A Millimeter-Wave Monolithic Load Switching Twist Reflector for Compact Imaging Cameras

G. Richard Huguenin, *Senior Member, IEEE*, Ellen L. Moore, *Senior Member, IEEE*, Sudarsanam Bandla, and John J. Nicholson

***Abstract*—A monolithic load switching twist reflector (LSTR) has been built and tested for use in 94 GHz passive imaging cameras. In this paper, we describe the LSTR component, which switches between the dual roles of load comparison in a radiometer and reducing the length of the camera. Radiometric and quasioptical tests show that the array has an insertion loss of 0.25 dB and a switching ratio of ≥20 dB. This active array of p-i-n diodes can replace the mechanical choppers often used in load comparison.**

I. Introduction

Millimeter-wave imaging systems are being developed for detecting metallic or nonmetallic contraband concealed under people's clothing [1]. Plastic weapons and explosives concealed under clothing present unique challenges to conventional detection technology. Common techniques that can reveal nonmetallic, nonmagnetic materials involve X-rays or high energy neutrons [2], which cannot be safely used on a living subject. Most clothing is opaque to infrared wavelengths. Passive millimeter-wave imaging exploits the difference in emissivity between a human body and hidden contraband without irradiating the subject or generating signals which could be monitored by an adversary. These features make it a preferred method for scanning humans for contraband.

A passive millimeter-wave camera detects and processes the emitted radiation from the subject and contraband. It then generates a picture comprising pixels, which are encoded by color or black and white to display varying signal strength. The contraband shows up as a silhouette against a human body. This technique requires a high sensitivity heterodyne receiver to distinguish small differences in emissions at low power levels.

Load comparison is a necessary part of such a receiver to remove the effects of gain fluctuations of receiver components which can mask the detection of small scene contrast changes. In the load comparison mode, the receiver alternately compares the scene to a reference load at a rate high enough to overcome the low frequency peak of the receiver gain fluctuation spectrum. The load comparison must also be done in such a manner as to not cause visible blanking of the resulting image. The observation by all channels of the same comparison load also facilitates channel to channel gain normalization, also known as flat fielding. Most research radiometers use a waveguide switch or a mechanical chopper for load comparison, but with focal plane arrays this method is too cumbersome for commercial or law enforcement applications.

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The authors are with Millimetrix, LLC, Hadley, MA 01035 USA.

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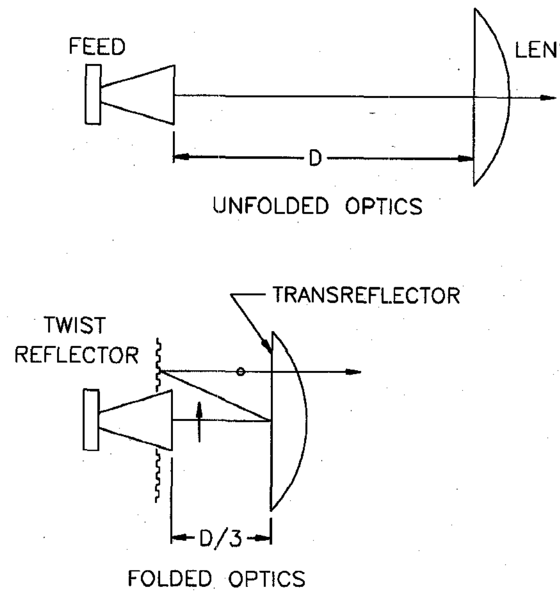

Fig. 1. Unfolded and folded optics.

In addition to performing the load comparison function, the LSTR with a quarter wave plate is an essential component in the camera's compact optics configuration. This layout, shown in Fig. 1, shortens the distance between the feed and the lens by about a factor of 3 compared to the unfolded version. Following the path of the beam in Fig. 1, the beam is launched from the feed and is incident on the transreflector. The transreflector is a dielectric slab with parallel metalized lines in one direction. The field component parallel to the lines is reflected and the perpendicular component transmits through. The reflected beam is incident on the twist reflector. A passive twist reflector can be a metal disk with $\lambda/4$ deep slots cut at 45° with respect to the incident field polarization, or it can be a quarter wave plate mounted against a flat plate. The field incident on the twist reflector has one polarization component delayed with respect to the other by 180° on reflection, with the result that the exiting beam is in the orthogonal polarization state. The beam is now perpendicular to the lines in the transreflector and transmits through and is focused by the lens. This optics configuration results in a sensor which is sensitive to a single linear polarization.

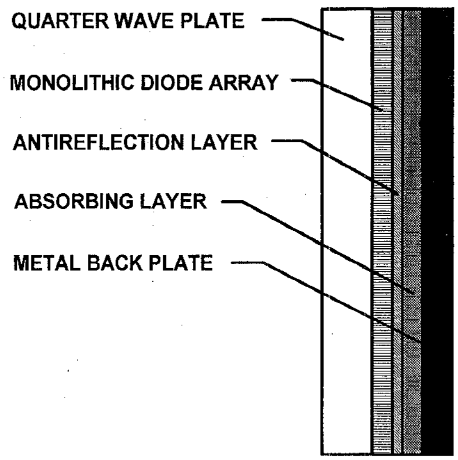

Fig. 2. A cross section of the load switching twist reflector.

The cross section of the LSTR is shown in Fig. 2. This device comprises a slotted dielectric quarter wave plate, the monolithic diode array, an absorbing layer with an antireflection layer, and a metal back plate for structure and temperature control. When the p-i-n diodes are biased OFF the LSTR reflects the incident signal because the monolithic array and the quarter wave plate are a twist reflector. With the diodes biased ON the power emitted from the scene transmits through the wave plate and the monolithic array to the load, while a noise source (not shown) transmits directly into the focal plane array. This occurs during 1/18 of the duty cycle.

The system requirements of the LSTR array are 1) a good switching ratio, or a difference of $\geq$17 dB in reflected power between the diode ON and OFF states, 2) low insertion loss, which means that the power must be reflected without loss when the array is biased OFF, and 3) a low excess radiometric noise level. In the diode off state the LSTR array delivers power from the scene to the focal plane array. Any loss in reflected power is detrimental to the performance of the camera. During the transmission state the return loss from the monolithic array should be at least 20 dB below the reflected power level in the diode OFF state. There is no requirement for insertion loss through the tiles during the ON state, as the power is absorbed by the load.

The 17-dB switching ratio is determined by the efficiency η of the switch. A perfect switch with a very high isolation has $\eta = 1$. If no frequency or time dependence are assumed, the following derivation gives the required switch ratio. The camera is used to view a scene characterized by an equivalent brightness temperature distribution $T_b(\theta, \varphi)$ [K]. The scene antenna temperature T_{Ai} of the ith channel is given by the convolution of $T_b(\theta, \varphi)$ with the antenna gain g_i of the sensor's ith channel. The antenna temperature of each independent channel is

$$T_{Ai} = \iint T_b(\theta, \varphi) g_i(\theta - \theta_i, \varphi - \varphi_i)\, d\Omega[\mathrm{K}]. \quad (1)$$

The square law detected output of the ith channel when viewing the scene is given by

$$v_{Ai} = G_i(T_{Ri} + T_{Ai}) + v_{oi} \quad (2)$$

where G_i = gain of the ith receiver channel, T_{Ri} = noise temperature of the ith receiver channel, and v_{oi} = the dc offset.

The output when viewing a comparison load with effective temperature T_L is given by

$$v_{Li} = G_i(T_{Ri} + T_L) + v_{oi}. \quad (3)$$

When the load switch is inefficient, the camera observes both the load and the scene simultaneously. The output voltage from the load is then

$$v_{Li} = G_i[T_{Ri} + \eta T_L + (1 - \eta)T_A] + v_{oi}. \quad (4)$$

T_L is the same for all channels using the LSTR. Using a load comparison algorithm, the difference v_{ci} between the receiver scene and the load detected output is

$$v_{ci} = v_{Ai} - v_{Li} \quad \text{or} \quad (5)$$

$$v_{ci} = \eta G_i(T_{Ai} - T_L) \quad (6)$$

when the switch efficiency is factored in. The expression in (6) is the signal and when η is less than unity, the signal-to-noise ratio degrades. For a switching ratio of 17 dB, 2% of the power is lost.

In order to minimize the effects of gain fluctuations we see that

$$\Delta v_{ci} = \Delta(G_i \eta (T_{Ai} - T_L)) \quad (7)$$

and the effect of the gain variations ΔG_i is minimized as $T_{Ai} \approx T_L$, i.e., as $(T_A - T_L) \rightarrow 0$. When $T_{Ai} = T_L$ the load comparison radiometer is "balanced." For concealed weapons detection applications, T_b varies between room temperature ($\sim$293 K) and body temperature ($\sim$304 K). The comparison load will be between 303 and 313 K, thus there is an approximate balance. The load comparison switching rate must be rapid enough to overcome the low frequency peak of the receiver gain fluctuation spectrum.

II. Design of the Monolithic Array

The monolithic array is a later version of the one developed by Stephan, Spooner, and Goldsmith [3]. It is a 230-mm diameter mosaic of 12.7 $\times$ 12.7 mm tiles. Each tile has an active mesh on one side, a passive mesh on the second side, and a p-i-n diode between the nodes of the active mesh in both dimensions. The active mesh shown in Fig. 3 has rectangular geometry which lends itself to analysis more easily than the earlier design with dots. The passive mesh has only the 2 dimensional array of metal strips with the same metallization pattern as the active side. The meshes have a grid period of 70 μm and are fabricated on a 255 $\pm$ 5-μm-thick GaAs substrate, which is 22 μm thicker than $\lambda/4$ in GaAs. p-i-n diodes have low series resistance when forward biased and high resistance when unbiased or reverse biased, and are often the ideal device for switches. The diode array is 2 dimensional because of the requirement that the power must transmit through the array during part of the duty cycle. An array of 1-dimensional strips against a reflector would constitute only the twist reflector and exclude the load comparison function. In principle, a one-dimensional (1-D) array could be fabricated on each side of the tile, with the strips orthogonal. However, the fabrication and

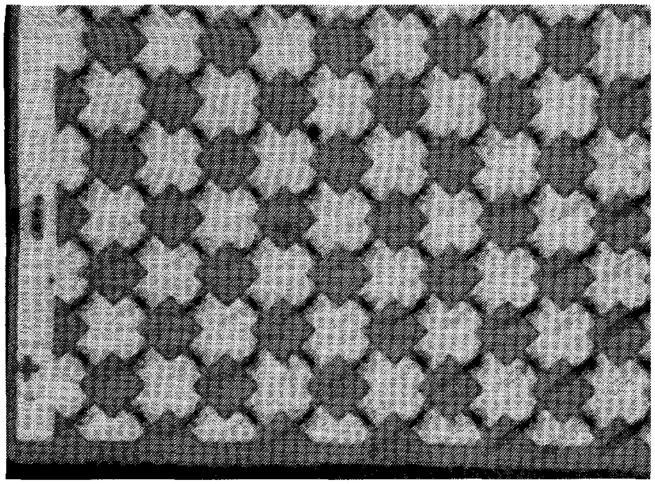

Fig. 3. A photograph of the active monolithic array.

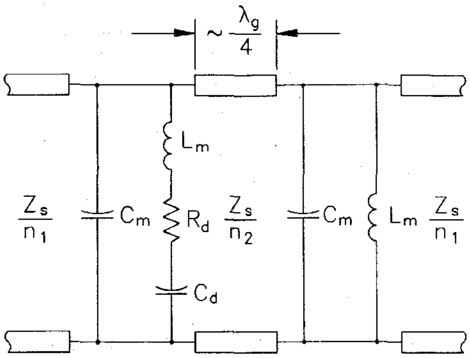

Fig. 4. The equivalent circuit used in the monolithic diode array model, with the mesh (m) and diode (d) components.

biasing would be arduous. The two-dimensional (2-D) array with one active surface is the simplest to fabricate and has the additional advantage of not losing an entire strip if one diode shorts or opens, thus making the tile yield higher.

The design software is a proprietary transmission line model [3] that calculates the power transmitted through and reflected from as many as four dielectric layers, two of which may have a 1-D strip array or a 2-D mesh. The meshes may have one or more diodes between the nodes of the mesh, and the strips may have diodes spaced at an interval that is equal to the grating constant. The user inputs the diode capacitance and series resistance, the grid spacing and strip width, the thickness and dielectric constant of the layers, and air gaps if any. The equivalent circuit for the mesh with the diodes shown in Fig. 4 is very similar to Fig. 4 of [3].

III. Tile Fabrication and Testing

All processing of the LSTR tiles was done at Millitech Corporation's (now Millimetrix) semiconductor facility. The MOCVD grown wafers consisted of a 1-μm P^+ layer, a 1-μm undoped I layer, and a 3.5-μm N^+ layer on a semi-insulating substrate. Anodes were formed by lifting off a P^+ ohmic metallization followed by a wet chemical etch to remove unwanted P^+ epitaxial material down to the I layer. After photomasking, a second etch to expose the N^+ layer and subsequent N^+ ohmic metal lift off formed the cathodes. Both ohmic metals

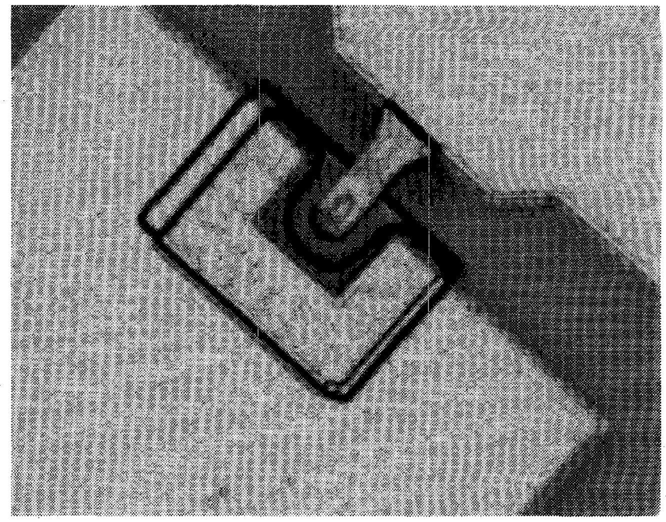

Fig. 5. A photograph of the p-i-n diode.

were alloyed in the same step. A wet chemical etch was next used to form diode mesas and the exposed semi-insulating material was probed to insure isolation. An evaporated metal lift off formed the circuit metal which was then coated with a silicon nitride dielectric using a UVCVD process. The dielectric was reactive ion etched to expose circuit areas. Air bridges connecting the anodes to the circuit were formed by masking a contact metal on supporting photoresist and then gold plating the exposed areas. All circuit areas were plated at the same time. The contact metal and photoresist layers were then stripped back and all diodes evaluated using an autoprober. With front side processing now completed, the wafers were thinned and polished in preparation for the back side metal lift off. Wafers were then re-probed and the tiles diced to separate them. A photograph of a p-i-n diode is shown in Fig. 5.

RF testing of the tiles is performed on a quasioptical test bench shown in Fig. 6. In this setup we measure the transmitted and reflected power swept from 88 to 102 GHz. To avoid overheating the tiles the bias is pulsed at 30 Hz rate with a 1/18 duty cycle. These measurements are automated and computer controlled for testing large quantities. Calibration in transmission and reflection was done, respectively, by measuring the amplitude of the power transmitted through an empty sampleholder and reflected off a flat metal mirror held in the sampleholder. The power shown in the data are referenced to these calibrations which are normalized to zero dB in the plots. We measured the tiles during 3 different states of the bias pulse; on, off, and as it ramped up. For all data, we found no difference in the tile response between power off and ramping up.

The lenses are matched with antireflection slots $\lambda/4$ deep and the return loss is below -25 dB. The beam waist at the sampleholder is about 0.6 cm. Using the approximation for edge taper of $\text{TE(dB)} = (a/.339w(z))^2$ [4] the edge taper of the beam in the fixture is about 15 dB, which is considered inadequate for quasioptical testing. In the next section on radiometric testing we show that we measured the same result for the insertion loss using a larger array of the tiles and a different technique.

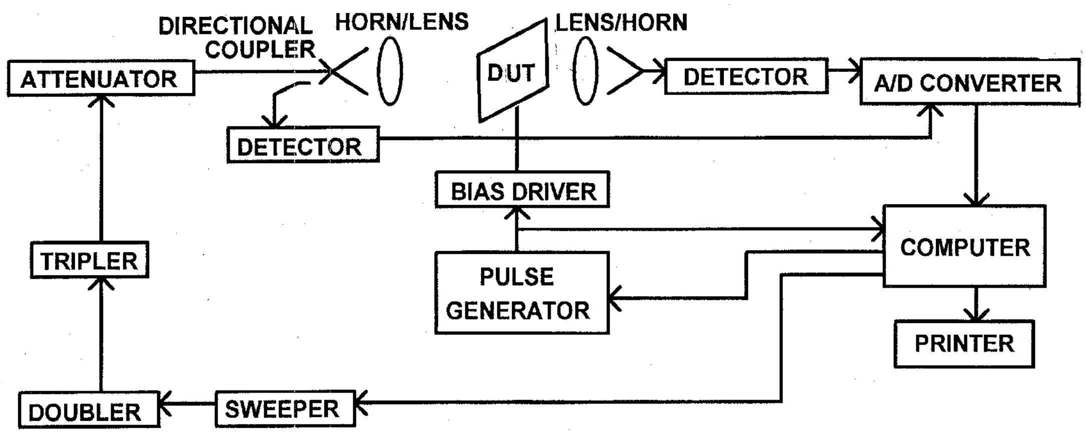

Fig. 6. Block diagram of the pulsed transmission and reflection measurement system used for testing the monolithic tiles.

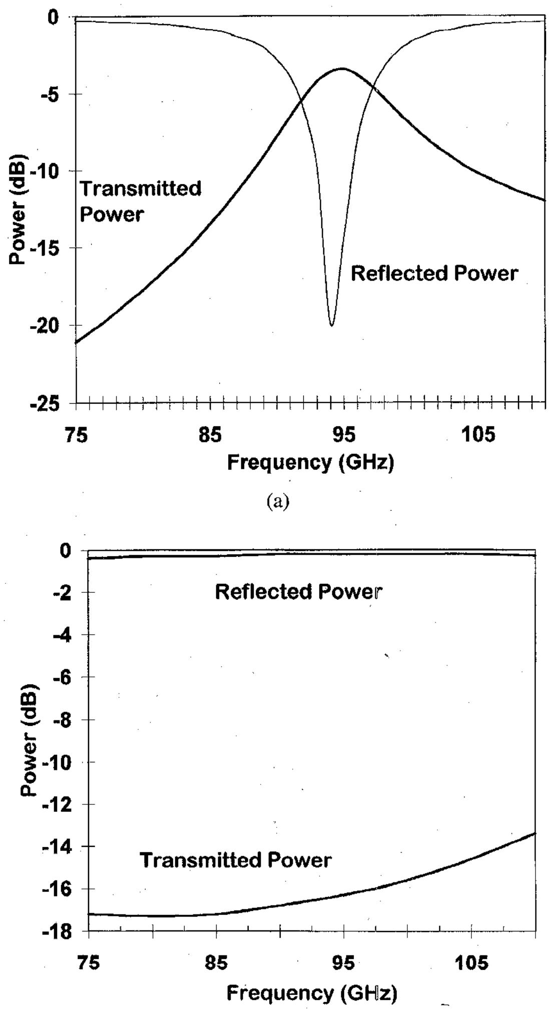

Fig. 7. Predictions of the monolithic diode array tile performance, (a) with the diodes biased and (b) with the diodes unbiased.

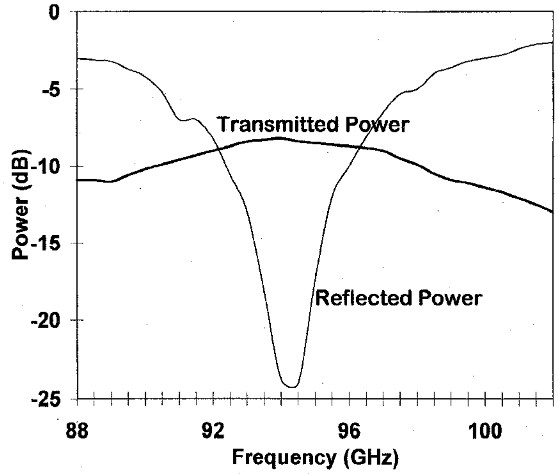

Fig. 8. Test data taken with the diode bias current pulsed, transmitted power and reflected power.

Fig. 7 shows the predicted performance for the diodes biased ON and OFF. The solid and dotted lines represent transmitted and reflected power, respectively. The change in reflected power between the ON and OFF states is 21 dB, which exceeds the minimum performance requirement of 17 dB. The −4-dB insertion loss in the transmitted power/diodes ON is predicted by the program to stem from series resistance in the diodes and circuit, and dielectric loss in the substrate. Actual data are shown in Figs. 8 and 9. Fig. 8 shows transmitted and reflected power for the biased state. The insertion loss is 10 dB, 6 dB more than the model predicted. The null in the reflected power shows that there is no loss to unwanted reflections. Fig. 9 shows that for bias OFF and when the pulse is just ramping up all but 0.1–0.2 dB is reflected.

For the case of diodes ON, the actual transmitted and reflected power levels are less than the predicted values by 6 dB and 3 dB, respectively. Two possible explanations are (1) scattering and (2) an error in the predictions. The grid period of $0.22\lambda o$ is conservative and the tiles are located at the beam waist with a 15 dB edge taper, which accounts for some but not all of the loss. We do not observe 6 dB of unaccounted-for loss or noise when the larger arrays are tested radiometrically, or when known dielectric samples are measured in the RF test bench. In any case, the power transmitted in the diodes ON case is lost to the absorber behind the tiles and does not affect the operation of the switch in its intended application.

IV. Radiometric Testing

A 6 × 5 tile array with a quarter wave plate and load was tested radiometrically. We needed to determine (1) the

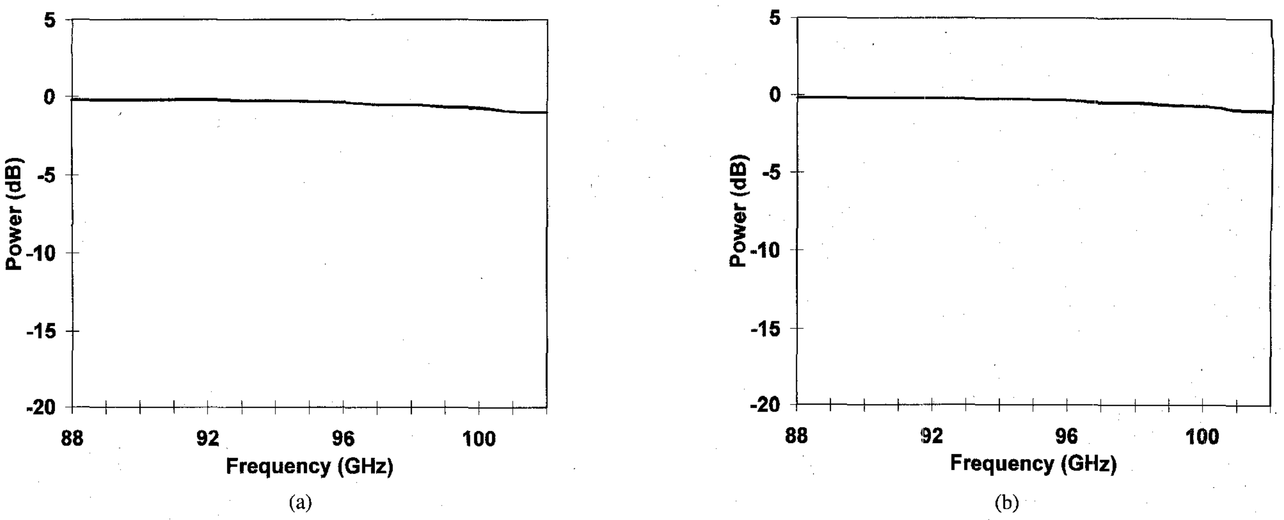

Fig. 9. Test data taken with the tiles unbiased (a) and the bias ramping up (b).

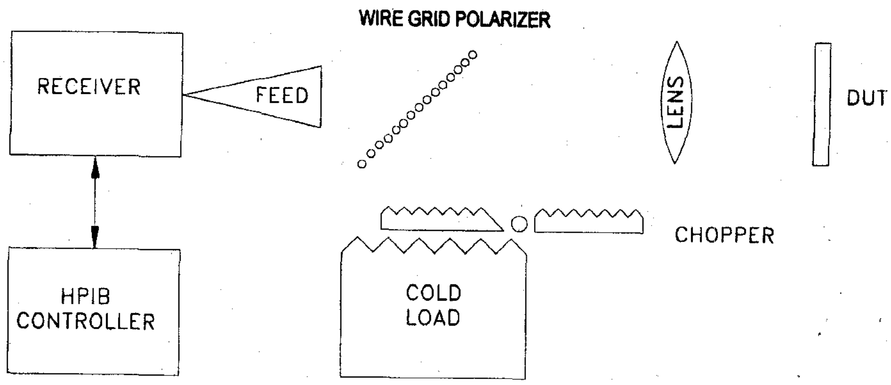

Fig. 10. Block diagram of the radiometric test bench used for measuring the 6 × 5 tile array.

radiometric noise and (2) whether the diode current adds noise to the system, as it would with IMPATT's. A test set-up for LSTR radiometric testing is shown in Fig. 10. The LSTR was one of the devices under test (DUT) in the Figure. The test setup measures the Y-factor, which is the ratio of the power detected when the system receives emissions from the warm and cold loads, respectively. The hot and cold temperatures are assumed to be 295 K (T_H) and 80 K (T_C), respectively. The noise temperature of the system is given by

$$T_S = (T_H - YT_C)/(Y - 1).$$

A warm load comprising a chopper with a microwave absorber material is placed in front of the cold load to do the Y-factor measurement when the components of the set-up are tested separately. In the baseline system calibration tests the receiver, feed, chopper wheel, and cold load are in a straight line. We measured the noise temperature of the receiver, then sequentially added the grid and the lens to determine the noise temperature of each set-up component. The calibration determined the radiometer sensitivity in Kelvins per volt using an aluminum reflector in place of the 6 × 5 LSTR array in the twist reflector. The amplitude of the switched signal was measured as a function of bias current. The results are shown in Table I.

TABLE I
BIAS CURRENT VERSUS RELATIVE NOISE TEMPERATURE, LSTR ARRAY

I. Amps	Rel. Noise Temperature K
0.0	177
0.5	174
1.0	186
1.5	193
2.0	199
2.5	203
3.0	203

A lossless LSTR would yield 215 K, the same as the aluminum reflector in the calibration. The loss of the array is given as 10 log(203/215), or −0.25 dB at 3A. This is in excellent agreement with the reflected power measurements shown in Fig. 9.

V. Application to an Imaging Camera

A photograph of the 204-tile LSTR array is shown in Fig. 11. The outer diameter is 230 mm and the 76 × 76-mm hole in the center accommodates the focal plane array. This array and others like it have been implemented into imaging cameras.

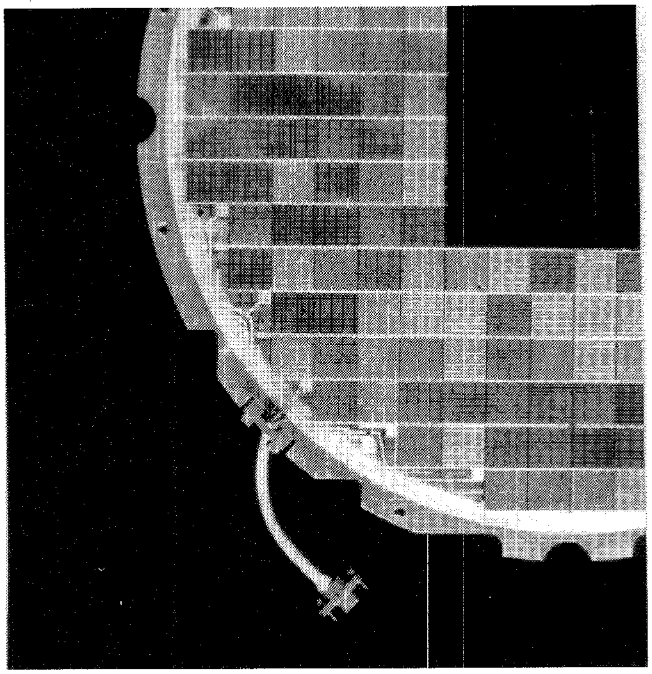

Fig. 11. Photograph of a section of the 204-tile LSTR array.

VI. Conclusion

We have described the design and test results of a 6 × 5 element monolithic array of p-i-n diodes used for load comparison at millimeter waves. The insertion loss under operating conditions is −0.25 dB and the maximum switching ratio is 24 dB, as measured by quasioptical and radiometric techniques. The switch ratio of 20 to 24 dB and the 0.25-dB insertion loss give a switch efficiency $0.93 \leq \eta \leq 0.94$. A much larger array of 204 elements, each 12.7 × 12.7 mm, has been implemented into a 94 GHz imaging camera.

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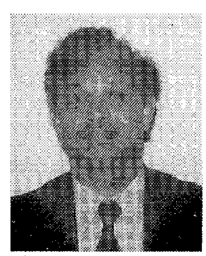
G. Richard Huguenin (M'82–SM'86) received the B.S. degree in physics from the Massachusetts Institute of Technology, Cambridge, in 1959, the Ph.D. degree in astronomy from Harvard University, Cambridge, MA, in 1964, and an honorary Doctor of Science degree from the University of Massachusetts/Amherst in 1994.

He is currently the President and Chief Executive Officer of Millimetrix, LLC. He was a member of Harvard's Society of Fellows from 1960–1963. From 1963–1968, he was on the faculty and directed Harvard's space radio astronomy effort, which was supported by the USAF, the Advanced Research Projects Agency and NASA. His group of over 20 engineers and technicians had complete responsibility for projects from conception and design through the analysis of the data collected. In 1968, after joining the faculty of the University of Massachusetts, he established the Five College Radio Astronomy Observatory program. He obtained funding for and built the largest, most sensitive millimeter radio telescope in the United States. Under his leadership, the Five College Radio Astronomy Observatory developed into a $2 million, 60 person organization. He also developed extensive facilities for millimeter and submillimeter-wave instrumentation development. The 1993 Nobel Prize in Physics was awarded to Taylor and Hulse for pulsar research done as part of this Five College program.

Dr. Huguenin has won the Bart J. Bok Prize from Harvard University, has been a Distinguished Visiting Professor at Chalmers University of Technology, and has written over 45 solely authored scientific or technical articles. Nine patents have been issued to Dr. Huguenin and several are pending. Dr. Huguenin founded Millitech Corporation in 1982 and served as President until 1996 when he formed Millimetrix, LLC, a management buyout of Millitech's Contraband Detection System Division.

Ellen L. Moore (S'76–A'81–M'83–SM'91) received the B.A. degree in physics from Mount Holyoke College, South Hadley, MA, the M.S. degree in astronomy, and the M.S.E.C.E. degree from the University of Massachusetts at Amherst.

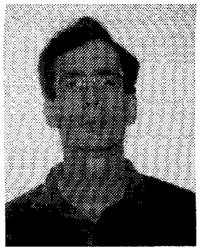
After graduating she joined the Raytheon Company Research Division where she worked on GaAs monolithic circuit design and millimeter-wave IMPATT diode development. In 1983–1996, she had been at Millitech Corporation where she was responsible for millimeter-wave antenna and quasioptics development. This work included the design and testing of the optics for imaging systems to be used for all-weather landing systems, plasma diagnostics, automobile and weather radars, remote sensing systems, and active quasioptical monolithic circuits. She has been the principal investigator on 5 SBIR programs, 3 of which have gone through Phase 2. Her affiliation with Millimetrix, Hadley, MA, commenced in June 1996.



Sudarsanam Bandla received the B.S. degrees in mathematics/physics and in electrical engineering from the University of Madras, India. He received the M.S. degree in electrical engineering from the State University of New York, Stony Brook, in 1981.

He has extensive background in MMIC design, fabrication and testing. He has worked in the past as Senior Research Engineer at General Instruments, Raytheon Research Laboratories, and later at Alpha Industries as manager of MMIC Design and Test Group. He was associated with MMIC Project sponsored by ARPA developing Ka-band MMIC's such as LNA's, Power Amps, mixers and switches using 0.25 um HEMT's. He was responsible for developing on wafer RF test capabilities of Ka-band MMIC's such as noise figure of LNA's and conversion loss of mixers. Mr. Bandla was employed at Millitech from 1991 to 1996 and was responsible for the Semiconductor Operations. He directed the effort of the group in developing p-i-n, mixer and varactor diodes and wave processing MMIC's such as Quasioptical Monolithic Diode Arrays for beam switching and beam steering applications in millimeter-wave imaging systems. Mr. Bandla has also designed, fabricated and tested W-band MMIC's such as DP3T p-i-n switch, and single balanced mixers for vehicle radar systems. He joined Millimetrix, LLC, Hadley, MA, in June 1996.

Mr. Bandla has published several papers on MMIC designs.



John J. Nicholson received the B.S. degree in marine biology from Southeastern Massachusetts University of North Dartmouth (presently University of Massachusetts) in 1976, and the Associate degrees in industrial technology/electronics and engineering science in 1984 and 1989, respectively.

From 1987 to 1996, he was with Millitech Corporation where he was reponsible for fabrication of whisker contacted millimeter-wave and submillimeter-wave multipliers before becoming a semiconductor process engineer. He has done layout design, process formulation, and processing on Schottky mixer diodes, p-i-n diode arrays, FET's and passive waveguide devices. He is presently with Millimetrix, LLC, Hadley, MA.