A 64 Element, 70-95 GHz Focal Plane Phased Array

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***Abstract*— We discuss the theory and implementation of phased array receivers in the focal plane of a telescope as applied to the mm-wave band. Simulated performance and construction details are given for a 64 element, 70-95 GHz array receiver for use on the Green Bank Telescope (GBT).**

I. Introduction

Focal plane phased array (FPPA) receivers use multiple elements to synthesize the ideal aperture plane field distribution to match a telescope, and are able to produce overlapping beams on the sky. Phased arrays built to date have been at low microwave frequencies (1.4 GHz for most) [1,2] where the best feed is a dipole-like element, and the typical spacing is ~λ/2, which is large compared to receiver components. These arrays are intended for use at the prime focus of telescopes with a focal ratio near 0.35. In the frequency range near 90 GHz, feeds are usually based on waveguide apertures, and larger element spacing is required in order to accommodate the receiver circuitry. A collaboration between groups at the University of Massachusetts and Brigham Young University is building a 64 element phased array to cover 70-95 GHz for use at the Gregorian focus of the GBT. For this telescope the ability to make a vector map of the focal plane may enable real-time corrections to the reflector surface.

II. System Design

The receiver uses cryogenic MMIC amplifiers as the input stage followed by room temperature amplification and frequency conversion. The closest feasible spacing between elements due to the size of the amplifiers is 6 mm, nearly 2λ at the highest frequency. For such a large element separation it is essential to minimize the single element beamwidth in order to prevent large losses into sidelobes of the array pattern. We have adopted a dual TE_{01} waveguide feed as shown in Fig. 1 to approximate a single aperture with nearly uniform illumination, and nulls that fall on the array grating lobes. The H plane splitter is very simple, and well matched.

The GBT has a focal ration of f/1.9, requiring a focal plane sampling interval of 1.96λ. This allows a 6 mm period array to work up to 98 GHz without additional optics. Fig 2 shows the aperture efficiency for an array of ideal feed pairs over a wide band. At the higher frequencies such a large element leads to significant losses into sidelobes, but at lower frequencies the efficiency increases. Increasing efficiency due to oversampling is a general result for large apertures since it suppresses sidelobes by moving them farther away from the main beam. Oversampling also increases the cost in the use of elements, and the best system design is to optimize observing efficiency for a fixed number of elements. This efficiency may be expressed as mapping speed per element which scales as:

$$\text{mapping speed} \; \alpha \; N_{beams} \, (\eta_{aperture}/T_{sys})^2 \, . \quad (1)$$

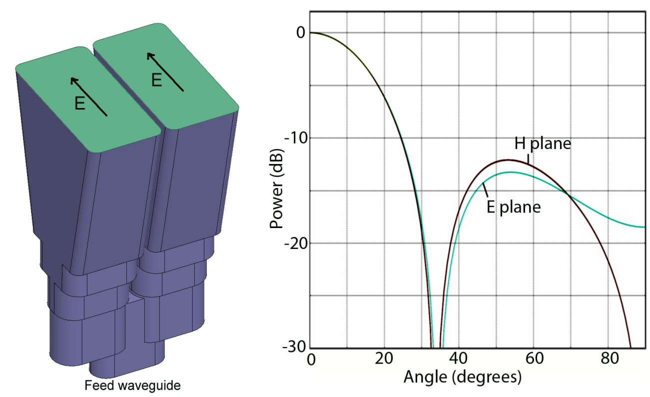

Fig. 1. Solid model of the dual feed, and E and H plane cuts through the pattern at 90 GHz. Each feed is 2.75 x 5.9 mm.

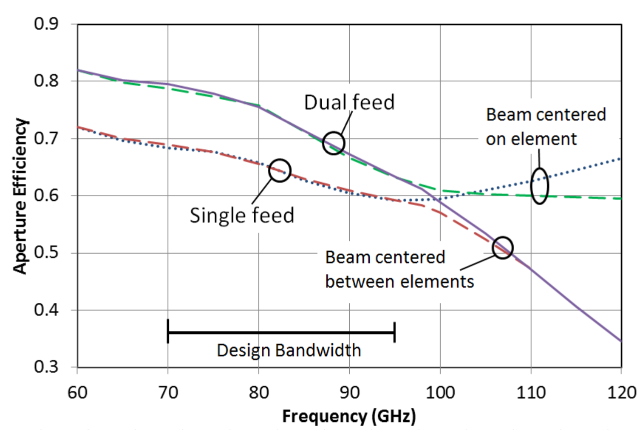

Fig. 2. Aperture efficiency of the near central beams of an 8x8 array of 6x6 mm dual feeds used to produce an f/1.9 beam. Beam centers are on an element or midway between elements. The efficiencies of an array using single TE_{10} feeds is also shown. Above 98 GHz the sampling is less than Nyquist.

An important figure of merit is how such an array compares to a conventional focal plane array (FPA) using discrete feeds. Amplitude measurements require half the sampling density relative to that needed for intensity in each dimension to meet the Nyquist criteria, so a large phased array can produce four times as many beams as its number of elements at minimal sampling. Below this frequency, the number of independent beams scales as frequency squared. Favorable comparison with a FPA requires that the receiver noise is similar, and while the FPPA analysis is very dependent on details, on-the-sky noise temperatures will be the same if the sidelobes are terminated at a temperature equivalent to that of the sky. Our system will use a cold load surrounding the array to terminate all the power far from the main beam at a temperature of 30K, which is as cold as the sky under typical conditions at the GBT. Only the beam within ~20° of the axis can leave the dewar, and this should fall on cold sky.

In a relatively small FPPA such as this one, the comparison is more complex because the sensitivity varies over the array due to edge effects. In this case one must use a weighted efficiency to account for this variation. Fig. 3 shows the variation in aperture efficiency at 70 and 90 GHz over this 8x8 array along two lines. The sensitivity is nearly constant for beams formed anywhere except on an edge element. Edge centered beams may be less useful because their truncated illumination can produce coupling into other beams. Summing all beams at 90 GHz with their weighted efficiencies, we get a mapping speed .925 as fast as with uniform sensitivity. At 90 GHz the speed is equivalent to a 117 element conventional FPA using scalar feeds, in producing a fully sampled map. This conventional FPA would be ~33x larger in area.

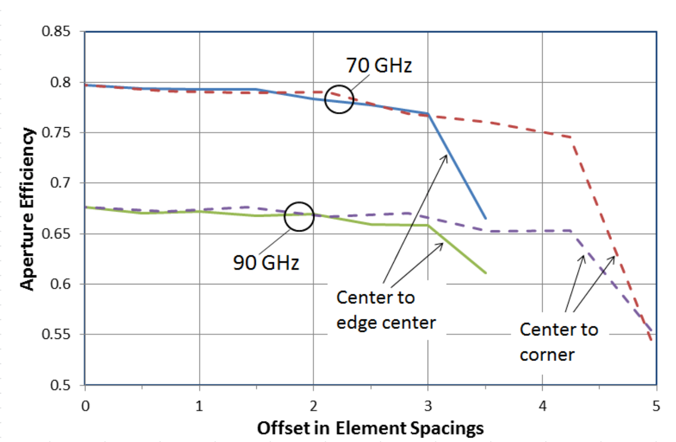

Fig. 3. Sensitivity vs beam center location in the array at 70 and 90 GHz along two lines from the array center outward. One element spacing is 0.71 HPBW at 70 GHz, and 0.92 HPBW at 90 GHz.

A feed element embedded in an array shows a significant mutual coupling with the array. This takes the form of direct coupling of one receiver to its neighbors, and scattering of the beam by the array, mostly in the form of surface waves. Direct coupling between nearest neighbors has been measured at <-30 dB for frequencies above 74 GHz, and so is a minor concern. Surface waves are quite evident in the array E plane beam patterns, but are quite directional, and account for little energy. Simulated and measured patterns agree well, and simulated efficiency is typically 2% lower than the results shown here.

Construction of such an array is quite challenging and has required the development of several new assembly techniques. The feed array, shown in Fig. 4, is machined from a single piece of aluminum, with each pair of feeds combined into a single waveguide in an H plane splitter. The cryogenic amplifiers with a gain of 25-30 dB and a noise temperature of ~30 K are all built on a single circuit board that is mated to the feed array, and the amplified output in waveguide is coupled out of the dewar. A room temperature custom SiGe MMIC [3] provides more gain, frequency conversion and IF gain from 5-30 GHz so that a single fixed 65 GHz LO may be used. Following this stage a second conversion results in a fixed IF of 1.4 GHz, using a construction in which every stage fits within the 6x6 mm cross section. The fixed IF is then converted to baseband, digitized and sent to a digital beamformer. The digital beamformer uses 8 bit A/D converters and ROACH (Reconfigurable Open Architecture Computing Hardware) boards to perform a Fourier transform of each input. Frequency binned data from all elements are then summed according to predetermined weights to form beams.

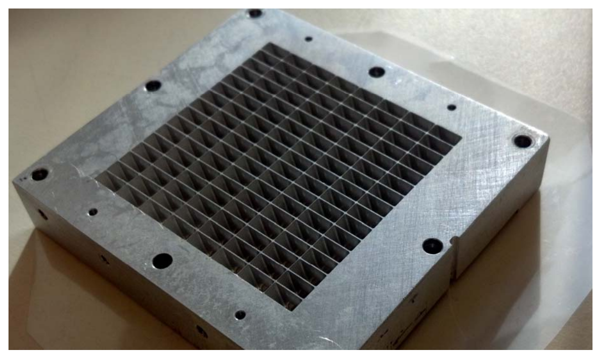

Fig. 4. Photo of the feed array with 128 apertures which are fed in pairs. The total size of the array is 48 mm square.

III. Conclusion

We have presented a phased focal plane array design extending this technique to much higher frequencies. The novel dual-horn feed achieves moderate aperture efficiencies and is simple to construct as an array. The approach is extendable to larger array sizes with reduced edge effects. This array is approaching completion, and when deployed on the GBT will enable new observation capabilities.

References

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