Single Chip, Beam Combining, Interferometric Detector for Submillimetre-wave Astronomy

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Abstract

We present results from an interferometer using a single chip, beam combining, superconducting detector. The interferometer consists of back to back corrugated horns feeding a back to back finline transition. The beams are combined in microstrip using a directional coupler. The detector was illuminated by a coherent source in the far field at frequencies between 320 GHz and 380 GHz. The resulting beam patterns show fringes with excellent visibility and the correct angular separation.

1 Introduction

The millimetre and submillimetre regions of the spectrum offer a great deal to astronomers. Perhaps one of the most valuable aspects of millimetre astronomy is the Cosmic Microwave Background (CMB). Encoded within its anisotropies, both in its temperature and looking to the future its polarisation, lies a wealth of information on the structure of the early universe and constraints on cosmological parameters. Interferometers offer certain advantages for studying the CMB, firstly, they sample the Fourier domain directly. Secondly, they offer a huge range in angular resolution and finally they have excellent intrinsic noise rejection due to their ability to filter out signals at frequencies other than the fringe rate. There is also interest in putting

FIR interferometers into space [1]. Here they would escape the difficulties imposed by the Earth's atmosphere and could explore early galaxy formation as well as nearby planet and star formation.

Interferometry at radio wavelengths has previously been limited to heterodyne systems where the signal is downconverted to a lower frequency. These systems use front-end amplifiers that limit the bandwidth. however. at optical wavelengths beam combination is carried out directly [2]. In order to study the very small anisotropies of the CMB and to explore early structure formation we require very high sensitivity, excellent noise performance and large numbers of detectors. Here we present results from a single chip. beam combining interferometer operating at submillimetre wavelengths. The technologies we demonstrate here at 350 GHz can be applied from the millimetre through to the FIR. By combining the beams directly we avoid the bandwidth limited front-end amplifiers required by heterodyne systems and can take advantage of the broadband. high sensitivity behaviour of bolometric detectors [3]. Furthermore, this approach offers all the potential of sophisticated microwave signal processing techniques as well as the possibility of placing many detectors on a single substrate.

2 Interferometer Design

The interferometer consists of two back to back corrugated horns forming a single baseline of 83.4 mm. The horns feed into back to back finline transitions which couples each horn to superconducting microstrip. The beams are then combined using a -15 dB directional coupler leading to two SIS tunnel junctions behaving as direct detectors. The key dimensions of the interferometer are listed in Table 1.

The corrugated horns and waveguide were machined out of a split aluminium block which was later gold sputtered. At each aperture a parabolic mirror was placed to form a horn-reflector with a flat phase front at the projected aperture. This can be seen in Figure 1. The heart of the interferometer is the superconducting chip. see Figure 2. This combines the two finline transitions. the directional coupler and two Nb/AlOx/Nb tunnel junctions all onto a single quartz substrate. Modelled using transverse resonance, spectral-domain analysis and the method of moments it was fabricated using photo-lithography and thin film sputtering techniques [4. 5]. Each finline is made of two niobium fins separated by a layer of silicon oxide 400 nm thick. These act to transform the high impedance of the waveguide to the low impedance of the microstrip.

Central to this design is that the beam combination is done before detection. This is done using a $-15\,\mathrm{dB}$ directional coupler which is shown in Figure 3. A directional coupler would not be used in an astronomical instrument, this would demand a more sophisticated correlator, for which there is plenty of room on the substrate. However, by using capacitive bridges to enhance the coupling, this design allows the system to demonstrate submillimetre beam combining interferometry without the need for the fabrication of dc blocks.

Another innovative aspect to this design was the use of two Nb/AlOx/Nb tunnel junctions. also visible in Figure 3. This offers the flexibility of allowing the tunnel junction on either arm of the directional coupler to act as the detector. By voltage biasing one of the junctions in the middle of the first photon step it acted as the detector while the other junction was biased above the gap so it behaved as a resistive load of around $21\,\Omega$. Since SIS tunnel junctions can detect photons both above and below the gap it was important to bias significantly higher than the gap voltage to make the junction a resistive load. SIS tunnel junctions were used as they have both high dynamic range and good sensitivity [6], however, an astronomical instrument would probably use TES detectors taking advantage of their greater sensitivity and noise performance.

The design we have implemented offers a significant amount of potential. The horns which are currently being used with parabolic mirrors to form horn-reflector antennas could be used to illuminate large aperture telescopes to achieve higher angular resolution. The large area of substrate could also be exploited to combine multiple baselines as well as implementing filtering and phase shifting, similar to the broadband correlation techniques being applied at microwave frequencies [7].

3 Theory

This interferometer implements pupil plane combination where afocal beams are superposed and the resulting intensity is measured by a single element detector. This differs from the more familiar image plane combination where beams are mixed in the focal plane forming an entire set of fringes that can be measured with an imaging array. In either case. however. the basic principle is the same, the signals from each of the two elements. E_1 and E_2. are added and the time averaged intensity measured by the detector.

$$\begin{aligned}\langle (E_1 + E_2)(E_1 + E_2)^* \rangle &= \langle |E_1|^2 \rangle + \langle |E_3|^2 \rangle + \langle E_1 E_2^* \rangle + \langle E_2 E_1^* \rangle \\ &= \langle |E_1|^2 \rangle + \langle |E_2|^2 \rangle + \langle 2|E_1||E_2| \cos\phi \rangle \qquad (1)\end{aligned}$$

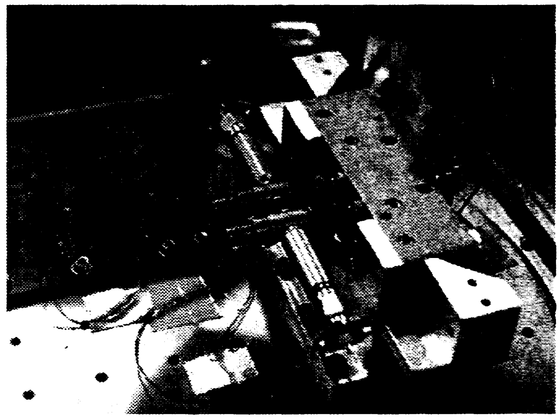

Figure 1: Exterior view of the interferometer. Two parabolic mirrors. two bias tees and the superconducting coil are clearly visible. attached to the split aluminium block in the centre.

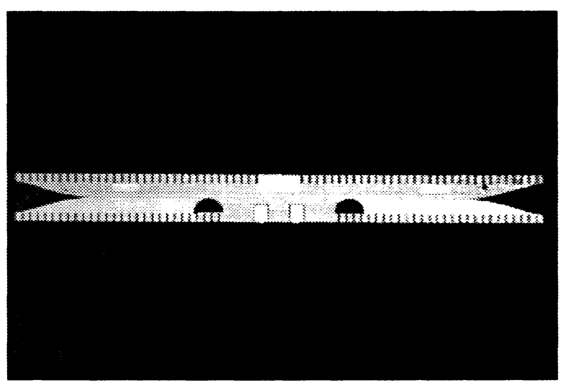

Figure 2: Superconducting chip containing two finline transitions, a beam combining directional coupler and two SIS tunnel junctions

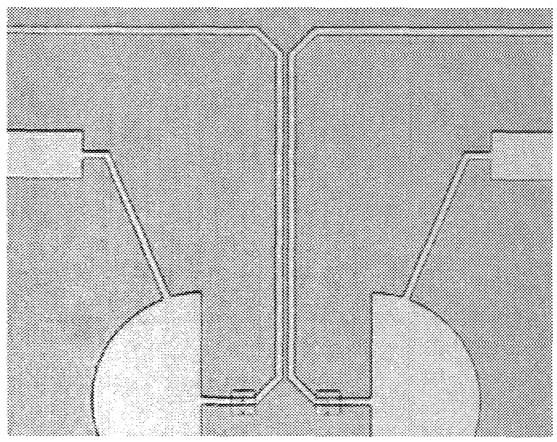

Figure 3: Close up view of the chip showing the microstrip from each finline coming together to form a directional coupler before entering radial stubs. Prior to each stub a SIS tunnel junction can be seen.

Diameter of horn aperture	10.8 mm
Axial length of horn	32.75 mm
Depth of corrugations	0.260 mm
Width of corrugation slots	0.210 mm
Width of corrugation walls	0.147 mm
Focal length of mirrors	19.3 mm
Distance between mirror centres	83.4 mm
Waveguide dimensions	0.700×0.350 mm
Substrate dimensions	$6.50 \times 0.55 \times 0.08$ mm
Resistance of tunnel junctions	21 Ω
Area of tunnel junctions	1.0 μm^2

Table 1: Key dimensions of the interferometer.

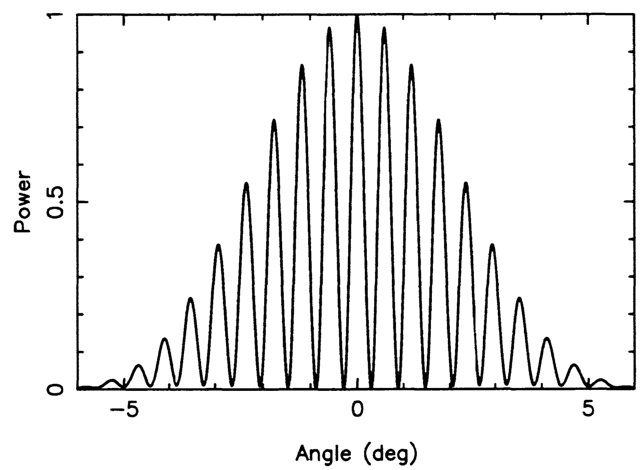

Figure 4: Expected fringe pattern from a 350 GHz source at a distance of five metres.

where ϕ is the phase difference between the two signals. In the case of a point source in the far field this is given simply by $\phi = \frac{2\pi B}{\lambda} \sin\theta$, where B is the baseline and θ is the direction of the source relative to the normal to the baseline.

Using modal matching the field at the horn aperture was calculated. Gaussian optics was then used to propagate this field in order to generate the beam pattern at five metres, the distance to the source. By combining the beam patterns of the two horns the predicted fringe pattern at a frequency of 350 GHz was calculated and is shown in Figure 4. The fringe separation, λ/B, is $0.59\,°$.

4 Results

The Dewar containing the interferometer was placed on a motorised rotating table. The Dewar windows were illuminated by a 350 GHz source five metres from the detector, consisting of a Gunn oscillator and two varactor multipliers. On the front of the Dewar two polarising grids were mounted to allow the radiation entering each window to be attenuated independently. The beam patterns for each channel of the interferometer were measured in turn by blocking off the other channel and measuring the photon assisted tunnelling current as the table rotated. The junction of the channel being measured was biased in the middle of the first photon step and the other junction was biased well above the gap to act as a load. Synchronous detection was

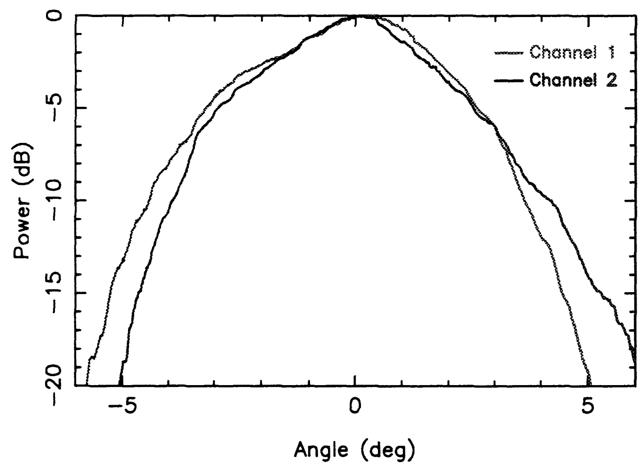

Figure 5: Measured beam patterns using a 350 GHz source at five metres. The two plots correspond to the two channels of the interferometer.

employed by electrically modulating the Gunn oscillator and using a lock-in amplifier. Figure 5 shows the beam patterns of both channels. In addition to some asymmetry the overlap differs from what is expected at this distance by about a degree. This is due to a small misalignment of the parabolic mirrors.

As mentioned earlier the beams from each channel are combined using a −15 dB directional coupler. The difficulty is that to achieve good visibility the signals from the two channels must be equal in magnitude. This was done by attenuating the beam entering the channel whose junction was being used as the detector. The results are shown in Figure 6. This shows two sets of fringes each with an angular fringe separation of 0.59°, as predicted, and visibility reaching 93 %. The visibility can be improved even further by better alignment of the mirrors, increasing the distance of the source and careful adjustment of the attenuation. One set of fringes is centred around zero, while the other is offset. The shifted set of fringes is the result of placing a slab of dielectric in front of one of the Dewar windows. This acts as a delay line increasing the path length of one of the channels thereby causing the fringes to shift. This demonstrates the principle of fringe rotation and confirms that the system behaves as an interferometer.

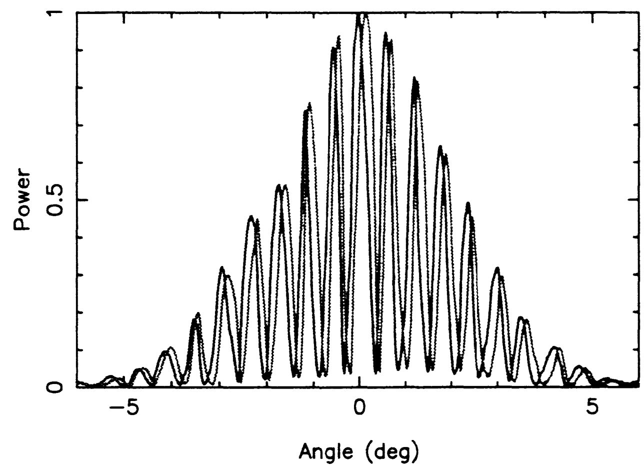

Figure 6: Two sets of interferometric fringes measured with a source placed at five metres. One of the sets of fringes is shifted due to the introduction of a dielectric slab in front of one of the Dewar windows.

5 Conclusion

These results show the successful design, manufacture and operation of the first ever single chip, beam combining interferometer. Excellent performance was seen over the entire frequency range of the source, 320–380 GHz. In terms of possible advances there is sufficient room on the substrate for a wide range of signal processing, allowing, for example, the measurement of multiple baselines. There is also the option of using TES detectors in combination with SQUID based readout electronics for improved sensitivity and noise performance.

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