Imaging Polarimeter Arrays for Near-Millimeter Waves

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Abstract—An integrated-circuit antenna array has been developed that images both polarization and intensity. The array consists of a row of antennas that lean alternately left and right, creating two, interlaced sub-arrays that respond to different polarizations. The arrays and the bismuth bolometer detectors are made by a photoresist shadowing technique that requires only one photolithographic mask. The array has measured polarization at a wavelength of 800 μm with an absolute accuracy of 0.8° and a relative precision of 7 arc min, and has demonstrated nearly diffraction-limited resolution of a 20° step in polarization.

I. INTRODUCTION

RECENTLY, imaging antenna arrays have been developed that make images at near-millimeter wavelengths [1]–[3]. The idea is that an image is focused on an array of antennas with individual detectors, and the power received by each antenna is plotted to form an image. Fig. 1 shows how these systems work. An objective lens focuses an image onto the array through a lens on the back of the substrate. This substrate lens takes advantage of the fact that antennas are most sensitive to radiation from the substrate side. These arrays have demonstrated diffraction-limited resolution at 1.2 mm [2]. The antennas in these arrays are all linearly polarized, and measure only one component of the electric field so that the polarization angle is not measured directly.

Polarimeters measure polarization, and can be useful in determining material properties. For example, radars can measure surface roughness by analyzing polarization changes on reflection because rough surfaces depolarize, while smooth surfaces maintain polarization [4]. In biochemistry, the concentration of sugars can be measured by the rotation of polarization of transmitted light [5]. In plasma diagnostics and semiconductors, the polarization change by Faraday rotation is proportional to the magnetic field [6], [7].

A variety of different polarimeter schemes have been implemented. In microwaves, two linearly polarized antennas measuring orthogonal components of an electric field form a polarimeter [8]. In optics, the two orthogonal components can be split by a Wollaston prism, and measured independently [9]. In near-millimeter waves, three other...
methods have been used for plasma diagnostics. In one, the polarization is modulated by a ferrite and one polarization component is measured after it passes through the sample material [10]. Two other schemes avoid the ferrite by frequency mixing techniques. In the first scheme, two waves with slightly different frequencies and opposite circular polarization are combined, generating a wave rotating at the beat frequency [11]. The phase of the rotation is measured after the wave passes through the sample. This measurement is independent of fluctuations in source power. In the final scheme, two waves with slightly different frequencies but orthogonal linear polarization are generated [12]. In this last method, the amplitude of the beat signal gives the polarization changes.

In all these methods, imaging can only be done by scanning or by adding more detectors. In this paper, we demonstrate an integrated-circuit imaging array with bolometer detectors that also allows polarization measurement at near-millimeter wavelengths. Using the fact that the antennas are linearly polarized, two bow-tie antennas with different orientations are laid down alternately to form a polarimeter antenna array.

II. POLARIMETER ANTENNA ARRAYS

Fig. 2 is a drawing of a polarimeter array designed for a fused-quartz substrate. The antennas slant alternately to the left and right. Fig. 3 is a photograph of an array in its package. All the antennas are linearly polarized. The idea is that there are effectively two interlaced subarrays (left-leaning and right-leaning) that sample two different polarization components of the image. We can recover the two components everywhere by interpolating between samples. Once the two components are known, the polarization can be calculated at all positions.

The spacing between antennas should be small enough to achieve the diffraction-limited resolution of the optics. Rutledge et al. show that, in order to achieve diffraction-limited resolution in ordinary imaging arrays, the intervals must be no greater than \( \lambda_d f^* / 2 \), where \( \lambda_d \) is the dielectric wavelength and \( f^* \) is the system f-number [13]. In [13], this f-number is not the conventional f-number \( f/D \), but is defined as \( 1/2 \sin \theta \), where \( \theta \) is half the angle subtended by the exit pupil of the optical system, as seen from the image point. For heterodyne arrays, this spacing doubles. If these sampling criteria are not satisfied, aliasing problems result. In general, for the polarimeter array, the required spacings halve because each subarray must satisfy the sampling criterion independently. It is a surprising fact, however, that the spacing requirements relax greatly if two conditions are satisfied. If the intensity varies slowly across the object and the polarization angles are small, then the required spacing is just \( \lambda_d f^* \) even for video detection. The reason is that, under these conditions, the changes in the video detector signal become proportional to the electric field and the spacing requirements become those of an ordinary array with heterodyne detection. This is significant in plasma magnetic-field measurements, where the field intensity is kept relatively uniform across the object and the Faraday rotation angles are small (<10°). Later, we will see this effect for a step polarization change of 20°.

To see this mathematically, consider an image which we characterize by an intensity \( I \) and polarization angle \( \phi \) that are functions of the position \( x \). The antennas in the polarimeter array receive power \( P \) given by

\[
P = AI(x) \cos^2(\theta \pm \phi(x))
\]

where \( A \) is an effective area for the antenna and \( \theta \) is the polarization axis of the antenna. The \( - \) sign applies if the antenna leans to the left, and the \( + \) sign applies if the antenna leans to the right. For small \( \phi \), we may write this as

\[
P = A(\sin 2\theta) \left( \frac{I}{2\tan \theta} \mp I\phi \right).
\]

If we interpret the power received by each antenna as a
The normalized filter response and sampled-image spectra for the polarimeter array. \( f_s \) is the sampling frequency.

Fig. 4. The normalized filter response and sampled-image spectra for the polarimeter array. \( f_s \) is the sampling frequency.

Fig. 5. Feed patterns measured on a scale model at 10 GHz.

sample of the image, and ignore the constant \( A \sin 2\theta \), there are two distinct parts of the spatial frequency spectrum of the sampled image, shown below in Fig. 4. The spectrum of \( I/2 \tan \theta \) is centered at \( f = 0 \) and repeated at multiples of the sampling frequency \( f_s \). The spectrum of \( I\phi \), however, is displaced by \( f_s/2 \). This arises from the alternating + and − sign in (2). The sampling frequency should be large enough so that these spectra do not overlap. This will allow us to recover the polarization angle \( \phi(x) \). If \( I \) is slowly varying, its spectrum will be narrowband, and the spectrum of \( I\phi \) will be only slightly wider than that of \( \phi \). In this case, \( f_s \) must be slightly higher than twice the highest spatial frequency of \( \phi \). When \( \phi \) is small, it is proportional to the component of the electric field perpendicular to the \( \phi \)-axis as shown in Fig. 2. This means that the diffraction-limited cut-off frequency for \( \phi \) is the same as the cutoff frequency for fields given by \( 1/(2\lambda_d f^*) \) [13]. The required sampling period, or antenna spacing, is then \( \lambda_d f^* \). This argument has been given for video detection, but the result is the same for heterodyne detection.

To recover \( \phi \), we filter the data to recover \( I \) and \( I\phi \) separately, and then divide the latter by \( I \) to get the polarization angle \( \phi \) that we seek. In our measurements, where the intensity does not change in time, we normalized the response of each detector so that it was not necessary to filter for \( I \) or divide it out. The filter we used to recover \( \phi \) was to take the difference between an antenna signal and the mean of the signals on the adjacent antennas. This gives the normalized filter response \( \sin^2(\pi f/f_s) \) shown in Fig. 4.

The array was designed by modeling at the microwave wavelength of 30 mm. The feed patterns for several different planes are shown in Fig. 5. Only the pattern on the dielectric side is shown. The patterns on the air side are at least 10 dB down. The antenna impedance has not been measured, but previous experiments with bow-tie antennas indicate that it should be nonresonant with a resistance of 150 \( \Omega \). One interesting feature of the array design is the slit between adjacent antennas (see Fig. 2). Without the slit, the antennas were elliptically polarized with a cross-polari-
zation ratio of 10 dB. With the slit, the cross-polarization ratio in the microwave measurement was 40 dB. After the microwave tests, a scaled down integrated-circuit version was then built for a wavelength of 800 μm.

III. Fabrication

The array is fabricated with only one mask and one photoresist exposure by a shadowing technique. The idea is to use a 2-μm wall of photoresist to cast a shadow during the silver evaporation. The photoresist pattern has openings for both the antennas and a 3-μm-wide channel connecting the antennas (Fig. 6(a)). Chlorobenzene is used to make an overhanging lip on the photoresist to aid the lift-off process [14]. A silver layer 80-nm thick for the antennas is evaporated first at a 70° angle. The photoresist wall casts a shadow so that no silver reaches the substrate in the channel. Then 200 nm of bismuth is evaporated at normal incidence. The photoresist is removed, leaving behind an antenna array with bismuth bolometers where the channels were previously. One problem arose in fabrication. Often silver strips formed along the wall of the photoresist channel. These did not break when the photoresist was removed and shorted out the bismuth bolometers. This problem was solved by making corners in the photoresist pattern to break the silver strips, so that they are removed with the photoresist (Fig. 6(b)). Fig. 6(c) shows the finished device. This channel process is simpler than the photoresist bridge technique reported by Neikirk and Rutledge [15], but the measured electrical NEP is $5 \times 10^{-10}$ W/Hz at a modulation frequency of 100 kHz, twice as large as for the bridge-fabricated bolometers.

IV. Near-Millimeter Wave Experiments and Results

A polarimeter antenna array was tested at a wavelength of 800 μm in the optical system shown in Fig. 7. The source was a Thomson-CSF carcinotron. A wire-grid polarizer ensured that the beam was linearly polarized [16]. Both the collimator lens and objective lens were made of polyethylene and had a diameter of 11.5 cm and a focal length of 12.7 cm. The beam was chopped at 100 Hz. A crystal-quartz half-wave plate (8.42 mm thick) was used to rotate the polarization a known amount [17]. The fused-quartz substrate lens had a diameter of 25 mm. The signal was measured by a model 5204 PAR lock-in. About 5-mW power reached the objective lens. The system responsivity was 0.5 V/W for a 90-Ω bolometer biased at 150 mV. The system $f^*$ was 0.8. For general polarization and intensity imaging, the spacing between the antennas for video detection should be no more than 0.2 $\lambda_d$. In our experiments, however, the intensity varied slowly across the array and the polarization angles were small, so that the required spacing is four times larger, 0.8 $\lambda_d$. Our array spacing, 0.5 $\lambda_d$, satisfied this more relaxed criterion.

Several different measurements were made, including a check to see that the antennas were linearly polarized, a
test of the array's response to small angular changes in polarization, and an imaging experiment with a step change in polarization to show the resolution of the array. From the measurements, the polarization axis was found to be 38° to the left from the ϕ-axis as shown in Fig. 2 for the left-leaning antenna and 38° to the right for the right-leaning antenna. Fig. 8 shows the response of a single antenna to different polarization angles. Comparison with the theoretical cosine-squared curve shows that the antennas are linearly polarized. In the next measurement, the polarization across the object plane was constant, and could be varied by rotating the half-wave plate. Fig. 9(a) shows the measured polarization angle from the array for one setting of the half-wave plate. The standard deviation of the data is 0.8°. The change in the measured polarization angle when the half-wave plate was rotated is shown in Fig. 9(b). Here the standard deviation among the data in measuring a 6° change is 5 arc min, and their average value differs from the theoretical value by 7 arc min.

Finally, the antenna array imaged the chevron aluminum grid shown in Fig. 10. After the wave passes through the array, the electric field is perpendicular to the metal lines. This causes a 20° step change in polarization at the center of the chevrons. Fig. 11 shows the polarization image, along with the images predicted by geometrical optics (a step change) and by diffraction theory for diffraction-limited optics, which can be shown to be

$$\phi(x) = \tan^{-1} \left[ \frac{2}{\pi} \text{Si} \left( \frac{\pi x}{\lambda f^2} \right) \tan \left( \frac{\phi_0}{2} \right) \right]$$ (3)

where \(\text{Si}\) is the sine integral \([18]\) and \(\phi_0\) is the step change (20° in this case). The agreement between the experimental points and the diffraction theory indicates that the array is nearly diffraction-limited. This demonstrates that, for slowly varying intensities and small angles, diffraction-limited resolution may be achieved by sampling much less often than the general sampling criterion.

V. CONCLUSION

By measuring two different components of the electric field, two interlaced integrated-circuit antenna arrays demonstrated the ability to reconstruct the polarization image of objects at a wavelength of 800 μm. The array measured the polarization with an absolute accuracy of 0.8° and a relative precision of 7 arc min, and demonstrated nearly diffraction-limited resolution of a 20° step in polarization.

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REFERENCES


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