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ABSTRACT (Maximum 200 words)

Quasi-optical power combining allows the combining of a large number of devices in free space without the usual transmission-line combiner losses. It is a particularly attractive idea at millimeter-wavelengths, where the devices can be made as a monolithic integrated circuit. During this contract we demonstrated the following significant "firsts"—

1. Monolithic quasi-optical millimeter-wave oscillator—35 GHz
2. Quasi-optical oscillator with significant power—10 W
3. Large-scale quasi-optical amplifier—200 devices
4. Quasi-optical amplifier with significant power—3.8 W
5. Monolithic millimeter-wave quasi-optical amplifiers with gain—5 dB at 40 GHz and 50 GHz. The saturated output power of the 40-GHz amplifier is 400 mW.

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Final Report Grid Amplifiers

David Rutledge

California Institute of Technology

March 1, 1992 through April 30, 1995

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GRID AMPLIFIERS

Solid-state devices have quite limited power outputs at microwave and millimeter-wave frequencies. To provide sufficient power for radar and communications transmitters, the outputs of many transistors need to be combined. Quasi-optical power combiners that combine the output power in free space are attractive for high-power circuits because they avoid the losses associated with transmission-line power combiners. The quasi-optical approach is suitable for millimeter waves because the spacing is small enough that the device can be made as a monolithic integrated circuit. In previous work in our group and other groups, many different quasi-optical devices, including oscillators, amplifiers, phase shifters, mixers, and multipliers have been demonstrated. Our research goals in this contract were using a large number of devices in an amplifier (of the order of one hundred), achieving substantial power outputs (1 Watt or larger), demonstrating monolithic quasi-optical devices, and pushing the output to frequencies above 300 GHz. During this contract, our group made progress in all these areas, establishing the following "firsts"—

1. Monolithic quasi-optical millimeter-wave oscillator—35 GHz.
2. Quasi-optical oscillator with significant power—10 W at 10 GHz.
3. Large-scale quasi-optical amplifier—Grid amplifier with 200 transistors at 10 GHz.
4. Demonstration of a diode-grid frequency doubler with a 300- μ W output at 1 THz.
5. Quasi-optical amplifier with significant power—3.8 W HEMT grid amplifier.
6. Monolithic millimeter-wave quasi-optical amplifiers with gain—5 dB at 40 GHz and 50 GHz. The saturated output power of the 40-GHz amplifier is 400 mW.

The first four projects have been described in previous annual reports. The recent results are described below.

HIGH-POWER PHEMT GRID AMPLIFIER

We have fabricated a 100-element hybrid grid amplifier with custom-made pHEMT differential amplifier chips made by Lockheed-Martin Laboratories. The grid is stabilized against spurious oscillations by resistors in the gate. The grid shows a peak gain of 12/dB at 9 GHz with a 3-dB bandwidth of 15%. The noise figure is 3 dB, and the saturated output power is 3.7 W. These figures are a considerable advance over previous quasi-optical amplifiers. A paper describing the grid has been submitted to *IEEE Transactions on Microwave Theory and Techniques*.

A 40-GHZ MONOLITHIC HBT GRID AMPLIFIER

A 36-element monolithic grid amplifier has been fabricated by Rockwell International. The active elements are pairs of heterojunction-bipolar-transistors. The peak gain is

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- [11] "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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- [18] "Grid Amplifiers," Ph.D. Thesis by Moonil Kim, Caltech, Pasadena, CA, 91125.
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[37] "A 16-Element Tunnel Diode Grid Oscillator," Michael P. De Lisio, John F. Davis, Shi-Jie Li, and David Rutledge, Antennas and Propagation Symposium, Newport Beach CA, June 1995.

[38] "40-GHz Monolithic Grid Amplifier," Cheh-Ming Liu, Emilio Sovero, and David Rutledge, Submitted to *IEEE Microwave and Guided Wave Letters*, May, 1995.

[39] "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, Submitted to *IEEE Transactions on Microwave Theory and Techniques* May, 1995.

STUDENTS

[1] Moonil Kim finished his thesis on the initial development of grid amplifiers and is now working at the Jet Propulsion Laboratory.

[2] Jon Hacker finished his thesis on grid mixers and high-power grid oscillators and currently working at Bell Communications Research.

[3] Michael De Lisio, an AASERT fellow, has been working on a 100-element MOD-FET grid amplifier and a 16-element tunnel-diode grid. In addition, Michael has been working on the 50-GHz monolithic millimeter-wave amplifier grid fabricated by Lockheed-Martin. He will be joining the University of Hawaii in the fall as an assistant professor.

[4] Victor Lubecke, an Hispanic student, is finishing his thesis on a 600-GHz tuning circuit, and will be joining JPL in the fall.

[5] Jung-Chih Chiao has demonstrated a grid-frequency doubler with an output power of $330 \mu\text{W}$ at 1 THz. He will be joining Bell Communications Research in the fall.

[6] Jeff Liu has been working on the monolithic 40-GHz amplifier grid fabricated by Rockwell International.

[7] John Davis, an African-American graduate student, has been working on the 16-element tunnel-diode grid. He is now working on high-efficiency switching power amplifiers.

[8] Shijie Li is working on a new high-gain quasi-optical grid amplifier that uses MIMIC amplifiers as the active components. The goal is to achieve single-stage gains of 20 dB.

[9] Polly Preventza is working on a 35-GHz InP oscillator grids using transistors provided by Mehran Matloubian at Hughes Research Labs in Malibu.

[10] Alina Moussessian is working with the Physical Optics Corporation to develop an electronic-beam steering system controlled by light.

ARMY INTERACTIONS

Dr. James Mink and I were co-editors of a special issue of the *IEEE Transactions on Microwave Theory and Techniques* on Quasi-Optical Techniques. This was published in October, 1993.

I attended a Workshop on Millimeter Wave Power Generation and Beam Control at the University of Alabama in Huntsville that was sponsored by the U.S. Army Missile command. I served on a panel that discussed quasi-optical oscillators.

I visited Fort Monmouth on several occasions for to give seminars and to get advice. At Fort Monmouth I visited Jim Harvey, Arthur Paoella, Felix Schwering, and Barry Pearlman's group.

I have participated in bi-annual Quasi-Optical Alliance meetings at Lockheed-Martin that have often been attended by Jim Mink and Jim Harvey.

INDUSTRIAL INTERACTIONS

We have ongoing collaborative efforts in monolithic amplifier grids with Lockheed-Martin Laboratories (Norm Byer and Sander Weinreb), the Jet Propulsion Laboratory (Peter Smith), and the Rockwell Science Center (Emilio Sovero and Aiden Higgins). We are also participating with Lockheed-Martin Corporation on their MAFET proposal, and met three times as part of their Quasi-Optical Alliance.

In addition, we have started a collaboration with Mehran Matloubian of Hughes Research Laboratories in Malibu CA to make millimeter-wave InP HEMT grid oscillators.

We collaborate on opto-electronic beam-steering with the Physical Optics Corporation (Lev Sadovnik) on an ARO SBIR.

ABSTRACTS

Modelling and Performance of a 100-Element pHEMT Grid Amplifier

Michael P. De Lisio, Scott W. Duncan, Der-Wei Tu, Cheh-Ming Liu,
Alina Moussessian, James J. Rosenberg, and David B. Rutledge

Abstract—A 100-element hybrid grid amplifier has been fabricated. The active devices in the grid are custom-made pseudomorphic High Electron Mobility Transistor (pHEMT) differential-pair chips. We present a model for gain analysis and compare measurements with theory. The grid includes stabilizing resistors in the gate. Measurements show the grid has a peak gain of 10 dB when tuned for 10 GHz and a gain of 12 dB when tuned for 9 GHz. The maximum 3-dB bandwidth is 15% at 9 GHz. The minimum noise figure at 10 GHz is 3 dB. The maximum saturated output power at 9 GHz is 3.7 W, with a peak power-added efficiency of 12%. These results are a significant improvement over previous grid amplifiers based on Heterojunction Bipolar Transistors (HBT's). This is the first report of a full-size 100-element grid amplifier using HEMT devices.

I. INTRODUCTION

Quasi-optical amplifiers combine the output powers of many solid-state devices in free space, eliminating the losses associated with waveguide or transmission-line combiners. The first quasi-optical amplifier was a 25-element grid amplifier [1]. A grid amplifier is an array of closely-spaced differential pairs of transistors. Fig. 1 shows the approach. A horizontally-polarized input beam excites rf currents on the input leads of the grid. This drives the transistor pair in the differential mode. Currents on the output leads produce a vertically-polarized output beam. Metal-strip polarizers provide independent tuning of the input and output circuits. Other types of quasi-optical amplifiers using amplifiers using patch antennas [2,3], back-to-back integrated horn antennas [4,5], folded slot antennas [6], and probe antennas [7] have been demonstrated. The largest number of devices have been incorporated in a 100-element HBT grid amplifier [8].

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S.W. Duncan and D.-W. Tu are with Martin Marietta Laboratories, Baltimore, MD 21227-3898.

J.J. Rosenberg is with the Engineering Department, Harvey Mudd College, Claremont, CA 91711.

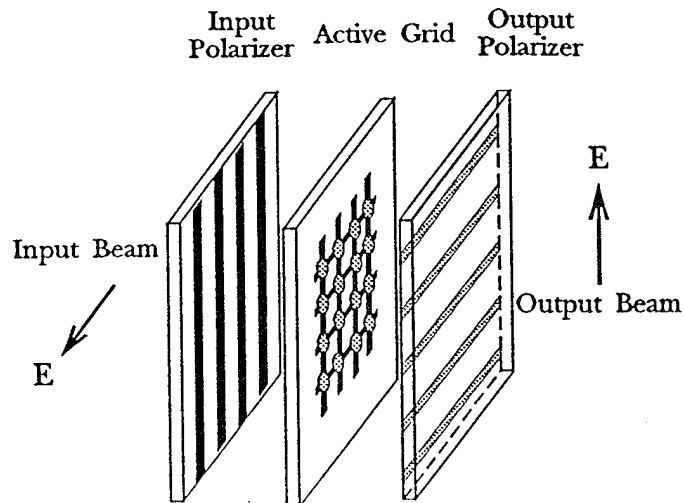


Fig. 1. A grid amplifier. A horizontally-polarized input beam is incident from the left. The output beam is vertically-polarized and is radiated to the right. The polarizers independently tune the output and input circuits.

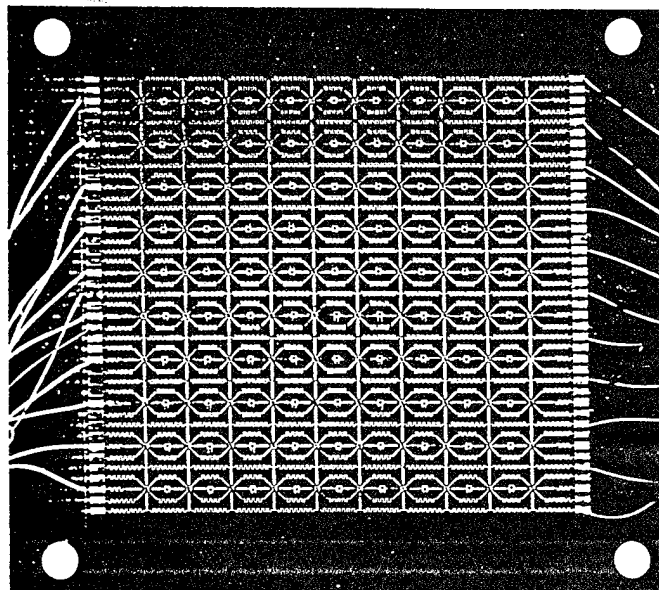


Fig. 2. Photograph of the amplifier grid. The grid is a 10 × 10 array of pHEMT differential pairs. The active area of the grid is 7.3 cm on a side.

A 40-GHz Monolithic Grid Amplifier

Cheh-Ming Liu, Emilio A. Sovero, Wu Jing Ho, J. A. Higgins, and David B. Rutledge

Abstract—A 36-element monolithic grid amplifier has been fabricated. The peak gain is 4 dB at 40 GHz with a 3-dB bandwidth of 800 MHz. The active elements are pairs of heterojunction-bipolar-transistor's (HBT's). The individual transistors in the grid have a maximum oscillation frequency, f_{max} , of 100 GHz. The grid includes base stabilizing capacitors which result in a highly stable grid. This is the first report of a successful monolithic grid amplifier.

I. INTRODUCTION

A grid amplifier is a spatial power-combining device that amplifies a microwave beam and combines the outputs of many transistors, making it possible to greatly increase power [1-4]. Because the power is combined in free space, grid amplifiers eliminate losses associated with waveguides and transmission-line networks. Fig. 1 shows a perspective view of a grid amplifier. The input beam is on the left-hand side with horizontal polarization. The input beam is received by the amplifier grid, amplified, and then reradiated with vertical polarization, as the output beam to the right. The first grid amplifier, using MESFET's, showed a gain of 11 dB at 3.3 GHz [1]. Later, grid amplifiers also demonstrated gains of 10 and 11 dB at 10 GHz with HBT's [2,3], and 12 dB at 9 GHz with pHEMT's [4]. Other spatial-power combining approaches are actively being pursued [5-10]. Recently, Hubert, Schoenberg, and Popović demonstrated a quasi-optical millimeter-wave amplifier using slot antennas, with 6-dB gain flange-to-flange at 29 GHz [11]. These spatial power-combining amplifiers were fabricated by hybrid technology with chips mounted on a printed-circuit board. The grid-amplifier structure is planar with all the devices on one side, making this approach attractive for monolithic fabrication. Here we report the first monolithic grid amplifier with gain—4 dB at 40 GHz.

Manuscript submitted June 18, 1995. This research was supported by the Air Force Materiel Command/Rome Laboratory and the Army Research Office.

C.-M. Liu and D.B. Rutledge are with the Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA, 91125.

E.A. Sovero, W.J. Ho, and J.A. Higgins are with the Science Center, Rockwell International Corporation, 1049 Camino Dos Rios, Thousand Oaks, CA 91385.

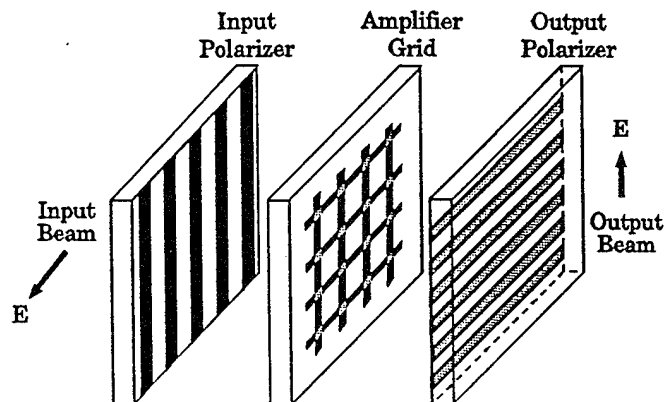


Fig. 1. A grid amplifier.

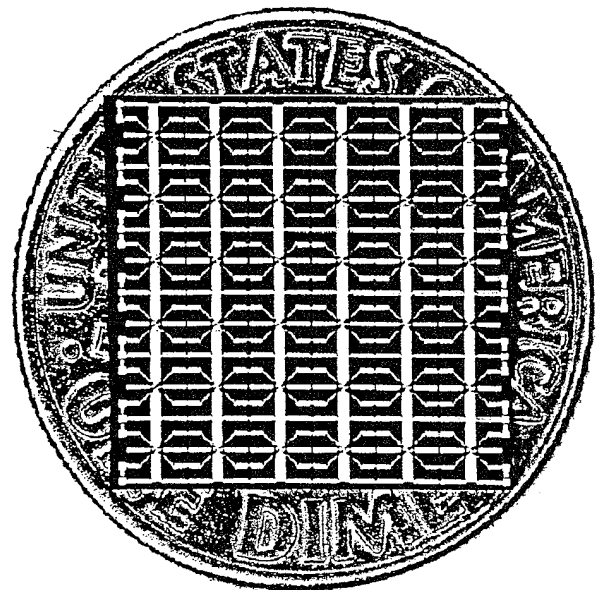


Fig. 2. Photograph of the 36-element monolithic grid amplifier compared with a dime.

The monolithic grid amplifier, shown in Fig. 2, is composed of 36 unit cells periodically distributed on a 565- μm GaAs substrate. The grid was fabricated with the HBT process established at Rockwell International [12]. The HBT under optimum bias (20 mA/transistor) has a maximum oscillation frequency, f_{max} , of 100 GHz and unity-current-gain frequency, f_t , of 60 GHz. The maximum available gain of an individual transistor at 40 GHz is 8.2 dB.