

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 10/6/99	3. REPORT TYPE AND DATES COVERED 5/10/95 - 5/09/99	
4. TITLE AND SUBTITLE Active Quasi-Optical Devices			5. FUNDING NUMBERS DAH04-95-1-0251	
6. AUTHOR(S) David Rutledge			8. PERFORMING ORGANIZATION REPORT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) California Institute of Technology Pasadena, CA 91125			10. SPONSORING / MONITORING AGENCY REPORT NUMBER ARO 33955.10-EL	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.	
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.			12 b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) <h2 style="text-align: center;">19991103 015</h2> <p>In active quasi-optics, we demonstrated the first successful monolithic HBT and pHEMT millimeter-wave grid amplifiers. In addition, we demonstrated a diode doubler grid with a record output of 24 mW at 1 THz.</p> <p>We also developed a series of Class-E amplifiers for communications and radar that are based on power MOSFET's with output powers in the frequency range from 7 to 14 MHz of 300 to 500 W, and efficiencies of 90%. We recently extended this work to demonstrate VHF and UHF Class-E amplifiers.</p>				
14. SUBJECT TERMS Millimeter Waves, Class-E Amplifiers, Quasi-Optics, Power Amplifiers			15. NUMBER IF PAGES 7	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

ACTIVE QUASI-OPTICAL DEVICES

FINAL PROGRESS

DAVID RUTLEDGE

October 6, 1999

U.S. Army Research Office
P.O. Box 12211
Research Triangle park, NC 27709-2211

Proposal 33955-EL

California Institute of Technology
Pasadena, California

APPROVED FOR PUBLIC RELEASE;

DISTRIBUTION UNLIMITED

THE VIEWS, OPINIONS, AND/OR FINDINGS CONTAINED IN THIS REPORT ARE
THOSE OF THE AUTHOR(S) AND SHOULD NOT BE CONSTRUED AS AN
OFFICIAL DEPARTMENT OF THE ARMY POSITION, POLICY, OR DECISION,
UNLESS SO DESIGNATED BY OTHER DOCUMENTATION.

Scientific Problem Studied

In this contract, we developed active quasi-optical devices that combine the power of many transistors or diodes to achieve a large output. Millimeter wavelengths are attractive for communications systems because extremely high-data rates can be achieved with modest antennas. They are suitable for terminal guidance radars because millimeter waves penetrate fog and smoke. The problem is that at millimeter wavelengths, the output power provided by solid-state devices is much less than required by communications and radar systems. Quasi-optics allows large-scale combining at the level of 100 or 1,000 devices without the losses that are associated with transmission-line combiners. In this contract, we demonstrated the first monolithic quasi-optical amplifiers, and well as record-setting outputs from a diode doubler grid at 1 THz.

A related goal of this project is to develop Class-E RF amplifiers for HF, VHF and UHF communications and radar transmitters that are simple and extremely efficient. The high efficiency often allows these amplifiers to be run without cooling fans. This project takes advantage of the continuing improvements in RF power MOSFETS.

Results

MONOLITHIC GRID AMPLIFIERS

Jeff Liu demonstrated the first monolithic grid amplifier with gain. He measured 5 dB of gain at 40 GHz. The grid produced an output power of 600 mW. Jeff also developed an approach for analyzing the stability of grids. Early grids showed a tendency to oscillate at about 80% of the frequency where the amplifier was designed to have maximum gain. Jeff's analysis predicted the oscillation frequency. Jeff's theory predicted that a series capacitor in the gate lead could either shift the oscillation frequency, or eliminate the oscillations. His experiments agreed with the theory. This theory is particularly important for monolithic grids, which need to work as designed the first time because of the long time delays in fabrication, and the extremely limited number of process runs. This work is now being extended under the Quasi-Optic Power Combining MURI to W-band with Mark Rodwell's new high-speed HBT's.

Michael DeLisio demonstrated the first successful pHEMT grid amplifier, which was fabricated by Lockheed-Martin laboratories. This amplifier gave a gain of 6.5 dB at 44 GHz. The amplifier could be spot-tuned at any frequency between 44 GHz and 60 GHz, giving a gain of 2.5 dB at 60 GHz. This work has recently been extended under the Quasi-Optic Power Combining MURI to a grid with an output power of 5 W at 35 GHz.

Michael DeLisio also demonstrated a 100-element 10-GHz hybrid pHEMT grid at 10 GHz. This work was published in the *Transactions on Microwave Theory and Techniques*. The work was significant in several respects. Previous work in quasi-optical amplifiers had much more limited comparison of theory and experiment. In this paper, the gain was measured for a wide range of frequencies, angles, and polarizer

positions, and there was excellent agreement between theory and experiment. This grid showed a gain of 12 dB at 9 GHz, with a 3-dB bandwidth of 3.7 W and a bandwidth of 15%. The measured noise figure is 3 dB.

THZ DOUBLER GRIDS

Alina Moussessian tested a doubler with 144 Schottky diodes with an output of 24 mW at 1 THz. This greatly exceeds the previous record for a doubler at this frequency, which was 330 μ W. These diodes were fabricated by Tom Crowe's group at the University of Virginia, and tested in Jim Allen's group at the University of California at Santa Barbara. The doubling efficiency is quite low, only 0.17%. We plan to investigate whether this can be substantially improved with a dielectric tuning slab.

CLASS-E AMPLIFIERS

Quasi-optical work in our group is now supported by the ARO Quasi-Optic Power Combining MURI. The final funds in the contract were spent developing high-efficiency power amplifiers. Efficiency is a critical issue in quasi-optical amplifiers, and we believe that it is important to understand the fundamental issues in amplifier efficiency. This is easier to study at lower frequencies, where the voltage waveforms are easily measured.

John Davis worked with a team of undergraduates, Eileen Lau, Kai-Wai Chiu, and Jeff Qin, to develop high-power RF amplifiers. These are Class-E amplifiers that are extremely efficient, with efficiencies in the 90% range at frequencies from 7 to 14 MHz. These amplifiers have output powers between 300 and 500 W, and are based on inexpensive MOSFET's that cost about \$10. This work is discussed in the paper that will be published in *QST*. These amplifiers are expected to find application in communications, medical imaging, and in semiconductor processing. We have also done experiments on a 54-W VHF and 1 15-W UHF Class-E MOSFET power amplifiers that show drain efficiencies in the range of 80%. We believe that these amplifiers will have important applications for military communications.

For the 54-W VHF amplifier, the drive power is 5 W. The amplifier features a novel output variable inductor which is a straight piece of the kind of metal tape that is used for coils in very large magnets. It can be tuned by sliding a piece of metal under the strip. This reduces the area underneath the strip, and it makes the inductance smaller. This raise the operating frequency of the amplifier.

For the 15-W UHF amplifier, the drive power is 1.4 W. One problem that we noted with this amplifier is that it was quite difficult to reduce the input VSWR to reasonable levels. Often it was as high as 5. It seemed that the conditions that lead to high efficiency also led to less efficiency. We do not know whether this reflects some fundamental issue in amplification at this frequency, or whether we just need to improve the design, or perhaps add feedback.

TECHNOLOGY TRANSFER

The monolithic grid amplifier demonstration was the leading edge of a wave of quasi-optical work being sponsored by DARPA Phase 3, monitored by Elliot Brown, and two MURI's on quasi-optical power combining, monitored by James Harvey. Many universities and all the leading manufacturers of millimeter-wave integrated circuits are involved in this program. The quasi-optical tunnel-diode oscillator work has been extended greatly with resonant tunneling diodes (RTD's), in Mark Rodwell's group at the University of California at Santa Barbara, in collaboration with Peter Smith at the Jet Propulsion Laboratory, with an output power of $28 \mu\text{W}$ at 350 GHz. Chiao's beam-steering idea has evolved into a collaborative effort with the Rockwell Science Center, who does the fabrication, and has since received funding from the Naval Surface Warfare Center, and is monitored by James Harvey of ARO.

INDUSTRY AND GOVERNMENT INTERACTIONS

Michael DeLisio's monolithic millimeter-wave HEMT grid was fabricated by Lockheed-Martin Laboratories.

Polly Preventza's transistors for her 43-GHz oscillator grids were fabricated by Mehran Matloubian at Hughes Research Laboratories.

Jeff Liu's monolithic HBT grid was fabricated by Emilio Sovero at the Rockwell Science Center.

David Rutledge attended the NATO Advanced Study Institute in Submillimeter Wave Technology at the Chateau de Bonas, France, along with Charles Church of the Army Research Office. He gave three lectures there that covered active quasi-optics, and Professor Rebeiz' research in millimeter-wave receivers and antennas at the University of Michigan.

As part of John Davis' Class-E amplifier work, we visited the ETO corporation in Colorado Springs, and gave a presentation of our work. ETO is a manufacturer of high-power RF amplifiers.

PEOPLE

Jung-Chih Chiao worked on a MEMS switch-based millimeter-wave beam steering system. Dr. Chiao received his Ph.D., and went to Bellcore, and then to the University of Hawaii.

John Davis, is the AASERT fellow. John has been developing high-power Class-E amplifiers for the HF frequency range. He will defend his Ph.D. thesis next month, and will go to work for JPL.

Michael DeLisio demonstrated a monolithic pHEMT grid amplifier with gain between 40 GHz and 60 GHz. Michael defended his thesis, and is now an assistant professor at the University of Hawaii.

Jeff Liu completed his work on the first successful monolithic grid amplifier, defended his thesis, and is now working in a wireless group at Rockwell Science Center.

Alina Moussessian completed her Ph.D. on self-complementary grid amplifiers and is now working at the Jet Propulsion Laboratory on planetary radar sounders.

Polly Preventza has been developing hybrid quasi-optical circuits for the 30 to 100-GHz range, complete her Ph.D., and is working at Lehmann Brothers.

Herbert Zirath is a Professor of Electrical Engineering at Chalmers University in Sweden. He was a visitor in our research group during the Spring and Summer of 1998. Dr. Zirath is an expert in the modelling of transistors.

INVENTIONS

None to report.

PUBLICATIONS

1. "A Millimeter-Wave Monolithic Grid Amplifier," Cheh-Ming Liu, Emilio Sovero, and David Rutledge, *International Journal of Infrared and Millimeter Waves*, 16, pp. 1901-1905, November, 1995.
2. "Metal Mesh Couplers Using Evanescent Waves at Millimeter and Submillimeter Wavelengths," Jongsuck Bae, Jung-Chih Chiao, Koji Mizuno, and David Rutledge, *International Microwave Symposium*, Orlando, FL, May, 1995.
3. "A 100-Element MODFET Grid Amplifier," Michael P. DeLisio, Cheh-Ming Liu, Alina Moussessian, David Rutledge, and James J. Rosenberg, *Antennas and Propagation Symposium*, Newport Beach CA, June 1995.
4. "Gain and Stability Models for HBT Grid Amplifiers," Cheh-Ming Liu, Emilio Sovero, Michael P. DeLisio, Alina Moussessian, James Rosenberg, and David Rutledge, *Antennas and Propagation Symposium*, Newport Beach CA, June 1995.
5. "A 16-Element Tunnel Diode Grid Oscillator," Michael P. DeLisio, John F. Davis, Shi-Jie Li, and David Rutledge, *Antennas and Propagation Symposium*, Newport Beach CA, June 1995.
6. "Active Grids for Quasi-Optical Power Combining," Jung-Chih Chiao, Michael DeLisio, Jeff Liu, and David Rutledge, *International Symposium on Signals, Systems and Electronics*, San Francisco, CA, October 25-27, 1995.
7. "Micromechanical Planar Tuning Elements," Victor Lubecke, William R. McGrath, and David Rutledge, *TELSIK'95 2nd Conference on Telecommunications in Modern Satellite and Cable Services*, Nia, Yugoslavia, October 1995.
8. "Micromechanical Sliding Planar Backshorts," Victor M. Lubecke, William R. McGrath, and David Rutledge, *1995 International Semiconductor Device Research Symposium*, Charlottesville, VA, December 1995.

9. "Progress in Grid Amplifiers," David Rutledge, Michael DeLisio, and Cheh-Ming Liu, 20th International Conference on Infrared and Millimeter Waves, Orlando, FL, December 1995.
10. *Quasi-Optical Components for Millimeter and Submillimeter Waves*, Ph.D. Thesis by Jung-Chih Chiao.
11. Chapter 9, "Grid Amplifiers," by Michael DeLisio and Cheh-Ming Liu, in *Active and Quasi-Optical Arrays*, Bob York and Zoya Popović.
12. Chapter 11, "Frequency Conversion Grids," Jung-Chih Chiao, in *Active and Quasi-Optical Arrays*, Bob York and Zoya Popović.
13. *Monolithic Grid Amplifiers*, Cheh-Ming Jeff Liu, Ph.D. Thesis.
14. *Hybrid and Monolithic Active Quasi-Optical Grids*, Michael DeLisio, Ph.D. Thesis.
15. "Micromechanical Tuning Elements for Submillimeter Wave Integrated Circuits," Victor M. Lubecke, William R. McGrath, and David B. Rutledge, URSI National Radio Science Meeting, Boulder, CO, January, 1996.
16. "Monolithic 40-GHz 670-mW HBT Grid Amplifier," Cheh-Ming Liu, Emilio Sovero, Wu Jing Ho, Michael DeLisio, and David Rutledge, The International Microwave Symposium, San Francisco, CA, June, 1996.
17. "A 44–60 GHz Monolithic pHEMT Grid Amplifier," Michael DeLisio, Scott Duncan, Sander Weinreb, C. M. Liu, and David Rutledge, The International Microwave Symposium, San Francisco, CA, June, 1996.
18. "Micro-Machining in Submillimeter-Wave Circuits," David Rutledge, The International Microwave Symposium, San Francisco, CA, June, 1996.
19. "Active Grids for Quasi-Optical Power Combining," David Rutledge, NATO Advanced Study Institute, Chateau de Bonas, France, July, 1996.
20. "Active Grids for Quasi-Optical Power Combining," David Rutledge, U.R.S.I., Lille, France, September, 1996.
21. "Active Grids for Quasi-Optical Power Combining," David Rutledge, Conference on the Future of MMIC's, Brooklyn, NY, September, 1996.
22. "Metal Mesh Couplers Using Evanescent Waves at Millimeter and Submillimeter Wavelengths," Jongsuck Bae, Jung-Chih Chiao, David Rutledge, and Koji Mizuno, *Trans. of the Institute of Electronics, Information and Communications Engineers, C-I*, pp. 370–377, 1996.
23. "Modelling and Performance of a 100-Element pHEMT Grid Amplifier," Michael DeLisio, Scott Duncan, Der-Wei Tu, Cheh-Ming Liu, Alina Moussessian, James Rosenberg, and David Rutledge, *IEEE Transactions on Microwave Theory and Techniques, MTT-44*, pp. 2136–2144, 1996.

24. "High-Efficiency, Class-E Power Amplifiers," Eileen Lau, Kai-Wai Chiu, Jeff Qin, John Davis, Kent Potter, and David Rutledge, *QST*, part 1, May, 1997, and part 2, June, 1997.
25. "High-Efficiency, Class-E Power Amplifiers," Eileen Lau, Kai-Wai Chiu, Jeff Qin, John Davis, Kent Potter, and David Rutledge, *CQ*, pp. 131-137. April 1998. This is a translation into Japanese of the previous article.
26. "Grid Amplifiers," D.B. Rutledge, *New Directions in Terahertz Technology*, J.M. Chamberlain, and R.E. Miles, eds., pp. 221-226, 1997.
27. "Properties of Periodic Arrays of Symmetric Complementary Structures and their Application to Grid Amplifiers," Alina Moussessian, James J. Rosenberg, and David B. Rutledge, *IEEE Transactions on Microwave Theory and Techniques*, *MTT-46*, pp. 1956-1963, 1998.
28. "A Terahertz Grid Frequency Doubler," Alina Moussessian, Michael Wanke, Yongjun Li, Jung-Chih Chiao, Frank A. Hegmann, James Allen, Thomas Crowe, and David Rutledge, International Microwave Symposium, Denver, CO, 1997.
29. "A 43-GHz AlInAs/GaInAs/InP HEMT Grid Oscillator," Polly Preventza, Mehran Matloubian, and David Rutledge, International Microwave Symposium, Denver, CO, 1997.
30. "Stability design for Grid Amplifiers," David Rutledge, 1997 Topical Symposium on Millimeter Waves, Hayama, Japan.
31. "Industrial Class-E Power Amplifiers with Low-Cost Power MOSFET's and Sine-Wave Drive," John Davis and David Rutledge, RF Design Conference, San Francisco, CA October, 1997.
32. "A Low-Cost Class-E Power Amplifier with Sine-Wave Drive," John Davis and David Rutledge, International Microwave Symposium, Baltimore, Md, June 1998.
33. "Active Quasi-Optics," David Rutledge, Asia-Pacific Microwave Conference, Yokohama, Japan, December 1998.
34. "Submillimeter-Wave Sideband Generation using a Planar Diode Array," David Kurtz, Jeffrey Hesler, Jon Hacker, Thomas Crowe, David Rutledge, and Robert Weikle, International Microwave Symposium, Baltimore, Md, June 1998.
35. "Self-Complementary Structures and their Application in Grid Amplifiers," Alina Moussessian, James Rosenberg, and David Rutledge, Antenna and Propagation Symposium, Atlanta, GA, June 1998.
36. "Active Antennas," Alina Moussessian, Ph.D. thesis, Caltech, 1997.
37. "An LDMOS VHF Class E Power Amplifier using a High Q Novel Variable Inductor," Herbert Zirath and David Rutledge, International Microwave Symposium, Anaheim, California, 1999.

38. "An LDMOS VHF Class E Power Amplifier using a High Q Novel Variable Inductor," Herbert Zirath and David Rutledge, to be published in the *IEEE Transactions on Microwave Theory and Techniques*, December, 1999.

39. *UHF and X-Band Class-E Amplifiers*, Caltech Ph.D. thesis by Shi-jie Li, Pasadena, CA, June 1998.