Corrugated Feedhorns at Terahertz Frequencies — Preliminary Results

B.N. Ellison, M.L. Oldfield*, D.N. Matheson, B.J. Maddison, C.M. Mann and A.F. Smith

Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX, UK.
* University of Kent at Canterbury, Canterbury, Kent, CT2 7NT, UK.

Abstract

Corrugated feedhorns radiate a near perfect Gaussian beam and are often used as feeds for receiver systems at millimetre and, increasingly, submillimetre wavelengths. Perceived constructional difficulties of such feedhorns have tended to limit their use to frequencies below 1 THz. We demonstrate that corrugated feedhorns can be constructed that will allow operation at frequencies well in excess of 2.5 THz and that the resulting antenna patterns are of excellent quality.

Introduction

There is increasing interest in using heterodyne receiver systems at frequencies in excess of 1 THz. This interest has originated primarily from the astronomical and atmospheric science community who wish to study the emission of molecular species from space or the Earth's atmosphere respectively.

Although heterodyne systems operating at frequencies above 1 THz have been demonstrated previously [1], the structure in which the detecting element (normally a Schottky diode) is embedded is not necessarily optimum. For example, it is known that the radiation pattern from a corner cube is not ideal with the best calculated coupling efficiencies being < 80% [2]. Further, due to the relatively long diode contact whisker used which also forms part of the antenna structure, these devices can be unreliable when cooled to low temperatures and may not lend themselves readily to space flight qualification.

Waveguide structures, on the other hand, have shown excellent performance when used with Schottky and superconducting tunnel junction (SIS) detectors at frequencies up to 700 GHz [3], [4] and waveguide/feedhorn combinations provide efficient coupling to the radiation field at microwave and millimetre wavelengths.

Of the various feedhorn types available the corrugated, or scalar, feed is generally considered to be superior due to its relatively large operational bandwidth, symmetric (Gaussian) power distribution and low sidelobe and cross-polarisation levels. To date, the highest frequency at which corrugated feedhorns have been used is ~ 700 GHz [3], the primary disadvantage being the perceived difficulty of construction. Although it is clear that using corrugated feeds in the terahertz frequency range necessitates the machining of structures with dimensions on the scale of microns and to sub-micron accuracy, we demonstrate that such feedhorns can be produced by a combination of conventional machining and novel coating techniques. A corrugated feedhorn has been fabricated and tested at 2.5 and 3.1 THz using a far-infrared laser as a source. The preliminary beam patterns measured are of high quality, exhibiting low sidelobe levels and Gaussian power distribution.

Feedhorn Design and Manufacture

The corrugated feedhorn described here has been scaled from an existing and successful 490 GHz design; the feedhorn mandrel, which is a 'negative' of the actual feedhorn, is shown in Figure 1. The aperture size is 0.84 mm diameter and the slant angle and length are 5.98° and 4.04 mm respectively. Along the slant length of the mandrel 64 corrugations are machined with a width, pitch and average depth of 26, 52 and 32 μm respectively. The last 10 corrugations in the throat region vary in depth to a maximum of 52 μm in order to provide a good impedance match between the feedhorn and the circular waveguide output. The corrugation structure selected allows a typical operational bandwidth of ± 20% about the centre frequency of 2.5 THz. The design methods used are based on those described by Thomas [5] and Clarricoats [6].

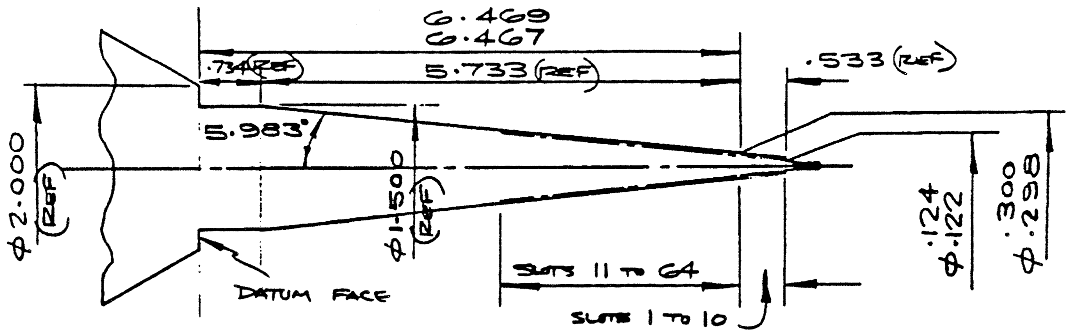

Figure 1: Drawing of aluminium mandrel

The aluminium mandrel was manufactured by using a high precision lathe and conventional machining techniques. Figure 2a shows a machined mandrel with a circular waveguide output; this type was used during the current measurements. Figure 2b shows a similar mandrel, but in this case with step sections added to allow an interface to a reduced height rectangular waveguide of dimensions 96 by 24 μm.

Once the mandrel is machined it must be coated with gold and copper and the aluminium etched away to produce the feedhorn. Normally the mandrel is coated using an electroforming process. A difficulty often encountered with this is that copper grows preferentially around the top of the corrugations leaving voids filled with the electrolyte solution which can leach out and damage the interior of the feedhorn. This problem is exacerbated as the structure size decreases. In addition, aluminium is difficult to gold or copper plate directly and a pre-etch, which tends to degrade the mandrel surface finish, is required.

Although techniques have been developed to try to control these problems, e.g. by filling the voids with solder or epoxy, we have avoided these difficulties by developing a novel form of coating procedure that uses RF sputtering which, as a consequence, does not require the mandrel to be pre-etched and effectively closes the corrugations in a low pressure argon atmosphere. Using this process means that at worst harmless low pressure argon may be trapped in any residual voids and at best the corrugations are completely filled with copper. This may prove a considerable advantage for devices required for space flight.

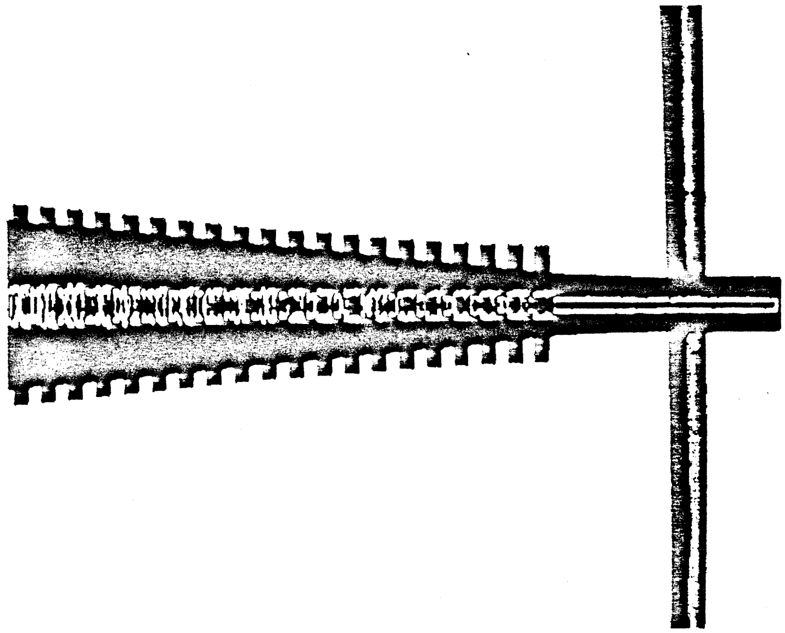

Figure 2a: Machined mandrel with circular waveguide output (shown with a human hair).

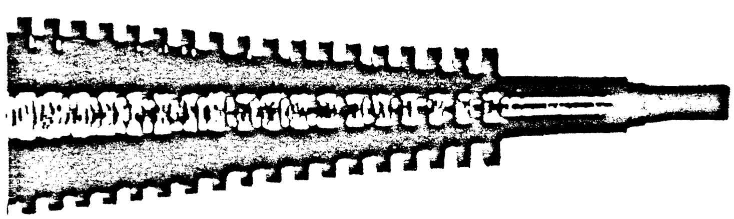

Figure 2b: Machined mandrel with integrated circular to rectangular waveguide transition.

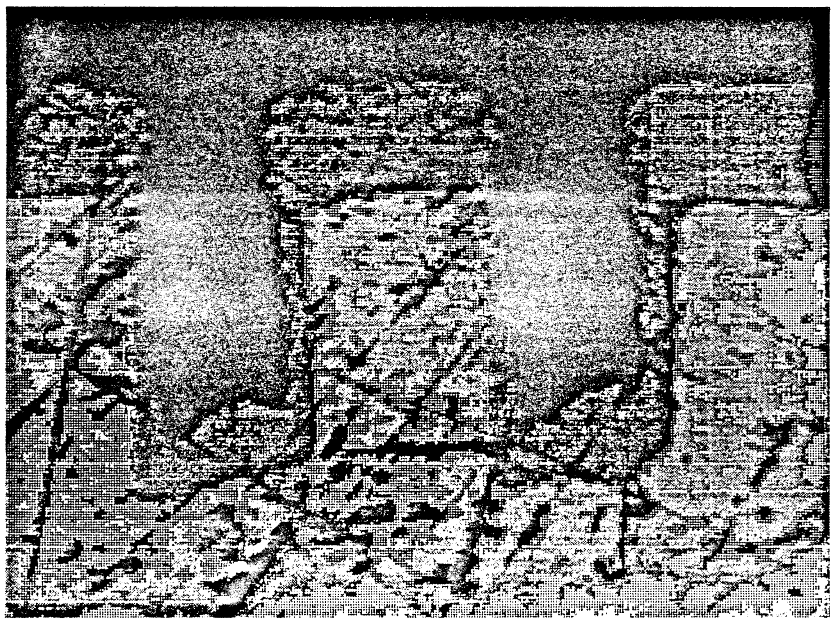

Figure 3: Sectioned test piece with partially filled corrugations.

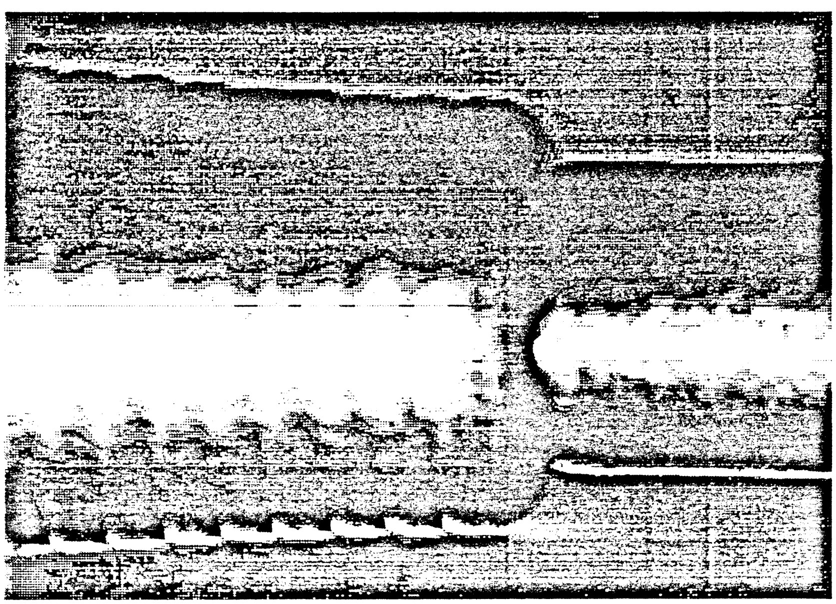

Figure 4: Sputter coated mandrel

During the coating process the mandrel is chemically cleaned and placed on a 'rotating spit' inside the sputtering system [7]. An initial thin (~ 2 μm) layer of gold is deposited onto the surface. Copper is next deposited until the corrugations are filled or a substantial thickness is achieved. The copper provides a support layer for the corrugation and is protected by the gold layer during the aluminium etching process. The sputtering parameters, e.g. rate of deposition time etc., that provide coating of the top, base and vertical walls of the corrugations were established by at series of trials on test pieces. A sectioned test piece with partially filled corrugations is shown in Figure 3 and a coated mandrel is shown in Figure 4.

After deposition of the copper is complete a further thin layer of gold is deposited to prevent oxidation of the copper and the whole mandrel is finally electroformed with copper to provide a bulk structure which can be machined and inserted into a suitable holder. The final process step is to etch the aluminium in a bath of sodium hydroxide which leaves the finished feedhorn. Figure 5 shows an example of a finished feedhorn mounted in a holder.

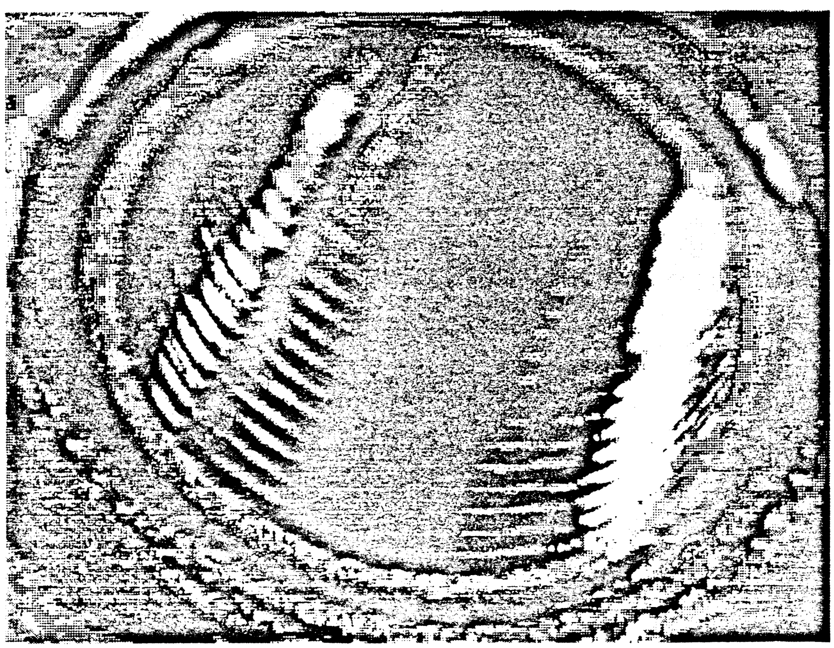

Figure 5: Finished feedhorn mounted in holder.

Measurement Technique

Figure 6 illustrates the measurement scheme which consisted of a far infrared (FIR) CO_2 pumped laser used as a source, a polyethylene coupling lens and a Golay cell detector. The coupling lens coupled the FIR laser beam into one of two feedhorns that were mounted back to back and the emergent beam from the second feedhorn was scanned by a Golay cell, the aperture of which was stopped down by a small (~ 0.4 mm diameter) hole cut into paper (paper is a good block, though not necessarily an absorptive one, to 120 µm radiation). The output of the Golay cell was amplified and integrated by a phase sensitive detector and the voltage output digitised and stored in a computer. A second Golay cell was used to monitor the laser output power and to correct for level variations during a scan. With this set-up it was possible to perform linear scans across the feedhorn in both E and H planes and to a generate a 2D raster image of the complete pattern. In addition, the scanning mechanism could be moved along the axis of propagation in order to investigate the beam expansion and standing wave effects. Finally, a Fabry-Pérot interferometer was used to check the frequency of the source.

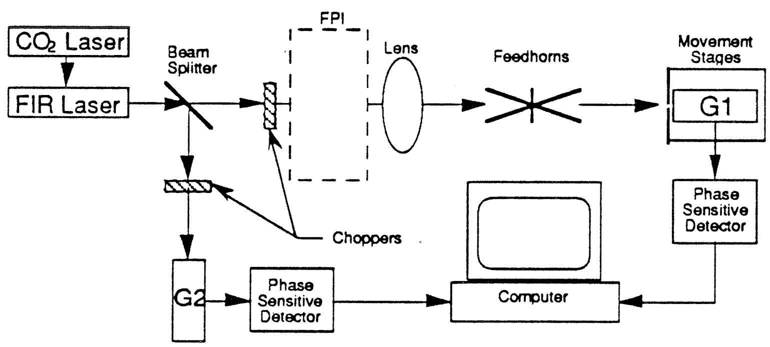

Figure 6: Measurement set-up using FIR laser as source.

Ideally, the radiation patterns would be measured by moving the detector in an arc about the phase centre of the feed. However, it proved difficult to configure our system to allow both E and H plane measurements to be made and to keep the detector close to the feedhorn in order to give the best signal to noise ratio. The half angle divergence of the beam from the feedhorn is typically 15° at 25 dB below the on axis value and truncation effects due to the aperture being moved off-axis are small.

Results

The radiation patterns produced by the feedhorn have so far been measured in the far field at 2.5 THz (the design frequency) and 3.1 THz and the data presented here are not corrected for the effects of the measurement aperture. In Figure 7 we show the measured intensity distributions for both the E and H planes at 2.5 THz and include a fitted Gaussian profile. Figure 8 presents similar measurements performed at 3.1 THz. From these data it appears that at the design frequency the E and H plane patterns have a high degree of symmetry. At 3.1 THz the E and H patterns are slightly asymmetric, but this frequency was beyond the nominal feedhorn bandwidth due to a restriction in the FIR laser lines available. At both frequencies the sidelobes are below -18 dB, implying a beam efficiency for the feedhorn of > 90%.

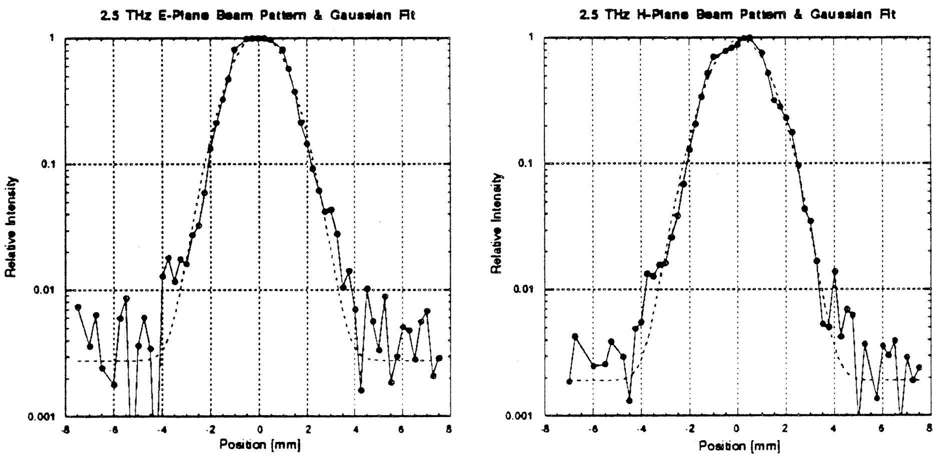

Figure 7: 2.5 THz E- & H-plane intensity distributions.

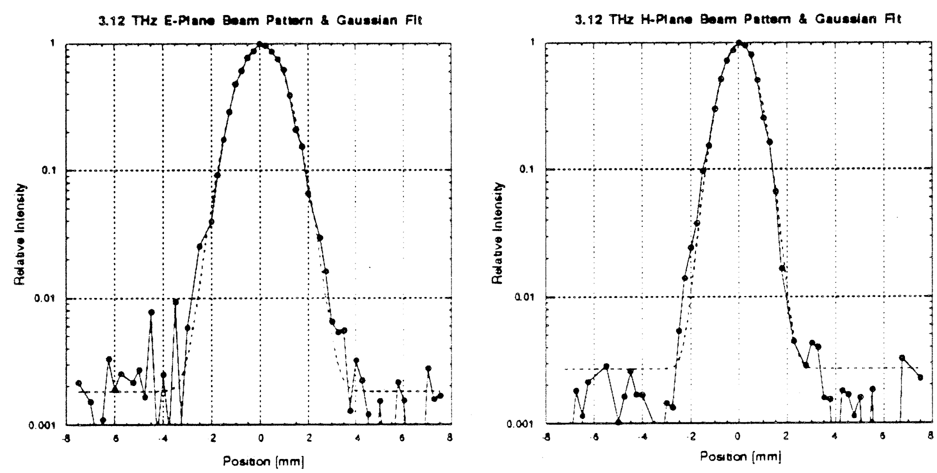

Figure 8: 3.1 THz E- & H-plane intensity distributions.

A curve fit to data obtained at different points along the axis of propagation gives an estimate of the feedhorn minimum beam waist size of ~ 0.33 mm at

2.5 and 3.1 THz. This compares reasonably well with the predicted value of ~ 0.25 mm [8].

Finally, Figure 9 shows a full 2D raster scan of the feedhorn at 2.5 THz with contour lines plotted at 3 dB intervals. This plot emphasises the symmetry of the beam pattern.

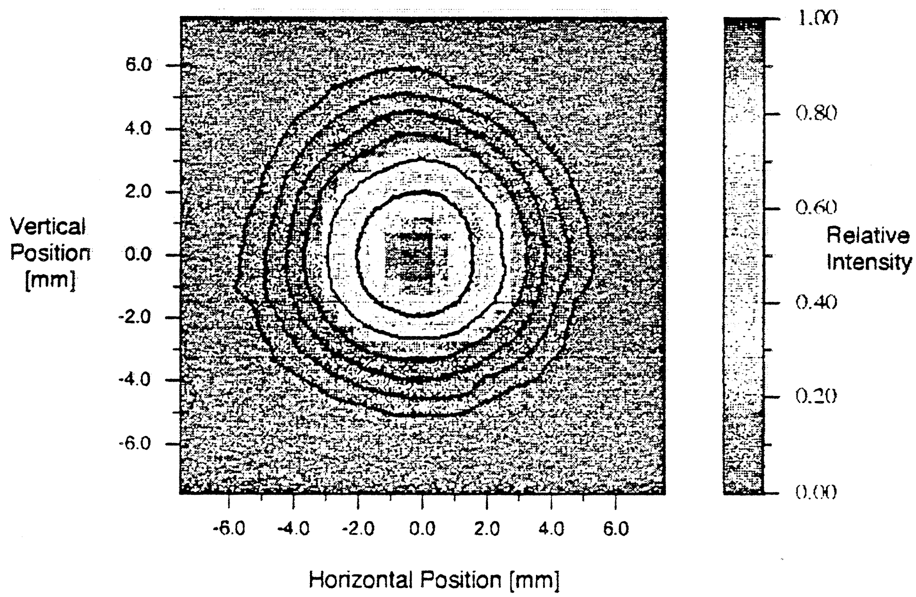

Figure 9: 2D raster scan of feedhorn radiation pattern at 2.5 THz.

Conclusion

A corrugated feedhorn has been fabricated and tested at 2.5 and 3.1 THz. Conventional mandrel machining techniques have been used and a novel method of mandrel coating has been developed.

The data presented are of a preliminary nature: for example we have not rigorously examined the effect of the measurement aperture on the measured patterns, but expect this to be small. Also there are outstanding measurements yet to be made, including additional frequencies, cross-polarisation and insertion loss. However, it would appear that the beam profiles in both E and H planes exhibit excellent symmetry at the design centre frequency, a Gaussian distribution to <-15 dB and have sidelobe levels < - 18 dB, the latter implying a beam efficiency > 90%.

Finally, use of these feedhorns need not be confined solely to heterodyne systems. For example, applications may exist with bolometric detectors in which the use of fundamental mode waveguide coupled with high quality beam patterns could yield improvements in sensitivity for devices operated at terahertz frequencies.

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