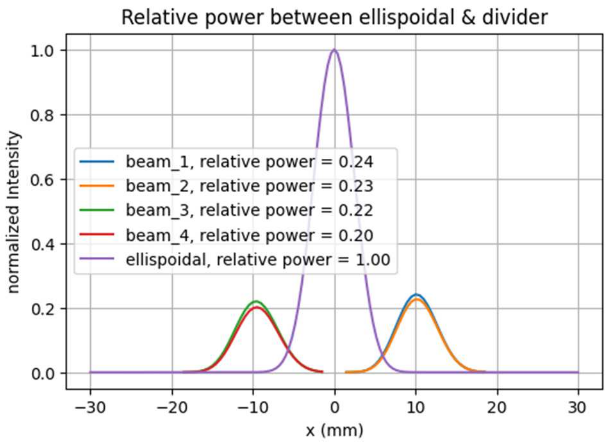

Figure 7. Comparison between the intensity of the divided 4 beams and that of the beam reflected by the ellipsoidal mirror.

4. Fabrication, Measurements and Analyses

4.1. Fabrication

The focusing divider mirror is manufactured in the mechanical workshop of Paris Observatory (Figure 8), using a 5-axis CNC machine. The surface of the mirror is structured with a 3 mm diameter milling cutter. This milling cutter is a bit large but we think it's acceptable for this prototype since the induced uncertainty in machining precision is estimated lower than 50 µm only in the zones with the steepest slopes (less than 1% of the total surface). The rest of the surface has an accuracy in the range of 10 µm or better. The mesh defining the surface is integrated in the mechanical structure using two open-source software.

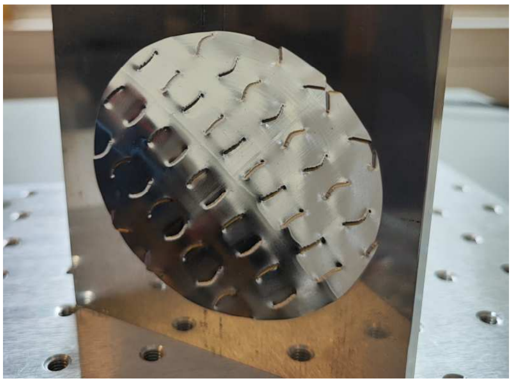

Figure 8. Focusing beam divider manufactured at Paris Observatory.

4.2. Measurements and Analyses

The measurement setup is composed of a solid-state oscillator source around 600 GHz, fed by a signal generator providing a signal between 16 – 17 GHz. This frequency is multiplied with different stages of frequency multipliers to reach a factor of 36. The 600 GHz signal passes through a Potter horn to propagate in free space. The horn is placed in the first focal plane of the mirror under test (i.e. elliptical mirror or focusing divider mirror) and a pyroelectric detector is mounted onto a 3-axis displacement platform controlled by three Thorlabs motors LTS-300 to scan the second focal plane (i.e. image focal plane).

Table 3. Characteristics of the measured beams with fitted waist.

Beam number	x (mm)	y (mm)	Waist (mm)	Relative Intensity (dB)
1	10.2	10	4.77	-0.16
2	10.2	-10	5.15	0.0
3	-9.8	-11	5.71	-0.31
4	-9.8	9	5.08	-0.23

The pyroelectric detector works in synchronous detection, a chopper is used to modulate the signal and the detection is read out by a lock-in amplifier Stanford Research SR-510. The focusing divider mirror was measured and the results are shown in Figure 9. As for the simulation, all beams are fitted with the Gaussian function in order to extract their waist and their maximum position. Table 3 summarizes the results. The four beams meet well the main goal of this study in terms of beam positions and waists. The relative intensities have less deviation than in the case of the simulation. The difference between the relative powers is lower than 7% (i.e. 0.31 dB). This is a promising first result and we already started a new version of focusing mirror using a smaller milling cutter in order to increase the machining precision and thus probably the quality of the divider. Many improvements are ongoing in parallel to increase the signal to noise ratio.

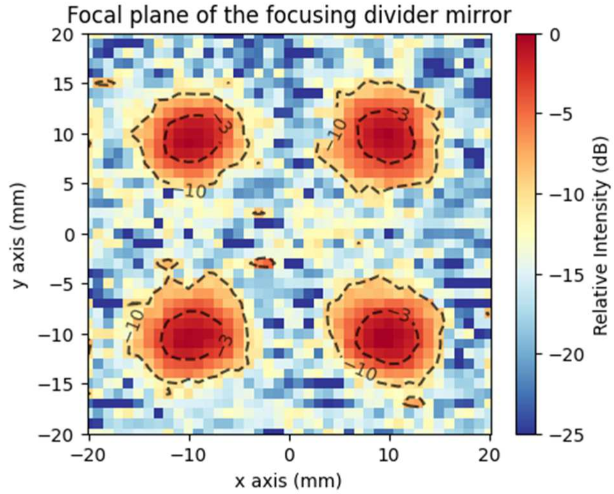

Figure 9. Measured beam pattern at the second focal plane of the focusing divider mirror at 600 GHz.

6. Conclusion

This study has proved that the concept of focusing divider works. The simulation and the fabrication of this kind of mirror are two challenging points. First, about the simulation, the structure is very large compared to the wavelength and it is difficult to find a simulation solution both reliable and inexpensive in terms of machine resources. Concerning the second point, the fabrication, our proximity with mechanical technicians is very important to find a way to transform the simulated mesh to the machining process with a sufficient fabrication precision. Finally, this study enables us to continue working on more efficient focusing divider and also at higher frequencies.

7. Acknowledgements

We thank Fabien Defrance for developing the calculation code of the phase grating and Laurent Pelay for his help in the mirror fabrication. This work was mainly supported by the CNES.

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