High performance smooth-walled horns for THz waveguide applications

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Abstract— **For the coupling from free space to waveguide corrugated horns are presently the optimum choice. Currently the extension of the waveguide technology towards THz frequencies, e.g. with silicon micromachining techniques, looks very promising, which increases the demand for THz horns. The HIFI project has shown that even at submm frequencies it is not easy to manufacture reliable corrugated horns for cryogenic applications. For small corrugations it is difficult to avoid fluid inclusions in the corrugations during electroforming. In addition experience has shown that dust or small metal particles can easily settle in between the corrugations and are very difficult to remove. Smooth-walled horns do not have these disadvantages. We will present measurements of a prototype smooth-walled horn for 756-924 GHz. The horn is designed by C. Granet [1] and manufactured by RPG [2]. The measurements were done at 800, 840 and 860 GHz with an AB-mm vector network analyzer at the University of Bern. We have also simulated the performance of the horn in CST Microwave Studio [3]. The simulation results are in a good agreement with the measured data. With the same measurement setup we measured a corrugated horn for the HIFI band 2 Mixer Unit. We conclude that we can replace the corrugated horn by a properly designed smooth-walled horn without significant loss of performance. This is an important step towards building THz waveguide mixers.**

I. Introduction

The fabrication of corrugated horns at THz frequencies is complicated by its small dimensions. For example at 1.9 THz (GREAT receiver for SOFIA [4]) the corrugations are smaller than 25 μm. In general a metal mandrill of the horn-inside is machined, subsequently electroformed, and then removed by etching. The madrills itself are already a major challenge for THz frequencies, but in addition during the electroforming process corrosive fluid inclusions may be formed in the narrow corrugations that break corrugations of the horn for example when it is thermally cycled. Although a method has been found in the course of the HIFI project [2] to avoid the inclusions for horns up to 1.1 THz this method is expensive, time consuming and rather dependent on workmanship. Another method would be, if the mandrill can still be machined, to fill the mandill corrugations by other methods than electroforming [5] or fabricate the horns in split block technique by silicon micro machining [6] and metal plate them afterwards. Both methods are also time consuming, expensive and/or require large investments.

To overcome the limitations imposed by the corrugations Granet et al. at the ICT centre, CSIRO, Australia, have developed a method [1] for optimizing the shape of a smooth-walled spline-profile feed horn to overcome these limitations imposed by corrugations. The optimizing method allows to model feed horns that produce good Gaussian beam shapes at a certain distance from the horn. This method is an algorithm that varies the spline-profile and checks the resulting antenna pattern via a mode matching algorithm for compliance with the pattern to be met. A resulting horn profile is shown in figure 1.

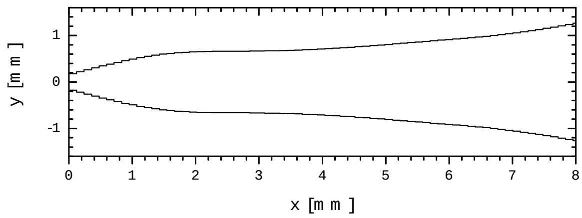

Fig. 1. *Horn profile of the smooth-walled horn for 840 GHz center frequency.*

This technique makes it possible to manufacture high performance feed horns considerably easier than up to now. That is especially interesting since at KOSMA, besides the efforts at submm frequencies, there are (array) instruments being developed at 1.4 and 1.9 THz, and the development of this feed horn technology mitigates the difficulties that arise from the high frequencies. To validate the horns we have measured the pattern of a smooth-walled horn with a center frequency of 840 GHz with a vector network analyzer. With the same set-up, within the HIFI project we have done also measurements at a HIFI band 2 corrugated horn. To calculate the horn performance we use a 3D field simulation. This is a good check for the measurement results and helps to include machining tolerances into the calculation. We also used the simulation to compare the smooth-walled horn and the corrugated horn which are designed for different center frequencies.

II. Measurement

The complex beam patterns of the horn antenna were measured with a vector-network analyzer from *AB-Millimetre*

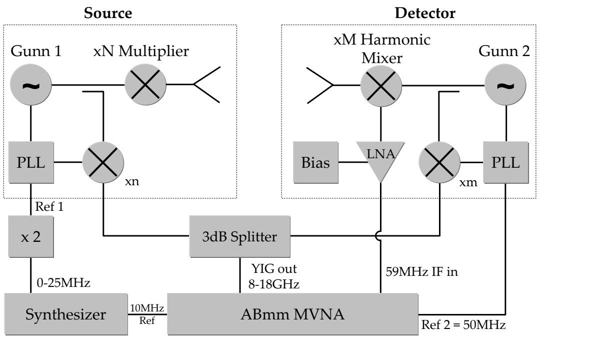

Fig. 2. *Measurement setup, the horn under test is mounted at the detector*

[7]. Coherent submm radiation is generated by a phase-locked Gunn oscillator using harmonic multiplication and transmitted to free space with a potter horn antenna. Although the horn radiates polarized radiation, a grid is used to be sure there is no radiation with the wrong polarization present at the horn under test. This is primarily important for the cross polarization measurement. The horn under test is feeding a harmonic Schottky diode mixer which is pumped by a second Gunn oscillator. This oscillator is phase-locked to the same reference signal as the first one (Fig. 2). A small frequency offset is maintained between the two oscillators which allows heterodyne detection of amplitude and phase with high dynamic range. The far-field distance $2D^2/\lambda$ of the horns under test is the largest in the case of the corrugated horn at 800 GHz with 80 mm. All measurements described in this paper were done at a distance between the source and the test horn of around 200 mm. The measurement test setup comprises a rotational stage where the feed horn under test is mounted with its phase center close to the rotation axis of the stage. Seen from the device under test the transmitter rotates on a spherical surface. This corresponds to the definition for the coordinate system of Ludwig 3 [8] as it is used in the next section for the 3D-simulation.

TABLE I
DESIGN PARAMETERS OF BOTH HORNS. A = APERTURE; F_r = FREQUENCY RANGE; F_c = CENTER FREQUENCY

smooth-walled horn			corrugated horn		
A [mm]	F_r [GHz]	F_c [GHz]	A [mm]	F_r [GHz]	F_c [GHz]
2.9	756-924	840	3.86	620-820	720

The single mode waveguide is tapered via a transition block towards the waveguide with different dimensions of the room temperature Schottky mixer. The signal source is mounted on a x-y-z-linear stage which allows to change the horn-to-horn distance with a relative accuracy of about a micron. To reduce the influence of standing-wave patterns, the signal source linear stage is moved 4 times about $\lambda/4$ towards the horn under test, with an angular sweep at each position. The retrieved amplitude and phase information then allows to correct for standing waves [9].

We have done measurements of the corrugated horn at 625,

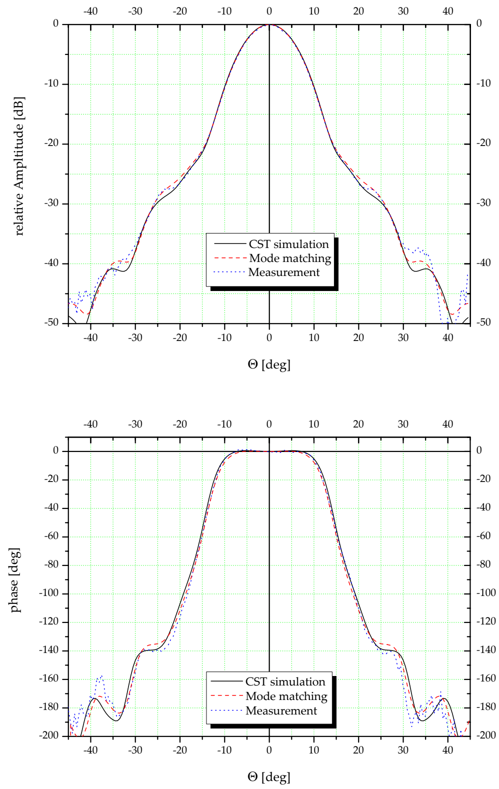

Fig. 3. *The simulation results and measured data are in excellent agreement, here in H-plane for 800 GHz at the smooth-walled horn*

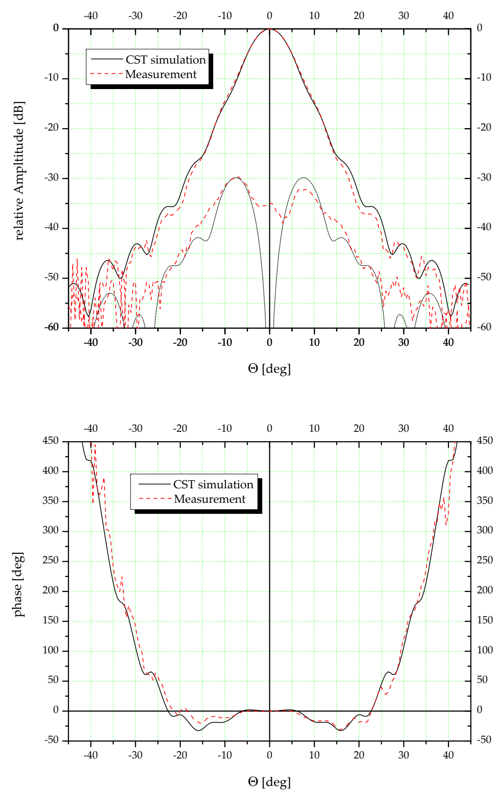

Fig. 4. *The data of the corrugated horn and the simulation match equally well, here in D-plane for 800 GHz*

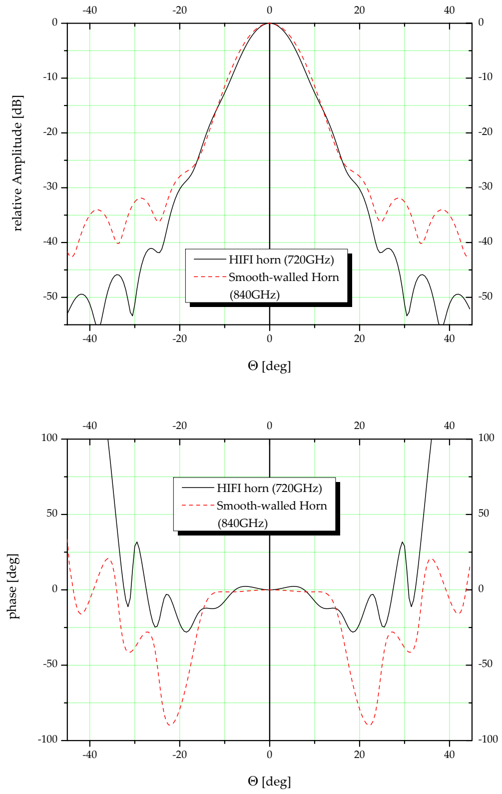

Fig. 5. *The data of the smooth-walled horn compared to the data of the corrugated HIFI horn in E-plane. Both at their respective center frequency.*

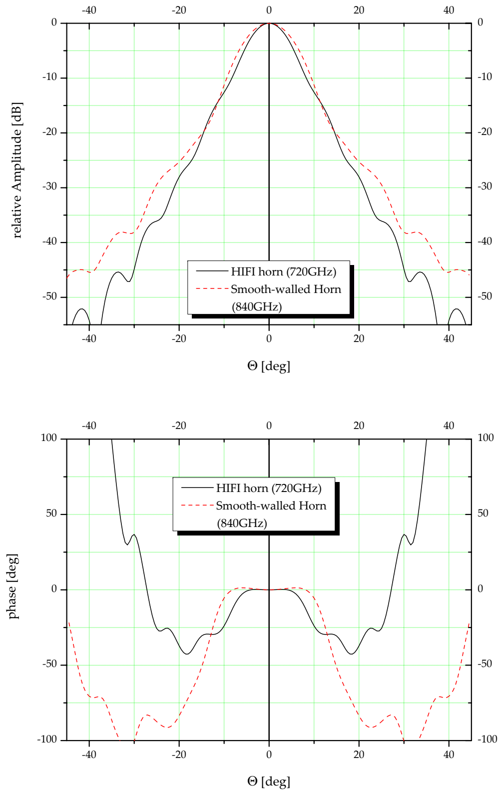

Fig. 6. *The data of the smooth-walled horn compared to the data of the corrugated HIFI horn in H-plane. Both at their respective center frequency.*

714 and 800 GHz. Near the band center ($F_C = 720$ GHz) at 714 GHz we have only measurements with a dynamic range of approx. 25 dB. The smooth-walled horn is tested at 800, 840 and 860 GHz. The range was limited by the frequency range of the source oscillator (795 - 860 GHz). For all measurements a Gunn with multipliers is used as a source. The design parameters of both horns are shown in table I. To measure E-, H- and D-plane the horn and the source (with grid) is rotated around the longitudinal axis by respectively 90 and 45 deg. Further detailes about the measurements of the smooth-walled horn are given in [10].

III. 3D SIMULATION

For the 3D simulation the transient solver of CST Microwave Studio is used. This is a time domain solver which calculates the development of fields through time at discrete locations and at discrete time samples. It calculates the transmission of energy between the exiting port and open space of the investigated structure. The far-field components are derived from the calculated fields inside the horn. The software makes the calculation of patterns for arbitrary frequencies in every plane possible. As already mentioned in section II the definition by Ludwig 3 is used to get the 1D data in E-, H- and D-plane. In this definition the vertical and horizontal

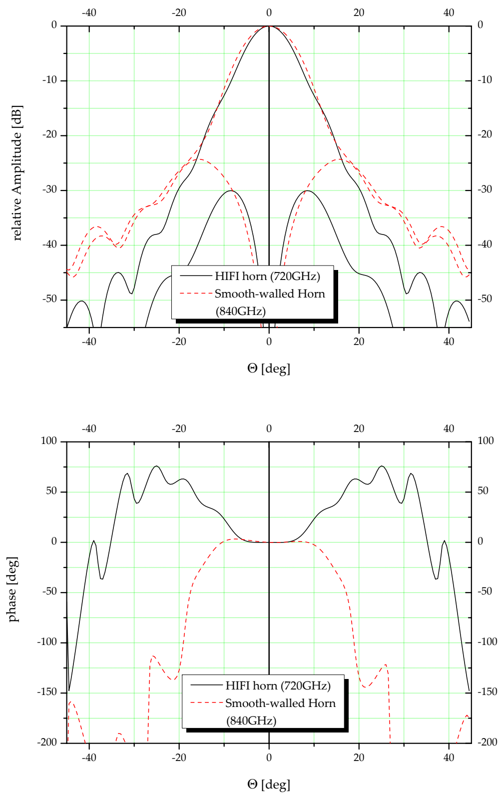

Fig. 7. *The data of the smooth-walled horn compared to the data of the corrugated HIFI horn in D-plane. Both at their respective center frequency.*

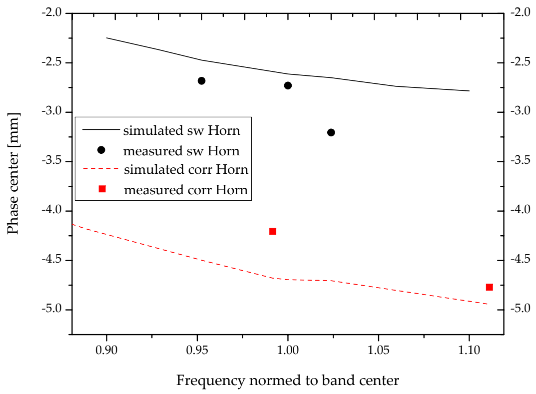

Fig. 8. *Distance of phase center to horn aperture*

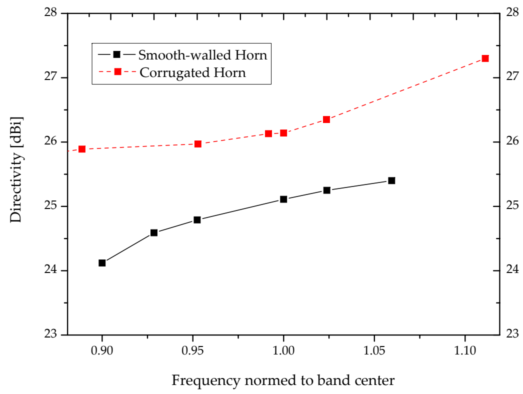

Fig. 10. *Directivity for both horns*

components are calculated as follows:

$$E_{horizontal} = E_\Theta \cos\phi - E_\phi \sin\phi \quad (1)$$
$$E_{vertical} = E_\Theta \sin\phi + E_\phi \cos\phi \quad (2)$$

The phase is calculated using the real (Re) and imaginary (Im) part of the signal measured at a certain position:

$$\angle E = \arctan\left(\frac{Im(E)}{Re(E)}\right) \quad (3)$$

An illustration of the coordinate system is shown in figure 9. In addition the 3D simulation gives us the field distribution inside the horn. An advantage to the mode matching method is the possibility to simulate fabricational imperfections like a burr. We have done it successful for interpretation of measurements within the HIFI project. A comparison of the simulation with measured data is done for 625 and 800 GHz at the corrugated horn and for 800, 840 and 860 GHz at the smooth-walled horn. The simulated data are in excellent

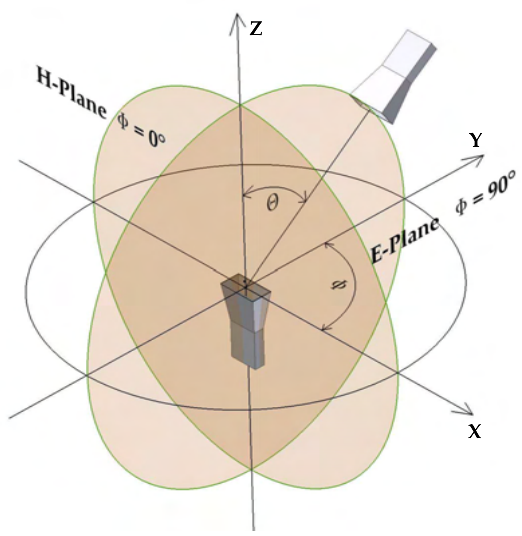

Fig. 9. *The Ludwig 3 coordinate system as it is used in the simulation with CST Microwave Studio. The coordinates are fixed with the horn under test.*

agreement with the measured data, examples are given in figure 3 and 4. For the smooth-walled horn we have additional results calculated with mode matching by C. Granet. These data correspond also well with the measurements.

Because the two horns have different center frequencies (see table I) a comparison of both horns is done with simulated data at the center frequencies (figure 5-7). The beam width of both horns is comparable, the side lobe level of the smooth-walled horn is at an angle of 40 deg approx. 10 dB higher than at the corrugated horn. Also the cross polarization level is higher (5 - 10 dB) at the smooth-walled horn. The main criterion for the phase is, that it is flat over an angle as large as possible, because this will simplify to design the optical components like mirrors etc.. This claim is satisfied by the smooth-walled horn very well. In addition, it is of advantage if the phase center lies in the same position over the frequency range. The phase center is calculated in Microwave Studio. It is used the phase of the phi or theta component of the electric field and the calculation is limited by an angle of 50 degrees around the main lobe. The phase center is calculated from phase values in E-Plane. To compare this data with the measurement, the measured phase is fitted to the simulated data by

$$\Delta\Phi = 2\pi\frac{\Delta z}{\lambda}(1 - \cos\Theta) \quad (4)$$

with the axial offset $\Delta z \ll z$ [11]. At the smooth-walled horn is the variation of the phase center position comparable with the corrugated horn. In figure 8 is shown, that the drift in the phase center is comparable for both horns. The plot shows also some measured points, of which the accuracy is limited by the mounting of the horns, that is not more exact than 1 mm. In addition the directivity (simulated in Microwave Studio) is evaluated. The directivity of an antenna is defined as the ratio of the radition intensity in a given direction from the antenna to the radiation intensity averaged over all directions. At this the radiation intensity is given by the power radiated per unit solid angle $P(\Theta, \phi)$ by the antenna divided by the total radiated power P_{total}:

$$D(\Theta, \phi) = 4\pi \cdot \frac{P(\Theta, \phi)}{P_{total}} \qquad (5)$$

The directivity (figure 10) for the smooth-walled horn is 1 to 1.5 dBi less than for the corrugated horn. This is a design parameter, therefore it is possible to optimize a smooth-walled horn for this requirement for a dedicated application.

IV. Conclusion

High quality phase and amplitude measurements of a HIFI Band 2 corrugated horn and a novel smooth-walled horn are presented. The data are compared to mode matching calculations and to full 3D electromagnetic simulations. Data and simulations are in excellent agreement. The 3D simulation is used to compare the smooth-walled horn and the corrugated horn. Their performance is comparable. The easier machining of the smooth-walled horn is bought at the expense of a little smaller directivity. The phase flatness is similar. Smooth-walled horns are a good choice to replace corrugated horns, especially for applications in the THz range; because they are much easier to manufacture with standard technique.

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