Paul F. Goldsmith received A.B. and Ph.D. degrees from the University of California, Berkeley, in 1969 and 1975, respectively.

After two years as a Member of the Technical Staff at Bell Laboratories, he joined the faculty of the University of Massachusetts, Amherst. He is presently Associate Professor of Physics and Astronomy and acting director of the Five College Radio Astronomy Observatory. He is vice president for engineering at the MilliTech Corporation, founded in 1981.

Jose L. R. Marrero was born in Las Palmas, Spain, on April 4, 1957. He studied "Ingeniero de Telecommunications" at the Universidad Politecnica de Barcelona, Spain. He then joined the Electrical Engineering department at the University of Massachusetts in Amherst, where he got a M.S. degree in 1981. He is now with the Physics Department at that institution working towards a Ph.D. degree in the area of theoretical high-energy physics.

Imaging Polarimeter Arrays for Near-Millimeter Waves

PETER P. TONG, STUDENT MEMBER, IEEE, DEAN P. NEIKIRK, PETER E. YOUNG, W. A. PEEBLES, NEVILLE C. LUHMANN, JR., AND DAVID B. RUTLEDGE, MEMBER, IEEE

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 subarrays 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.

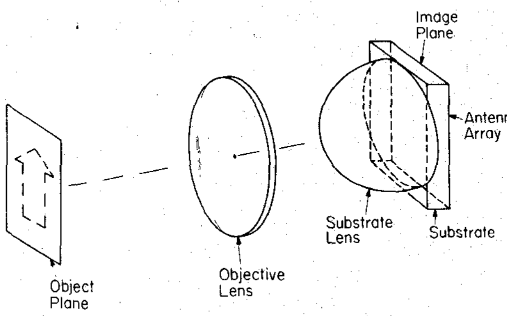


Fig. 1. Substrate-lens coupled optical system.

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

Manuscript received September 1, 1983; revised January 10, 1984. This work was supported in part by the Department of Energy and the Army Research Office.

P. P. Tong and D. B. Rutledge are with the Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA 91125.

P. E. Young, W. A. Peebles, and N. C. Luhmann, Jr., are with the Department of Electrical Sciences and Engineering, University of California, Los Angeles, CA 90024.

D. P. Neikirk is with the Department of Electrical Engineering, University of Texas, Austin, TX 78712.

0018-9480/84/0500-0507$01.00 ©1984 IEEE

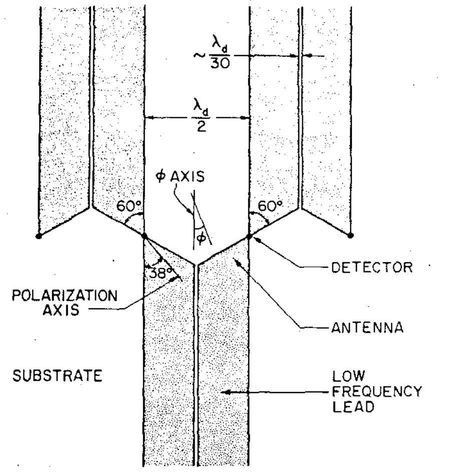


Fig. 2. Polarimeter antenna array designed for use on a fused-quartz substrate ($\epsilon_r = 4$).

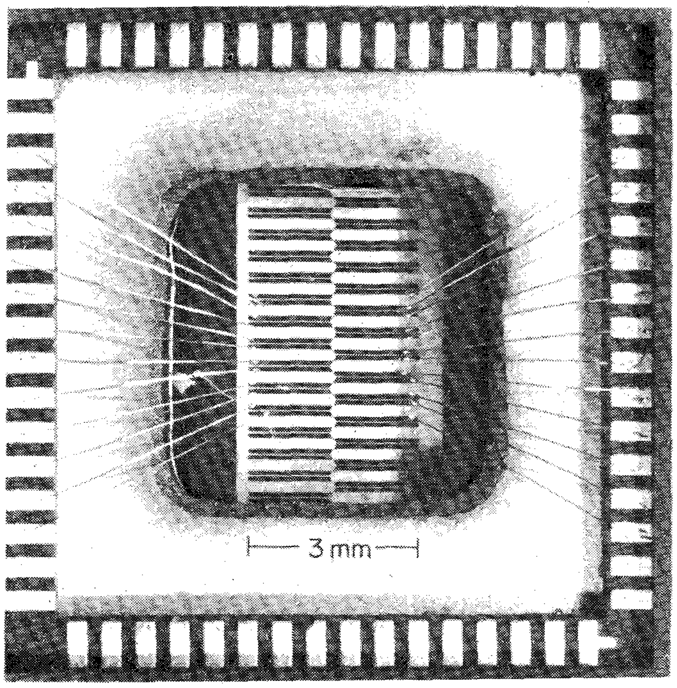


Fig. 3. Polarimeter antenna array in a standard DIP package.

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 λ_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 θ 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 ϕ that are functions of the position x. The antennas in the polarimeter array receive power P given by

$$P = AI(x)\cos^2(\theta \pm \phi(x)) \tag{1}$$

where A is an effective area for the antenna and θ 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 ϕ, we may write this as

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

If we interpret the power received by each antenna as a

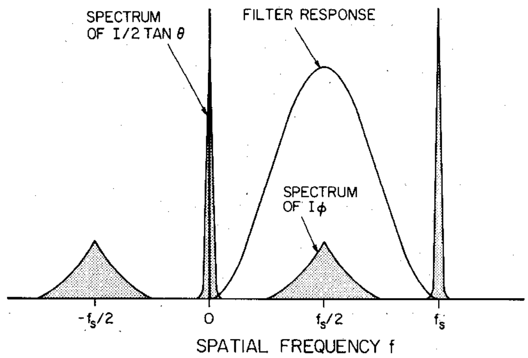


Fig. 4. The normalized filter response and sampled-image spectra, for the polarimeter array. F_s is the sampling frequency.

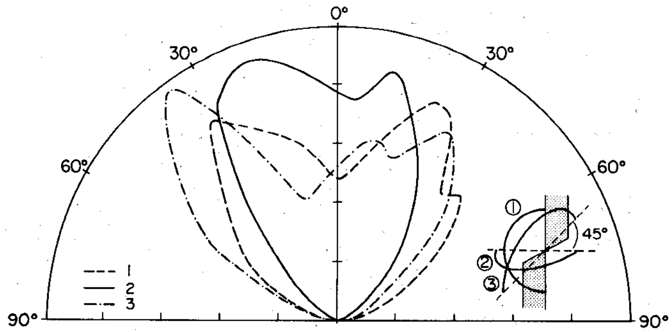


Fig. 5. Feed patterns measured on a scale model at 10 GHz.

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 ϕ. In this case, f_s must be slightly higher than twice the highest spatial frequency of ϕ. When ϕ is small, it is proportional to the component of the electric field perpendicular to the ϕ-axis as shown in Fig. 2. This means that the diffraction-limited cut-off frequency for ϕ 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 ϕ, we filter the data to recover I and $I\phi$ separately, and then divide the latter by I to get the polarization angle ϕ 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 ϕ 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.

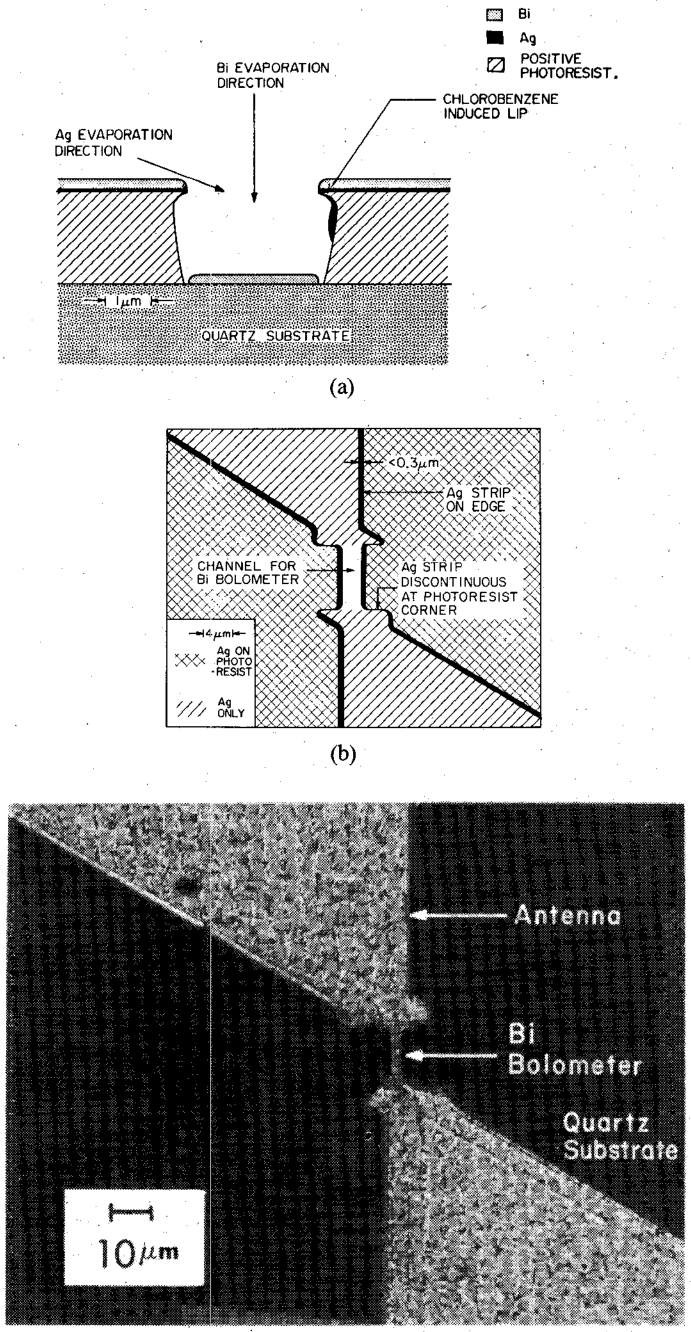


Fig. 6. Photoresist shadowing technique. (a) Cross-sectional view showing photoresist channel. (b) Top view with photoresist corners that break off silver strips. (c) Photomicrograph with liftoff showing bismuth bolometers. The quartz substrate appears black.

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 Ω. 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-

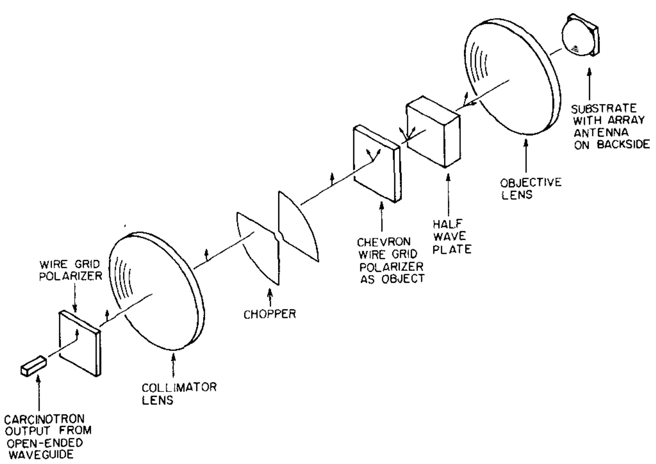


Fig. 7. Near-millimeter wave optical setup.

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 $5\times10^{-10}\mathrm{W}/\sqrt{\mathrm{Hz}}$ 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

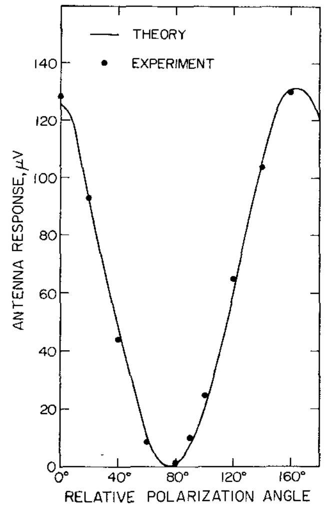


Fig. 8. Single antenna response as a function of the polarization angle.

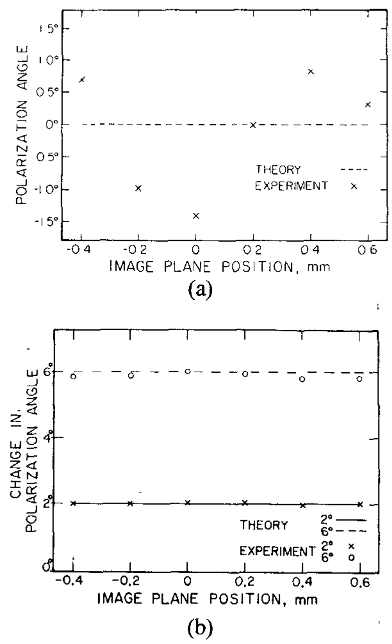


Fig. 9. The array response to small polarization angle. (a) The measured polarization angle for one setting of the half-wave plate. (b) The change in the measured polarization angle caused by rotating the half-wave plate.

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 λ_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 λ_d. Our array spacing, 0.5 λ_d, satisfied this more relaxed criterion.

Several different measurements were made, including a check to see that the antennas were linearly polarized, a

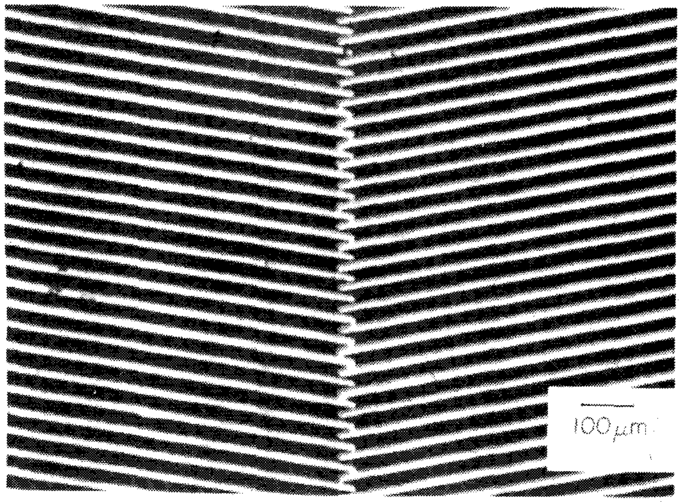


Fig. 10. Photomicrograph of the chevron gird. The light strips are aluminum, 20 μm wide, spaced 20 μm apart, and 300 nm thick (twice the skin depth at a wavelength of 800 μm). The fused-quartz substrate appears black. The grid is made by standard contact photolithography and liftoff.

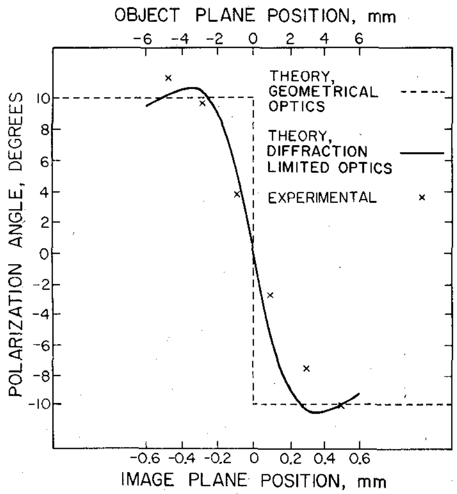


Fig. 11. Polarization image of the chevron grid.

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

$$\phi(x) = \tan^{-1}\left[\frac{2}{\pi}\,\mathrm{Si}\left(\frac{\pi x}{\lambda_d f^\#}\right)\tan\left(\frac{\phi_0}{2}\right)\right] \tag{3}$$

where Si is the sine integral [18] and ϕ_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.

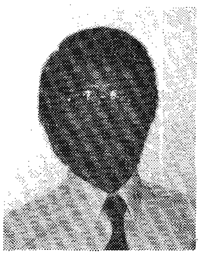
Acknowledgment

The authors thank C. Zah of Caltech and M. Miurav and M. Sergant of UCLA for help in mask making.

References

[1] D. B. Rutledge and M. S. Muha, "Imaging antenna arrays," *IEEE Trans. Antennas Propagat.*, vol. AP-30, pp. 535–540, 1982.
[2] D. P. Neikirk, D. B. Rutledge, M. S. Muha, H. Park, and C. X. Yu, "Far infrared imaging antenna arrays," *Appl. Phys. Lett.*, vol. 40, pp. 203–205, 1982.
[3] P. P. Tong, D. P. Neikirk, D. Psaltis, D. B. Rutledge, K. Wagner, and P. E. Young, "Tracking antenna arrays for near-millimeter waves," *IEEE Trans. Antennas Propagat.*, vol. AP-31, pp. 512–515, May 1983.
[4] G. R. Valenzuela, "Depolarization of EM waves by slightly rough surfaces," *IEEE Trans. Antennas Propagat.*, vol. AP-15, pp. 552–557, July 1967.
[5] J. W. Gates, "An automatic recording saccharimeter," *Chem. Ind.*, pp. 190–193, Feb. 1958.
[6] W. Kunz and G. Dodel, "On the measurement of poloidal field distributions in Tokamaks by far-infrared polarimetry," *Plasma Phys.*, vol. 20, pp. 171–174, 1978.
[7] E. K. Galanov, G. N. Potikhonov, V. V. Sorokhin, and O. M. Sheshin, "Infrared polarimeters and questions of method relating to contactless measurement of free-carrier concentrations in semiconductors," *Ind. Lab.*, vol. 42, pp. 1530–1533, Oct. 1976.
[8] S. Suzuki and A. Tsuchiya, "A time-sharing polarimeter at 200 MC," *IRE Proc.*, vol. 46, pp. 190–194, Jan. 1958.
[9] E. Hecht and A. Zajac, *Optics*, 4th ed. Reading, MA: Addison-Wesley, 1979, p. 238.
[10] C. H. Ma, D. P. Hutchinson, and K. L. Vander Sluis, "A modulated submillimeter-laser polarimeter for the measurement of the Faraday rotation by a plasma," *Appl. Phys. Lett.*, pp. 218–220, Feb. 1979.
[11] G. Dodel and W. Kunz, "A far-infrared 'polari-interferometer' for simultaneous electron density and magnetic field measurements in plasmas," *Infr. Phys.*, vol. 18, pp. 773–776, 1978.

[12] H. Soltwisch and T. F. R. Equipe, "Experimental test of far-infrared polarimetry for Faraday rotation measurements on the TFR 600 Tokamak," *Infr. Phys.*, vol. 21, pp. 287–298, 1981.
[13] D. B. Rutledge, D. P. Neikirk, and D. P. Kasilingam, "Integrated-circuits antennas," in *Infrared and Millimeter Waves*, vol. 10, K. J. Button, Ed. New York: Academic Press.
[14] M. Hatzakis, B. J. Canavello, and J. M. Shaw, "Single-step optical lift-off process," *IBM J. Res. Develop.*, vol. 24, pp. 452–460, July 1980.
[15] D. P. Neikirk and D. B. Rutledge, "Self-heated thermocouples for far-infrared detection," *Appl. Phys. Lett.*, vol. 41, pp. 400–402, Sept. 1982.
[16] G. R. Bird and M. Parrish, Jr., "The wire grid as a near-infrared polarizer," *J. Opt. Soc. Am.*, vol. 50, pp. 886–891, Sept. 1960.
[17] F. A. Jenkins and H. E. White, *Fundamentals of Optics*, 4th ed. New York: McGraw-Hill, 1976, p. 567.
[18] M. Abramowitz and I. A. Stegun, *Handbook of Mathematical Functions*. New York: Dover Publications, 1965, ch. 5.



Peter P. Tong (S'79) was born in Hong Kong on December 17, 1956. He received the B.S. degree in electrical engineering from the University of Hawaii at Manoa, Honolulu, in 1980, and the M.S. degree in electrical engineering from the California Institute of Technology, Pasadena, in 1981.

From 1981–82, he was associated with the Microwave Advanced Technology group at the Jet Propulsion Laboratory of the California Institute of Technology, Pasadena, where he worked with frequency multipliers in waveguides. He is now pursuing his Ph.D. degree in electrical engineering at the California Institute of Technology. His work is on millimeter and submillimeter wave integrated circuits and imaging.

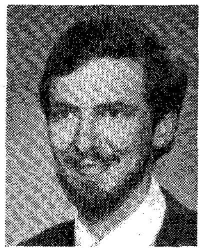
Dean P. Neikirk was born in Oklahoma City, OK, on October 31, 1957. He received the B.S. degree (1979) in physics from Oklahoma State University, Stillwater, and the M.S. (1981) and Ph.D. (1984) degrees in applied physics from the California Institute of Technology, Pasadena.

He joined the faculty of the University of Texas at Austin in 1984, and is currently Assistant Professor in the Department of Electrical Engineering. His research interests include far-infrared imaging systems and monolithic microwave integrated circuits.

Peter E. Young received his B.S. and M.S. degrees in physics from the University of Florida, Gainesville, in 1976 and 1977. He expects to receive his Ph.D. in physics from the University of California at Los Angeles in 1984.

W. A. Peebles photograph and biography unavailable at the time of publication.

Neville C. Luhmann, Jr. photograph and biography unavailable at the time of publication.



David B. Rutledge (S'75–M'80) was born in Savannah, GA, on January 12, 1952. He received the B.A. degree in mathematics from Williams College, Williamstown, MA, in 1973, the M.A. degree in electrical engineering from Cambridge University, Cambridge, England, in 1975, and the Ph.D. degree in electrical engineering from the University of California at Berkeley.

From 1975 to 1976, he was associated with the communications group of General Dynamics Corporation, where he worked with airborne microwave data systems. In 1980, he was appointed an Assistant Professor of Electrical Engineering at the California Institute of Technology, Pasadena. He is working on millimeter and submillimeter devices and their applications.