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13. ABSTRACT (Maximum 200 words)

JPL/Caltech is pursuing millimeter-wave imaging technology for the Army Research Office because of the potential of penetrating smoke, fog, and darkness. During this reporting period, we made progress on varactor diode processing approaches appropriate for millimeter and submillimeter wave electronics, on fabricating and measuring diode grids for frequency multiplication and beam control, and especially in the area of grid amplifiers, which promise to deliver higher power at greatly reduced cost for millimeter-wave generation.

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JPL Final Report on Millimeter Wave Imaging Technology

Quasi-optical grids offer the possibility of large-scale solid-state power combining without the limitations of transmission-line approaches, and, at higher frequencies, may permit large-scale integration of amplifiers and control circuitry for imaging applications. On this contract, we have been developing grid amplifiers (JPL, Caltech), beam control arrays (UCLA), and multiplier arrays (UCLA). Development of relevant devices and fabrication approaches was done at JPL and UCLA.

Grid Amplifiers

Figure 1 shows a generalized grid amplifier [1]. This configuration allows the polarizers to tune the input and output independently. The first 10x10 grid amplifier was made with custom differential-pair heterojunction bipolar transistor (HBT) chips. This grid had a gain of 10 dB at 10 GHz with a 3 dB bandwidth of 1 GHz and a noise figure of 6.5 dB at 10 GHz. In order to improve the noise performance of grid amplifiers the use of high electron mobility transistors (HEMT's) was proposed.

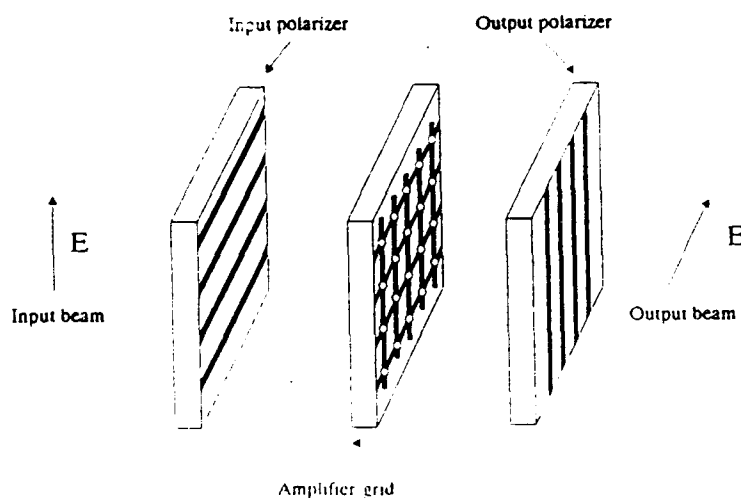


Figure 1. Perspective view of a grid amplifier. The input beam is horizontally polarized and the output beam is vertically polarized.

In order to make the design of the grid convenient, differential pairs of HEMT transistors embedded in biasing and stabilizing circuitry were designed and fabricated at JPL. The devices

delivered to Caltech so far have relatively low transconductance (approximately 300 mS/mm), and thus gain, for the technology used, but better circuits should be available soon.

Two different designs were chosen and used to fabricate two 4x4 HEMT grid amplifiers. In the first design, the metal pattern was chosen to have exactly the same dimensions as the HBT grid amplifier [1]. The unit cell design is shown in Figure 2. The unit cell size is 8 mm, the radiating leads are 0.8 mm wide, and the bias lines are 0.1 mm. In this case, the measured grid did not have any gain in the frequency range of interest (8 to 12 GHz). In the second approach, an approximate transmission line model (using *Puff*, a microwave CAD program, developed at Caltech) was used to predict the gain of the amplifier. Using the expected HEMT device performance provided by JPL and this model, the unit cell dimensions and polarizer spacings were changed to achieve the best possible gain in a wide bandwidth. The best design predicted a maximum gain of about 9 dB at 10 GHz, and a 3-dB bandwidth of about 6 GHz. The unit cell configuration is the same as before (Figure 2), except that in this case the unit cell size is 7 mm, the radiating leads are 0.3 mm and the bias lines are 150 μ m wide. In the case of the HBT grid amplifier, it was necessary to open a 0.1 mm gap in the input antenna lead (base lead). The unit cell design for the HEMT amplifier has no gaps at the input leads, so that we can first do the measurements without gaps and then later open up gaps at the input leads if necessary. With the unit cell design of Figure 2 the measured amplifier gain is 8 dB at 7 GHz, but the bandwidth is very narrow. One possible reason for disagreement between the theory and measurement is that our model assumes an infinitely large grid, whereas the measurement was done on a 4x4 grid in which only four of the sixteen unit cells is an interior cell. Also, the unit cell of the amplifier grid (Figure 2) has a complicated metal pattern, but the transmission line model ignores the meandering lines and the coupling between them.

Even though this grid does not have a high gain, measuring the noise figure of this grid could give us valuable information to compare with the HBT grid amplifier performance. We also expect to get some better HEMT's from the JPL group in the near future which would enable us to build a HEMT grid amplifier with a better performance.

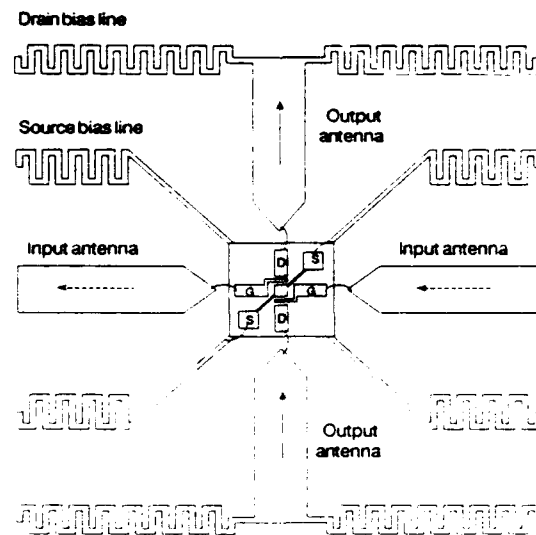


Figure 2. Sketch of the grid amplifier unit cell.

Some longer-term goals are the fabrication of the second version of the HEMT chips. This chip will integrate some of the radiating elements, which would work better for a smaller unit cell size. Once we successfully demonstrate gain at X-band and Ku-band, we will be able to design a monolithic grid amplifier for Ka-band. There are also some efforts going on in the Caltech MMIC group and in the Communications Division at JPL to come up with a more complete theoretical model for the grid amplifier, which would enable us to have more reliable designs for the future amplifier grids.

Varactor Diodes

Much of the effort in this contract focused on the development of III-V varactor diodes for the efficient multiplication of millimeter and submillimeter wave signals.

At JPL, GaAs/AlGaAs diodes were developed with the goal of producing devices with good high frequency response and high efficiencies. It was determined that the original B⁺N (Barrier-Intrinsic-N⁺) diode concept was inadequate in that the lack of charge in the intrinsic region severely limited the devices speed and power handling capability. Replacing the intrinsic region with a moderately doped N-type region results in a device that has much better speed (over 500 GHz is easily possible) with good breakdown voltages (10V is typical). Also addressed was the difficulty in processing devices with the extremely thin barriers that must be used as frequencies approach one terahertz. The current processing approach is to do the mesa etching from the back of the wafer after laminating the front side down and thinning the bulk of the material from the backside. This approach avoids the problems inherent with alternate schemes such as planarization (difficulties in re-contacting the front-side material without damage) and selective implants (isolation implants have questionable reliability, and masking material can be difficult to remove). We have succeeded in producing back-to-back devices with this process that have good $C_{\max}/C_{\min}$ ratios of up to three and breakdown voltages of approximately 10V.

In related work relevant to the development of terahertz power sources, JPL has collaborated with Mark Rodwell's group at the University of California, Santa Barbara, in demonstrating Schottky-Collector Resonant Tunneling Diodes (RTDs) (2-4). By replacing the top ohmic contact with a Schottky contact, much of the parasitic resistance of an RTD can be eliminated. By greatly reducing the size of this contact, it appears that the device has less than 10% of the resistance of a comparable ohmic contacted device. This reduction in resistance results in the possibility of higher power output at higher speeds with planar geometry devices. We expect such GaAs-based RTDs to operate at speeds of up to 700-800 GHz ($f_{\text{cut-off}} \sim 1$ THz), while other material systems could work at over two THz. Devices have been fabricated with contacts as small as 0.1×0.3 microns using JPL's T-gate technology. Low frequency measurements have been promising, with no loss observable at up to 50 GHz, but more time will be required to fabricate oscillators using these devices.

U.C.L.A. has focused on the development of large arrays of diodes for both multiplication and beam control.

Electronically controlled beam control arrays have been fabricated with device yields in excess of 99%. Phase shifts as high as 110° have been measured in reflection mode, with a useable phase shift range of about 70° with a measured insertion loss of 3.5 dB. With this array, beam steering and beam focusing/defocusing functions have now been demonstrated at 120 GHz. The arrays have been used successfully to amplitude modulate a transmitted beam at 165 GHz. The response is observed to be flat out to 50 MHz, with a 3 dB point of about 150 MHz. Simulations show that a modulation speed as high as 5 GHz should be achievable through the use of an optimized coplanar waveguide biasing arrangement. This type of fast millimeter-wave switch should have numerous applications in such areas as Dicke-switch radiometry and relectometry.

Recent improvements both in fabrication and testing have produced record power levels and efficiencies for our diode frequency multiplier arrays. A BNN (Barrier-n-n-) doubler array (720 devices) has produced 2.5 W at 66 GHz with 7.5% efficiency. an MQBV (Multiple Quantum Barrier Varactor) tripler array (3200 devices) has produced 1.25 W at 99 GHz with 0.7% efficiency.

Work on varactor process approaches (JPL) promises to improve very high frequency circuit performance by making it possible to integrate process-sensitive electronic devices such as extremely thin varactor diodes or HEMTs on low-dielectric substrates, substantially reducing passive circuit losses. We have fabricated BNN diodes onto quartz 0.003" thick for waveguide multipliers using this technique. Because little or no processing is done prior to Schottky contact deposition, this process is ideal for devices that need contacts to be placed within a few angstroms of the original wafer surface. For our most recent process runs, we are fabricating devices with Schottky fingers as small as one micron. We are also fabricating devices for measurement in coplanar waveguide.

Efficiencies for these quasi-optical multiplier arrays are strongly limited by diffraction losses due to the finite size of the arrays fabricated to date. These diffraction losses prevent the input and output Fabry-Perot tuning plates to optimally match to the low impedance of our arrays. This problem is especially acute for the RTD arrays, whose small size (1 cm^2) and extremely low resistance may account for more than an order of magnitude reduction in tripling efficiency. The fabrication of larger arrays, the reduction of ohmic contact losses, and improvement in the tuning system should greatly improve the efficiencies of the arrays.

With our improved diode processing (reduced R_s and increased $C_{\text{max}}/C_{\text{min}}$ ratio), we expect to achieve useable phase shifts of 180° and a significantly lower insertion loss. Hence, with two arrays arranged in series, a total phase range of 360° should be realized, enabling the arrays to electronically beam steer any angle desired.

Work is also underway to fabricate beam control arrays in which millimeter-wave beams are controlled optically through the illumination of Schottky photodiodes. Back-to-back photodiodes have been fabricated which demonstrate capacitance variations from 1.06 fF to 1.5 fF with the application of 1.85 mW of light per device. We expect to obtain results at levels up to 8.5 mW per device shortly.

Summary

Much of the technology necessary to do millimeter wave or submillimeter wave imaging was addressed. Grid amplifiers, currently demonstrated at microwave frequencies, promise to greatly reduce the cost of moderate power transmitters and increase the dynamic range of receivers in the millimeter-wave region. Grids of diodes were demonstrated for multiplication to higher frequencies and for beam control.

JPL Final Report: September 1993

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- (2) L.B. Sjogren, H-X.L. Liu, X-H. Qin, W. Wu, E. Chung, C.W. Domier, and N.C. Luhmann, Jr., "A Monolithic Millimeter-wave Diode Array Beam Transmittance Controller," submitted to *IEEE Transactions of Microwave Theory and Techniques*.
- (3) H-X.L. Liu, L.B. Sjogren, C.W. Domier, N.C. Luhmann, Jr., D.L. Sivco, and A.Y. Cho, "Monolithic Quasi-optical Frequency Tripler Array with 5 W Output Power at 99 GHz" submitted to *Electron Devices Letters*.
- (4) X-H. Qin, C. Domier, N.C. Luhmann, Jr., H-X.L. Liu, E. Chung, L. Sjogren, and W. Wu, "Millimeter-wave Monolithic BNN Diode Grid Frequency Doubler," to be published in *Applied Physics Letters*.
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- (10) D. Rutledge, "Failures in Power-Combining Grids," submitted to *IEEE Transactions on Microwave Theory and Techniques, Special Issue on Quasi-Optical Techniques*, (Sept. 1992).
- (11) A. Moussessian, and D.B. Rutledge, "A Millimeter-wave Slot-V Antenna," submitted to *The 17th International Conference on Infrared and Millimeter Waves*, Dec. 14-18, 1992, Pasadena, CA.
- (12) M. Kim, E.A. Sovero, R.M. Weikle, J.B. Hacker, M.P. DeLisio, S-J. Li, and D.B. Rutledge, "A 35 GHz HBT Monolithic Grid Oscillator," submitted as a short paper for the *IEEE-MTT Special Issue on Quasi-Optical Techniques*, October 1993.
- (13) M. Kim, E.A. Sovero, J.B. Hacker, M.P. DeLisio, J-C. Chiao, S-J. Li, D.R. Gagnon, J.J. Rosenberg, and D.B. Rutledge, "A 100-Element HBT Grid Amplifier," submitted to *IEEE International Microwave Symposium*, Atlanta, GA., June 1993.

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"Oscillator and Amplifier Grids," David B. Rutledge, Jonathan B. Hacker, Moonil Kim, Robert M. Weikle II, R. Peter Smith, and Emilio Sovero, IEEE MTT International Symposium, Albuquerque, NM., June 1992.

"Probe Modelling for Millimeter-Wave Integrated-Circuit Horn Antennas," Yong Guo, Jung-Chih Chiao, Kent A. Potter, and David B. Rutledge, IEEE AP-S International Symposium, Chicago, ILL., July 18-25, 1992.

"A Millimeter-Wave Slot-V Antenna," Alina Moussessian and David B. Rutledge, IEEE AP S International Symposium, Chicago, ILL., July 18-25, 1992.

"Active grids for quasi-optical power combining," Moonil Kim, Jon Hacker, David Rutledge, Emilio Sovero, James Rosenberg, 2nd International Workshop of the German IEEE MTT/AP joint chapter on Integrated Nonlinear Microwave and Millimeter Wave Integrated Circuits, Duisburg, Germany, October 1992.

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"High Power Millimeter-wave Quasi-optical Frequency Tripler Arrays Using Resonant Tunneling Devices," E.I. Chung, H-X. Liu, C.W. Domier, and N.C. Luhmann, Jr., presented at the *17th International Conference on Infrared and Millimeter Waves* (Dec. 1992).

"New Developments for Monolithic Millimeter-wave Diode Array Beam Controllers," L.B. Sjogren, F. Wang, T. Liu, X-H. Qin, E. Chung, C.W. Domier, and N.C. Luhmann, Jr., presented at the *17th International Conference on Infrared and Millimeter Waves* (Dec. 1992).

"Development of Advanced Technology and Techniques for Reflectometry," C.W. Domier, E. Chung, H-X.L. Liu, A. Lapidus, N.C. Luhmann, Jr., W.A. Peebles, X-H. Qin, T.L. Rhodes, and L. Sjogren, presented at the *1992 APS Division of Plasma Physics Meeting* (Nov. 1992).

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"A Millimeter-wave-slot-V antenna," Alina Moussessian and David Rutledge, 17th International Conference on Infrared and Millimeter Waves, Pasadena, CA, December 1992.

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"Microswitch beam-steering grid," Jung-Chih Chiao and David Rutledge, 17th International Conference on Infrared and Millimeter Waves, Pasadena, CA., December 1992.

"A 100-element HBT grid amplifier," Moonil Kim, Emilio Sovero, Jonathan Hacker, Michael DeLisio, Jung-Chih Chiao, Shi-Jie Li, David Gagnon, James Rosenberg, and David Rutledge, submitted to the IEEE International Microwave Symposium, Atlanta, GA., June 1993.

"Noise analysis by subnetwork growth," Scott Wedge and David Rutledge, submitted to the IEEE International Microwave Symposium, Atlanta, GA, June 1993.

"A 100-element HBT grid amplifier," Moonil Kim, Emilio Sovero, Jonathan Hacker, Michael DeLisio, Jung-Chih Chiao, Shi-Jie Li, David Gagnon, James Rosenberg, and David Rutledge, submitted to the Asia-Pacific Microwave Conference, Hsinchu, Taiwan, October 1993.

"A 100-element HBT grid amplifier," Moonil Kim, Emilio Sovero, Jonathan Hacker, Michael DeLisio, Jung-Chih Chiao, Shi-Jie Li, David Gagnon, James Rosenberg, and David Rutledge, submitted to PIERS, Pasadena, CA, July 1993.

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Jonathan Hacker, Ph. D., Caltech. Grid Mixers and Power Grid Oscillators.

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