



# THE GRID AMPLIFIER: ENABLING HIGH POWER MILLIMETER-WAVE SYSTEMS

There are a number of communications, radar and imaging applications spanning Ka-band through W-band (26 to 110 GHz) that require transmitter output powers in the range of a few watts to a few tens of watts. Vacuum-tube sources and amplifiers have long been available that can produce output power from 10 watts to over a kilowatt. These tubes are not readily mass-produced, and are not cost-effective on a dollar-per-watt basis for lower output powers. Additionally, the mechanical robustness and graceful degradation of solid-state amplifiers makes them preferable to vacuum tubes in many applications.

Unfortunately, conventional semiconductor amplifier technology has not provided single-chip solutions that meet the power requirements for many emerging millimeter-wave applications. At present, commercially available solid-state amplifier chips operating at Ka-band frequencies are limited to P1dB power levels below three watts.<sup>1</sup> At V-band and W-band, the available output power levels are less than one quarter watt.<sup>2</sup> Higher overall power levels can be reached by combining the outputs of multiple chips using microstrip or waveguide binary combiners, but losses associated with these conventional combining techniques limit the ultimate power and efficiency that can be achieved with this approach.

Many applications of millimeter-wave solid-state amplifiers call for their use in small outdoor terminals, both fixed and portable. In these applications, small size, low weight and high efficiency are very important. This is particularly true for portable terminal applica-

tions. A single-chip amplifier capable of producing in excess of ten watts at Ka-band or Q-band, or several watts at V-band or W-band, represents an enabling technology in many cases.

A new approach to millimeter-wave amplification called the grid amplifier, developed at the California Institute of Technology,<sup>3</sup> addresses the need for higher power solid-state amplification. The grid amplifier uses a technique known as spatial power combining, in which the outputs of many individual elements are combined into a beam in free space, circumventing the losses associated with conventional power combining schemes. Previously, spatial power combining has been demonstrated as a method for producing millimeter-wave output powers well in excess of 10 W.<sup>4,5</sup> However, the earlier implementations of spatial power combining used multiple chips and involved substantial hand assembly and tuning. The grid amplifier spatially combines the outputs of a large number of transistors fabricated on a single chip, resulting in a

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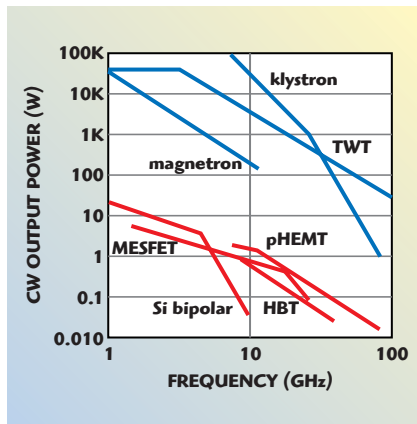
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mass-producible amplifier with the potential to produce tens of watts of millimeter-wave power.

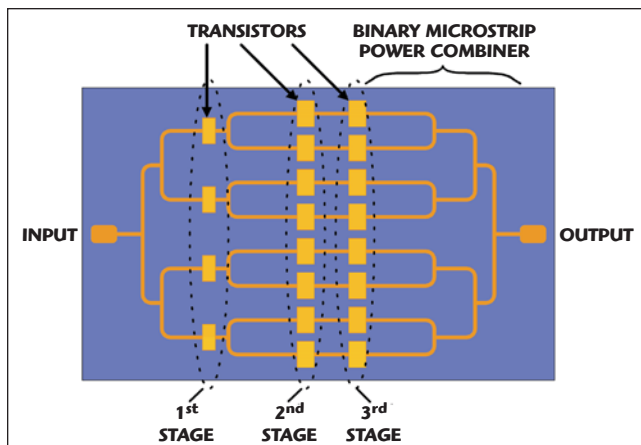
## CHALLENGES IN GENERATING MILLIMETER-WAVE POWER FROM SOLID-STATE AMPLIFIERS

The difficulty in producing high output millimeter-wave solid-state amplifiers stems from the fact that the amount of output power available from individual transistors falls off very rapidly with increasing frequency, as shown in **Figure 1**. Consequently, it is necessary to combine the outputs of many transistors to achieve watt-level output power.

The most common method of combining the outputs of transistors at the chip level is binary microstrip combining, schematically illustrated in **Figure 2**. The input signal is distributed to multiple transistors using microstrip splitters, and then combined using a binary microstrip combiner. Microstrip combiners are convenient to fabricate in standard MMIC processes, but suffer from



▲ *Fig. 1 Power generating capabilities of various devices as a function of frequency.*



▲ *Fig. 2 Typical microstrip combining circuit.*

losses due to the finite conductivity of the metal traces. In a typical GaAs or InP process, microstrip lines can have losses of approximately 1 dB per wavelength at millimeter-wave frequencies. As the number of combined elements is increased, losses increase for two reasons: the number of stages of combining increases, and the length of the microstrip lines required for the final stages of combination grows substantially. The implication of these losses on chip performance is illustrated in **Figure 3**, which plots the total output power of a set of binary-combined elements normalized to the output of a single element, versus the number of elements. The dashed line represents ideal, lossless power combining. The curve representing the performance of microstrip combining assumes 1 dB per wavelength losses and assumes that eight elements can fit within a quarter-wavelength. The curve shows that by the time 16 elements are combined, losses are significant; combining more than 64 elements is impractical.

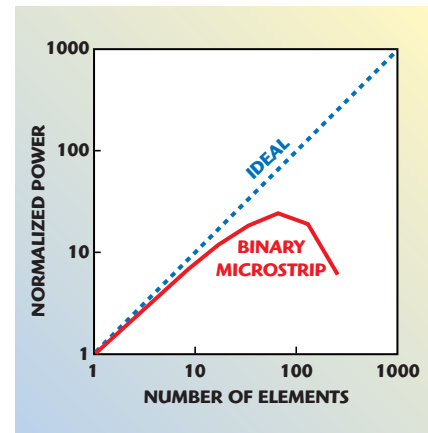
This analysis is actually optimistic in that it neglects the impact of phase and amplitude mismatches among the elements, which increase loss significantly. As a practical matter, it has proven difficult to advantageously combine more than 16 elements on a chip, typically limiting single-chip output to roughly 10 times that available from a single transistor. As mentioned in the introduction, among commercially advertised chips, the maximum output power available at Ka-band is slightly less than three watts,<sup>1</sup> and at W-band it is less than one quarter of a watt.<sup>2</sup>

## SPATIAL POWER COMBINING AS AN APPROACH TO GENERATING MILLIMETER-WAVE POWER

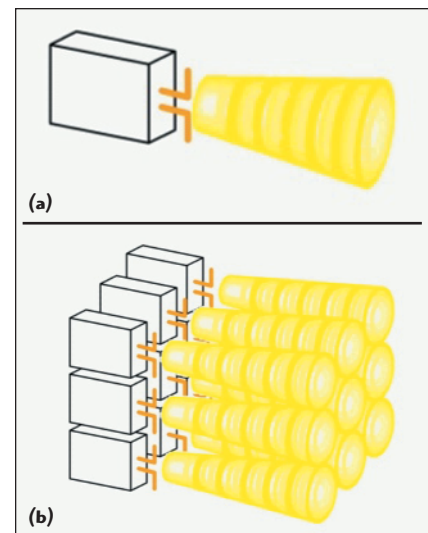
### What is Spatial Power Combining?

“Spatial” or “quasi-optical” techniques provide an alternative method to combine the outputs of a large number of transistors. These techniques, illustrated in **Fig-**

**ure 4**, provide enhanced RF efficiency by coupling the transistors to large-diameter guided beams or waveguide modes, rather than using planar transmission line combining structures. Using a large beam cross section allows the outputs of many devices to be added together in a single stage of combining. All of the elements are essentially operating in parallel, and the loss is roughly independent of the number of elements, allowing large numbers of devices to work together efficiently. Ohmic losses in these systems are minimal since the energy is distributed and combined in air via low loss waveguides or Gaussian beams. Most of the losses in these systems are associated with coupling from the active devices to the propagating beam and subse-



▲ *Fig. 3 Combined output power of a microstrip multi-element combiner showing the rapid increased effect of losses.*



▲ *Fig. 4 Spatial power combining; (a) a single radiating element and (b) combining several elements.*

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quently coupling to a power collection port, such as an output waveguide. Losses from both of these processes can be minimized through careful design.

Though there is no formal definition, the terms spatial and quasi-optical are usually understood to apply to electronic systems that employ high order beam guiding components (such as Gaussian beams defined by lenses or shaped mirrors, or overmoded metallic waveguide systems) for signal distribution and collection. It could be argued that any antenna array, particularly if feeding a large lens or shaped reflector, is therefore quasi-optical. A useful distinction between a quasi-optical system and a classical phased array is that the latter uses circuit-based feed networks to ensure that the array elements operate in phase, whereas a quasi-optical system employs spatial feeds for this purpose. Since many of the so-called quasi-optical systems are packaged in metallic waveguide enclosures, it is best to consider the term “quasi-optical” as indicative of a methodology in which the designer tailors the electromagnetic field profile within a guiding system to both distribute and collect the signals that couple to the individual devices, rather than using transmission lines or single-mode waveguides to couple to individual elements.

The quasi-optical advantage grows with increasing frequency of operation, where the shorter wavelengths allow very dense device integration. For example, quasi-optical multipliers at 1 THz have generated output powers 200 times greater than any competing technology, a clear testament to this high frequency advantage.<sup>6</sup>

Several other advantages of quasi-optical amplifiers have been noted.<sup>7</sup> Because noise from the individual devices is largely uncorrelated, the broadband noise figure of quasi-optical circuits tends to be similar to that of a single device. For similar reasons, the excess phase noise power in quasi-optical systems decreases in proportion to the number of elements. These properties allow an increased dynamic range in quasi-optical receivers. Finally, quasi-optical devices tend to degrade gracefully as devices fail, and are insensitive to the single-point failures that could be catastrophic in other systems.

## Previous Work in Millimeter-wave Spatial Power Combining

Significant progress has been made in the laboratory development of millimeter-wave solid-state spatial power combining; however, the results are too numerous to discuss here. The following two demonstrations have been chosen to highlight notable results.

- **Sanders 35 W, 60 GHz Tray Amplifier**

Arguably the most impressive accomplishment in multi-chip spatial combiners was reported by researchers at Sanders,<sup>4</sup> who described a combiner with 272 elements in operation simultaneously. This system uses a sectoral horn to feed a 17-element linear dipole array. Each dipole then couples energy to a tray containing 16 three-stage MMIC output amplifiers with 20 driver MMICs (one for each PA plus four additional preamps in the distribution network). The output signal from the 17 × 16 output dipole array network is collected by a pyramidal horn. This array generates 35 W CW output power at 61 GHz, with 60 dB of small-signal gain and a 4 GHz bandwidth. The AM-PM distortion is only 1°/dB. This combiner achieves an estimated 45 to 50 percent collection efficiency. The extremely high gain of this system compares favorably with tube sources. It is believed that this is the highest power solid-state V-band source reported to date.

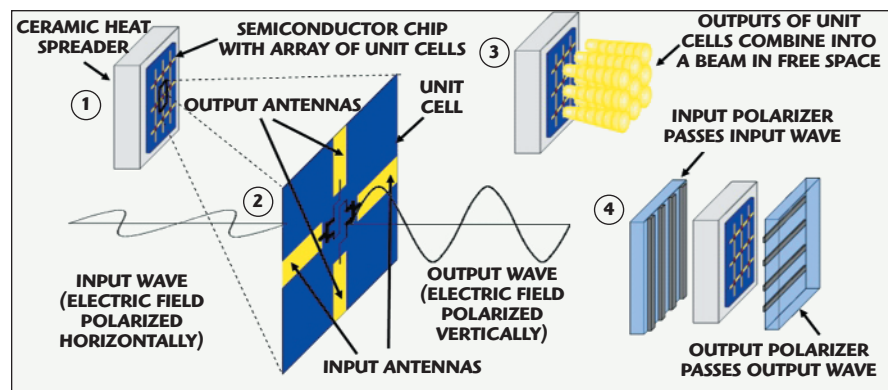
- **Lockheed Martin/NC State 25 W, 34 GHz Array Amplifier**

Researchers at Lockheed Martin and North Carolina State University recently demonstrated a planar “tiled” combiner system at Ka-band (34 GHz).<sup>5</sup> This system uses a 45-ele-

ment, double-sided active patch antenna array with a hard-horn feed. In this case, the input is coupled to the array through a waveguide port on the hard-horn feed, and the output power can be collected by a hard-horn collector, or radiated directly into space. The latter arrangement would find use as a feed structure for a large reflector antenna or lens-focused system. The MMIC amplifiers are mounted on a two-sided assembly, with patch antennas coupling the MMICs to the input and output waves. Each element has a driver MMIC mounted on one side and a 1 W power MMIC on the other. The signal passes from the driver amplifier to the power amplifier through a coaxial via penetrating the thick central ground plane. This thick ground provides good isolation and thermal management. Using the output collector, the authors report a 3 dB compressed output power of 13 W at 34 GHz, with a small-signal gain of 10 dB and a 3 dB bandwidth of 800 MHz. The power-added efficiency is 3.4 percent, and the power-combining efficiency is 28 percent. Better results were reported with the output radiating directly into air, thereby avoiding losses in power collection. In this case, the authors estimate a radiated 3 dB compressed power of 25 W at 34 GHz, corresponding to a power-added efficiency of 7.5 percent and a combining efficiency of 56 percent.

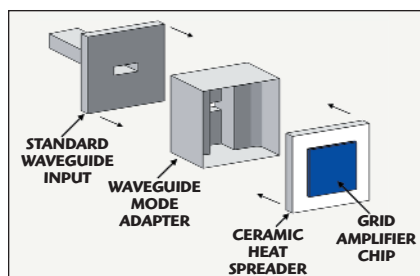
## THE GRID AMPLIFIER

The operation of the grid amplifier is illustrated in **Figure 5**. It consists of a single monolithic chip populated with an array of identical amplifying elements, or “unit cells.” Each unit cell contains a differential transistor

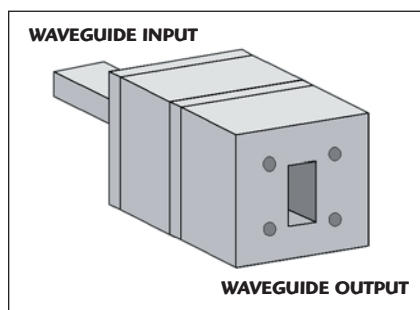


▲ Fig. 5 Operation of the grid amplifier.

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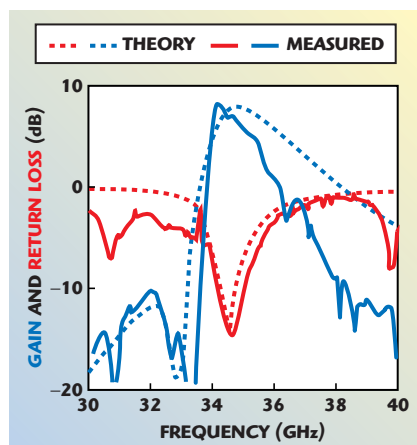
▲ Fig. 6 Input mode adapter for coupling to the grid amplifier.



▲ Fig. 7 Complete module with input and output adapters.

pair; printed metal leads attached to the gates and drains of the pair form the input and output antennas. The chip is mounted on a ceramic carrier that provides a low thermal resistance path for heat to be removed from the array and conducted to a heat sink. An input beam with an electric field polarized in the horizontal direction couples to the horizontal leads, exciting the gates of the transistor pair in the differential mode. The amplified signal is directed by the transistors' drains to the vertical leads, radiating an amplified output wave polarized with the electric field in the vertical direction. Because the input and output waves are cross-polarized, the potential for spurious feedback oscillations is reduced. Furthermore, off-chip passive polarizers are used to provide isolation and tuning. These polarizers can be as simple as printed metal stripes on a circuit board, or a cross-polarized waveguide. As shown in the diagram, the horizontally polarized input wave passes through the input-side polarizer but is reflected by the output-side polarizer. The opposite is true for the vertically polarized output. Changing the position of these passive polarizers will tune the input and output of the amplifier.

The designer of a grid amplifier must model how the electric and magnetic fields in the radiated waves will couple to the voltages and cur-



▲ Fig. 8 Gain vs. frequency for a waveguide-fed grid amplifier.

rents on the terminals of the active device. Modeling of grid structures is especially challenging since the elements are very strongly coupled and generally placed quite close together ( $< 0.1$  of a wavelength). Because of the strong interactions, modeling every element in large arrays is a computationally intensive task. Instead of modeling the entire grid, it is more convenient to consider an infinite two-dimensional lattice, and then take advantage of symmetry planes where the tangential fields vanish to define a single unit cell. This approach neglects edge effects and will be most valid for large arrays. The complexity of the modeling is reduced substantially, from analyzing the entire array to analyzing a single cell in an equivalent waveguide. Recent advances in commercially available CAD packages have enabled designers to model grids with remarkable success.<sup>8</sup> Once the designer has determined the unit cell design, the entire grid array size can be scaled to meet the power requirement. Because the array of active devices is very dense, the grid amplifier can be monolithically fabricated, making this a very attractive technology for applications that demand a single-chip mass-producible solution.

Efficient feeding of the input of a grid amplifier is another important issue. Uniform illumination is important for two reasons: it gives a well-formed radiated output beam, and it ensures that all the array elements saturate together. To preserve gain and noise figure, this transition must be made with as little loss as possible. The first quasi-optical amplifiers

were measured in the far field of two horn antennas. Quasi-optical amplifiers have also been tested using dielectric lenses to capture more of the power radiated from the input and output horns,<sup>3,9</sup> but this configuration is very bulky. The most attractive solution is to include the amplifier in a guided-wave system. Quasi-optical packaging fixtures have evolved steadily. An ideal feed would transition from a standard-guided wave to a quasi-plane wave with uniform amplitude and phase, as shown in **Figure 6**, efficiently illuminating the aperture of the quasi-optical array. For some applications, a radiated output beam may be ideal. For others, such as a drop-in replacement for a traditional power amplifier, the radiated output must be efficiently collected and transitioned back to a guided wave, as shown in **Figure 7**. Larger grids and arrays must be put into an overmoded guide, and care must be taken to insure that the arrays are illuminated uniformly by tailoring the excitation of the higher order modes.

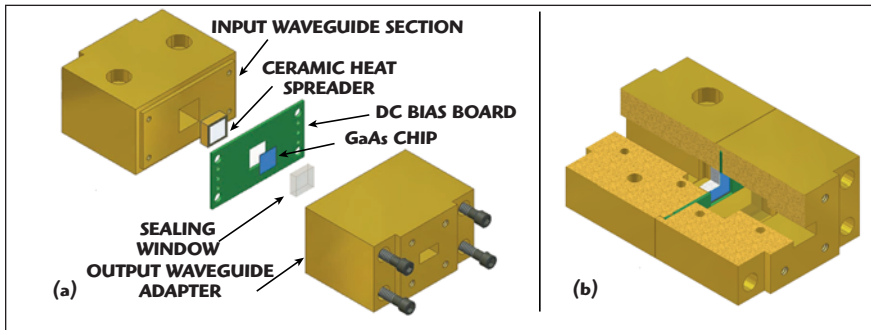
## SIMULATION AND MEASUREMENT RESULTS

Wavestream engineers have developed a single-chip monolithic grid amplifier using Rockwell pHEMT technology.<sup>9</sup> The entire array incorporates 512 low noise transistors. An aluminum-nitride ceramic heat spreader was used for thermal management. The grid was first characterized in a lens-focused system. The measured results are shown in **Appendix A**. The maximum small-signal gain is 8 dB with a 1.3 GHz (3.5 percent) 3 dB bandwidth. Under 3 dB gain compression, the CW output power is 37 dBm with a power-added efficiency of 17 percent. The output third-order intercept power extrapolated from one-watt-per-tone output power is 45 dBm. The AM-PM conversion is 2°/dB. This grid was also measured with a waveguide input feed structure and a directly radiated output.<sup>10</sup> **Figure 8** shows the results. The peak gain is 7.5 dB with a 1.7 GHz (5 percent) 3 dB bandwidth.

## CURRENT DEVELOPMENTS

Ka-band booster amplifiers are currently being developed for both commercial and government satellite terminal applications. The grid ampli-

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▲ Fig. 9 Grid amplifier module; (a) exploded view and (b) cutaway view.

fier chips are being fabricated in a standard, commercial 0.25  $\mu\text{m}$  GaAs pHEMT process, with targeted output power levels between 10 and 20 W. The estimated power-added efficiency of these booster amplifiers is 20 percent, substantially better than is typically reported for conventionally designed power amplifiers operating at these output power levels. The chips will be incorporated into a compact housing with WR28 waveguide input and output ports, as illustrated in Figure 9.

## CONCLUSION

Grid amplifiers have been successfully developed and refined during the past several years, culminating in several promising demonstrations at microwave and millimeter-wave frequencies. As demand for bandwidth increases and communications systems continue to exploit higher frequencies, these amplifiers are likely to play a key role in future millimeter-wave systems. ■

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**James J. Rosenberg** earned his PhD degree from Columbia University. He is president, director and founder of Wavestream Corp., and is co-inventor of the grid amplifier, the company's core technology, and the pHEMT transistor. He gained his operational experience as deputy manager of the MicroDevices Lab, a 50,000-square foot semiconductor fabrication facility at NASA's Jet Propulsion Laboratory, and as director of engineering at GPD Optoelectronics.

**Michael P. DeLisio** earned his PhD degree from the California Institute of Technology,

and taught engineering at the University of Hawaii before founding Wavestream, where he is currently the chief technical officer. He demonstrated the first watt-level output from a grid amplifier, and is an originator of the modeling technique used in the design of grid amplifiers. He is active in the IEEE Microwave Theory and Techniques Society, and has published more than 35 papers in industry-respected journals and conferences.

**Blythe C. Deckman** earned his PhD degree from the California Institute of Technology. He is director of research and development and founder of Wavestream Corp. His 38 GHz, 5 W single-chip grid amplifier still holds the record for the highest output power from a single chip at that frequency. Prior to co-founding Wavestream, he was a development engineer at Agilent.

**Chun-Tung Cheung** received his bachelor's degree in electrical and electronics engineering from the University of Hong Kong in 1997, and his master's and PhD degrees in electrical engineering from the California Institute of Technology in 1998 and 2003, respectively, during which time he developed the world's first grid amplifiers packaged in waveguide enclosures operating from Ka-band through W-band. He is currently an RF engineer at Wavestream Corp. developing high power, millimeter-wave amplifiers.

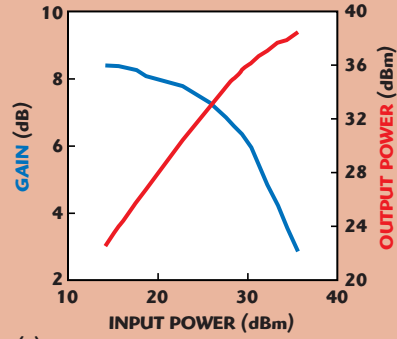
**David B. Rutledge** is a co-inventor of the grid amplifier. He has served as executive officer for electrical engineering at the California Institute of Technology and as director of Caltech's Lee Center for Advanced Networking. His interests include integrated-circuit antennas, active quasi-optics, computer-aided design and high efficiency power amplifiers. He was winner of the Microwave Prize and the Third Millennium Award of the IEEE, and has been a distinguished lecturer for the IEEE/APS. He is currently editor of the IEEE Transactions on Microwave Theory and Techniques. He is also Kiyo and Eiko Tomiyasu professor of electrical engineering at Caltech.

**Robert A. York** received his BS degree in electrical engineering from the University of New Hampshire in 1987, and his MS and PhD degrees in electrical engineering from Cornell University in 1989 and 1991, respectively. He is currently a professor of electrical and computer engineering at the University of California at Santa Barbara. His group at UCSB is involved with the design and fabrication of novel microwave and millimeter-wave circuits, high power microwave and millimeter-wave amplifiers using spatial combining and wide-bandgap semiconductor devices, and application of ferroelectric materials to microwave and millimeter-wave circuits and systems. He received the Army Research Office Young Investigator Award in 1993 and the Office of Naval Research Young Investigator award in 1996.

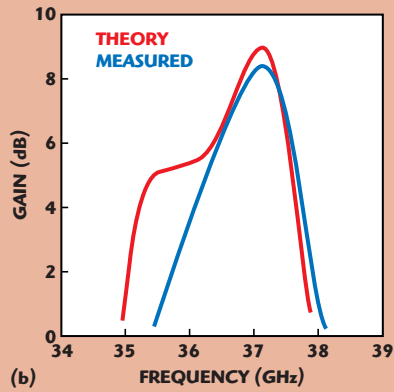
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## APPENDIX A

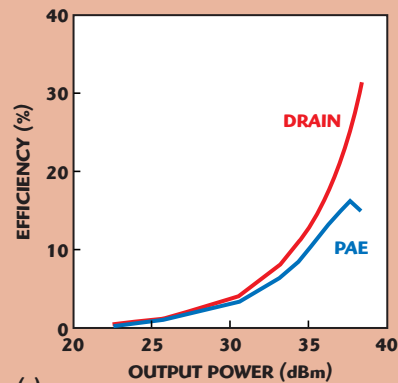
MEASURED RESULTS FROM A 38 GHz AMPLIFIER;  
(a) POWER AND GAIN VS. INPUT POWER,  
(b) GAIN VS. FREQUENCY, (c) EFFICIENCY  
vs. OUTPUT POWER AND (d) THIRD-ORDER  
INTERMODULATION vs. SINGLE-TONE  
OUTPUT POWER.



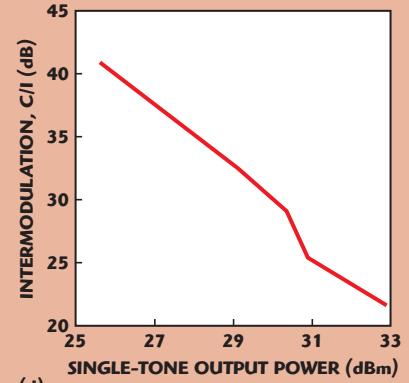
(a)



(b)



(c)



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