Investigation into Possible Planar Heterodyne Receiver Arrays with large (n≥100) number of pixels.

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Abstract—Heterodyne receivers are widely used in astronomy for observations of high spectral resolution. Most heterodyne receivers have a single pixel but thousands of frequency channels. To obtain spectra over a larger area of the sky, the first small (few to tens of pixels) heterodyne array receives have been built, consisting of a group of individual receivers. For large arrays (hundreds of pixels) we propose to radically rethink the design of heterodyne arrays and to develop planar heterodyne arrays that can be easily fabricated and need minimal assembly. In a first step, we want to replace the horn or the lens that are difficult to fabricate and assemble for large arrays by one planar structure. As a first attempt we have used FEKO to design an array of patch antennas to create a well-collimated beam using 256 patches. This array would replace one horn/ lens. Arrays of such patch arrays could be fabricated in a single process for array receivers. We describe the design approach, as well as the results for a test array at 600 GHz. The simulations show that the concept works, that a narrow, near Gaussian beam can be obtained and that losses can be kept low. In this paper we will also discuss the difficulties encountered, in particular, that a ground plane at 13 microns from the patches. The current design also has very low RF bandwidth. Nevertheless, we think that the concept might be interesting for future large receiver arrays.

INTRODUCTION

Heterodynes receivers are widely used in astronomy and the first arrays of heterodyne receivers have been developed, e.g. CHAMP[1], HERA[2], SMART[3], CHAMP+[4], HARP[5], Supercam[6], STO[7], upGREAT[8]. Some effort has been made to simplify heterodyne receivers for arrays (e.g. split block for several mixers[6]), but currently most array receivers consist more or less of an assembly of single pixel heterodyne receivers. We propose to radically rethink heterodyne array receivers and to try to build planar array receivers with integrated components, where a whole array can be produced on one monolithic chip akin to CCD cameras.

In a first step, we wanted to eliminate the horn or lens of the receiver. Instead, we aim to use a planar antenna structure. A simple single antenna will have a too divergent beam, and will require refocusing on a pixel basis. However, a narrow beam can be synthesized by an array of antennas, similar to flat radar arrays.

To our best knowledge, this paper is the first to investigate large phased arrays, with no active components, at high frequencies (> 500 GHz).

THE ANTENNA ARRAY

The array consists of many antennas connected together in phase. Due to the antennas working in phase, the beam becomes narrow. Antenna arrays are a very well-known principle. The classical array theory to steer the beam of the antenna arrays can be found in the most important books of antenna theory[9]. Antenna arrays are used in radar systems with active components to modulate and steer the beam, but such arrays are difficult to reproduce at high frequencies. However, no one has designed large arrays above 500 GHz with no active components, and as far as we know we are the first to attempt a design.

We have used FEKO to design an array of patch antennas to demonstrate the possibility of creating a well-collimated beam at 600 GHz. In our design, we used 256 patches that are connected with microstrip lines. The 16X16 microstrip patch array will be described below. A Hot Electron Bolometer (HEB) is located near the centre of the array and is connected by superconducting microstrips to the 256 patch antennas. The dimension of the patch has been optimized for the 600 GHz radio frequency (RF). The microstrip feedlines also provide impedance matching. The microstrip feedlines connect the patches such that the electrical path length from the mixer to any patch is the same. An intermediate frequency (IF) output line with filters blocking the RF is added. Two very small gaps on the transmission line near the centre of the array block the IF signal to avoid it going towards the patches. The design is a monolithic block, that does not require micron-level machining or optical alignment (e.g. lenses).

A. The Feeding Network

The microstrip lines connect the hot electron bolometer to the 256 patches of the array. All the lines have the same electrical length so that each antenna is in phase for our first design (fig 1 on the left). The microstrip lines are optimized for the RF frequency. It is therefore necessary to block the IF signal generated in the HEB. The blockage is realized by overlaying two microstrip lines separated by silicon (fig. 1 on the right) so that only a high frequency signal is allowed to pass.

Fig. 1 The microstrip lines. Single block of a 4X4 array (left) and IF blockage (right)

B. *The Losses*

The simulations show that the dielectric losses for silicon at 600 GHz are negligible, hence we focus only on metallic losses. The losses in a microstrip line are directly related to the resistivity. Since the resistivity increases with the frequency, the losses become very important at THz frequencies. A loss of 2dB/mm is computed for a gold microstrip line of 1µm width and 5µm dielectric thickness at 600GHz and T=4K. The efficiency of the antenna results degraded down to 20%. NbN superconductors cooled down to 4K are therefore necessary to avoid such losses.

C. *Array Size and resulting Beam*

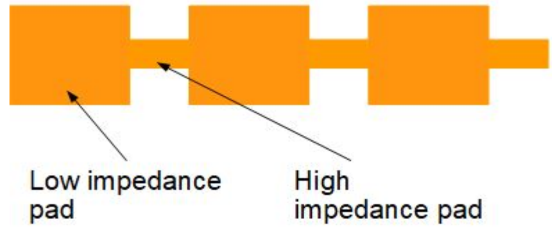
By connecting the patches in phase with the microstrip lines the beam becomes narrow. Actually the far field of an array is given by the product of the far field of the single element times the array factor *(AF)*, which is in general very narrow. The width of the array factor decreases with the number of patches and the distance between them. However the distance cannot be greater than the wavelength because in such case the side lobes increase. We aim to space two neighboring pixels at 2 FWHM beams apart. Which corresponds to a close packaging of Gaussian beams. Due to this goal and by assuming that no break out mirrors are employed we derived a maximum pixel size in the focal plane of about 5mm using typical focal ratios.

It can be numerically shown that the product of the *AF* times the far field of a single element is almost Gaussian, with 90% Gaussivity. However the microstrip lines radiate and generate sidelobes, which decrease the Gaussivity. The main lobe is however almost Gaussian.

D. *The Filter*

The mixer is positioned in the center of the array of patch antennas and connected to them by microstrips. In order to extract the IF signal we employ a strip line with a low pass filter to block the RF signal. A stepped impedance filter is chosen for this purpose, as is commonly used in microstrip designs (fig. 2).

Fig. 2 Stepped impedance filter. The narrow part of the microstrip line corresponds to the high impedance pad, the large part of the microstrip line corresponds to the low impedance pad. Such parts in series make a low pass



filter

E. *Description of the array*

The figure 3 shows the whole array. The sky signal is

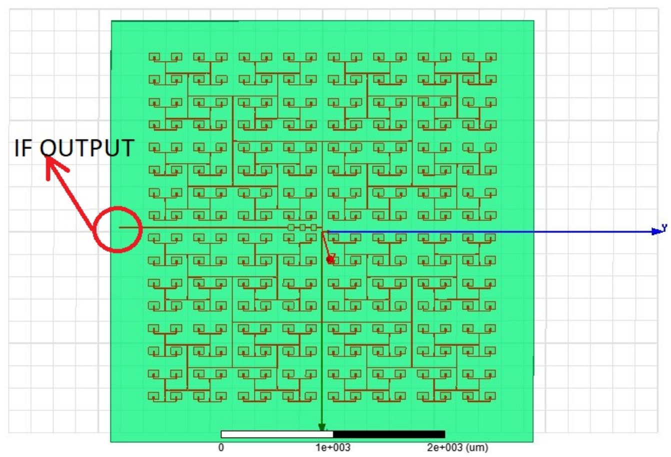


Fig 3 The whole array of 256 patch antennas which represents one pixel of the heterodyne

received by the 256 patches and feeds the HEB near the center of the array. The IF signal passes through the line on the left of the array to be amplified and detected. Two very small gaps on the transmission line near the center of the array block the IF signal to avoid it to go towards the patches (fig 1 on the right). In the same way the stepped impedance filter on the IF output on the left of the array blocks the RF signal from going to the amplifiers

RESULTS

A silicon substrate with ε=11,7 is used and has a thickness of 13µm. Superconductors are used. The dimension of the 18X18 patch array is approximately 16 mm^2. The results are very sensitive to the design parameters. Very small variations lead to great variations of the results, and this make the design very difficult. A genetic algorithm is used to adjust the design in order to obtain impedance matching in the RF band. In the simulation, the bolometer is set as the source of the RF signal. The S11 parameter and the far field is calculated accordingly. Fig 4 shows the S11 parameter.

The band is very narrow because of the resonating nature of the patches. The bandwidth would be sufficient for dedicated receivers to observe a specific line, but the bandwidth is too narrow for general purpose receivers.

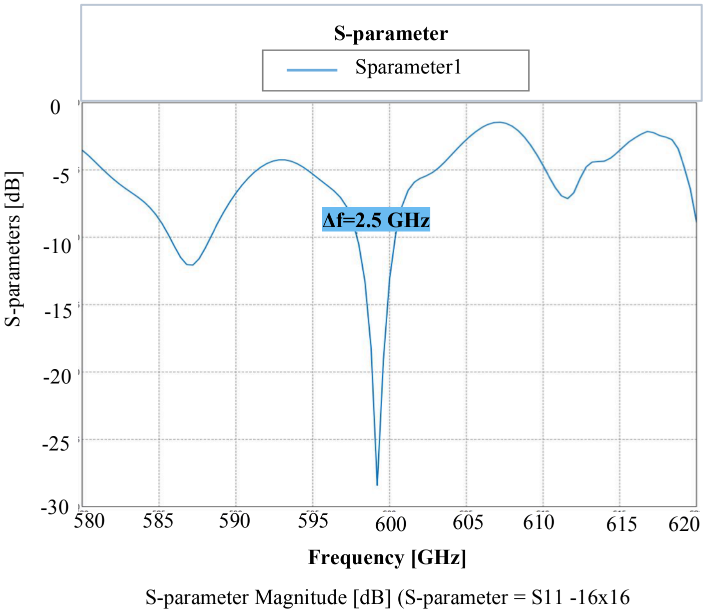


Fig 4 S11 plot, -10 dB bandwidth of 0.4%.

The far field is shown in fig. 5 and 6 in the XZ and YZ plane respectively (coordinate system of fig.3 where the z axis is normal to the array and the y axis is parallel to the IF output line with opposite direction). The largest side lobes are 12 and 14 dB below the main beam, which is acceptable in most cases. The half power full beam width is 7.6 and 6.1 degrees respectively. This collimation of the individual beams is good enough to allow reimaging of the entire array with common optical elements.

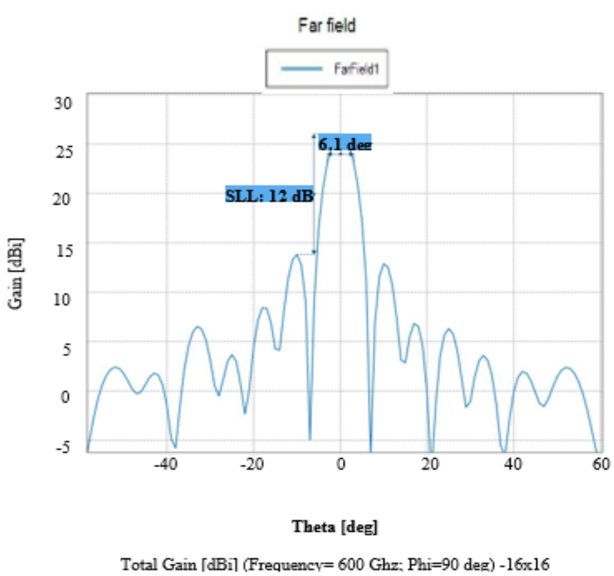


Fig. 5 Far field in the XZ plane. The gap between the main lobe and the side lobe is 12db. The HPBW is 6.1°

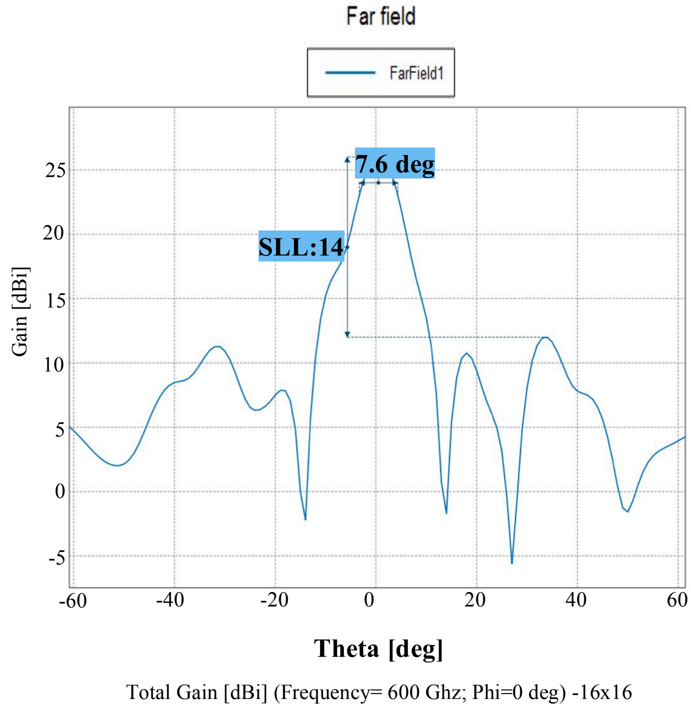


Fig. 6 Far field in the YZ plane. The gap between the main lobe and the side lobe is 14db. The HPBW is 7.6°

To understand the functioning of the array at the IF frequency, the bolometer is set as a 2 GHz source and the S12 parameter is calculated between the bolometer and a 50 Ohm resistance at the end of the transmission line which connects the filter to the IF chain (the IF output of fig. 4). The Measured S12 is acceptable, of the order of -0.15dB, while S11 =-15dB.

The simulation has shown that the phased array produces the narrow beam as expected, that the beams are nearly Gaussian and the side lobes are adequate. When a superconductor is used for the microstrip, line losses are also low. However, the array we present has also its shortcomings: the narrow RF bandwidth is acceptable only for receivers designed for specific observations; the microstrip line only works as a superconductor up to its gap frequency; it is difficult to fabricate the ground plane for a so thin substrate (too thin for etching and too thick for chemical deposition). The results are also very sensitive to the design parameters, which makes the fabrication difficult. We realize that the phased array could be further optimized, for example side lobes can be reduced by changing the illumination of the array from a top hat to a more Gaussian amplitude distribution and by adjusting the phase of the individual patches [10].

CONCLUSIONS

A 600 GHz phased array has been designed in our laboratory. The simulations show a beam with a narrow opening angle, and low loss. However, currently our design using patch antennas is too difficult to fabricate due to the necessity of a ground plane at a distance of 13µm. More work is required to find an entirely satisfactory solution, but we hope to have motivated the attractiveness of planar heterodyne arrays and have shown the first steps towards them as well as indicated the difficulties.

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