

CUSTOM DESIGN OF MONOLITHIC MICROWAVE INTEGRATED CIRCUITS

Monolithic microwave integrated circuits (MMIC's) have been designed at the Applied Physics Laboratory and fabricated at several gallium arsenide foundries since 1989. The design tools and methods for designing MMIC's have evolved to the present use of integrated computer-aided engineering software with programmable design components. Software elements that can be customized create multilayer mask descriptions of components for transistors, resistors, capacitors, inductors, microstrip connections, and other structures to improve the quality and productivity of MMIC's designed at the Laboratory. The schematic, physical layout, and simulation models are integrated into a single software tool, eliminating much potential for error. Experience with various foundries and various MMIC design techniques have increased our ability to design at higher and higher frequencies with confidence in achieving first-time success. The design improvements have been accompanied by improvements in measurement techniques for higher frequencies using microwave probe stations. This article summarizes MMIC designs at the Laboratory over the past few years and the progress shown and lessons learned.

COMPUTER-AIDED ENGINEERING DESIGN OF MMIC'S

Software computer-aided engineering tools from EEsof, Inc., are the predominant means of designing monolithic microwave integrated circuits (MMIC's) at APL. A key feature of EEsof's Academy software for MMIC layout is the ease of adding both layout macros and custom electrical models. Another feature is the ability to use a particular fixed or macro layout with any available electrical model, as long as they have the same number of nodal connections.

Macros

A macro is a software subroutine that creates the physical mask-layer descriptions for an element that can contain variable parameters (Fig. 1). The mask-layer descriptions are used to generate photo masks for each step in the foundries' integrated circuit processing. An example of a useful macro is a metal semiconductor field-effect transistor (MESFET), which consists of many mask layers but can usually be described as a given MESFET type with N parallel gate fingers each of width W .

One of the first macro libraries used with the Academy software was for the TriQuint foundry. It originated at EEsof but was modified by one of the authors of this article, John E. Penn, to create components having no design rule violations. Its first use was in a graduate MMIC design course at The Johns Hopkins University (JHU) in the summer of 1989. Since those initial student designs, the TriQuint library was modified by Penn; a graduate student at JHU later provided additional physical macros and custom electrical models. By late 1990, an entire multichip wafer was designed by using physical macros

and custom electrical models. Today, EEsof has a new TriQuint Smart Library containing physical and electrical macros, which is being used in the MMIC design course at JHU taught by both authors of this article.

A group of people including Dale Dawson of Westinghouse teamed together to teach a power MMIC design course at JHU that uses a custom physical and electrical library for Westinghouse's power GaAs process. Employees of APL have used Westinghouse's library through the JHU course and for MMIC design on APL programs. In 1992, several power amplifiers were designed and fabricated using the Westinghouse library and foundry process. Some were 2-W amplifiers at 6 GHz, and some were 0.5-W designs at 13 GHz. Another 200- to 250-mW

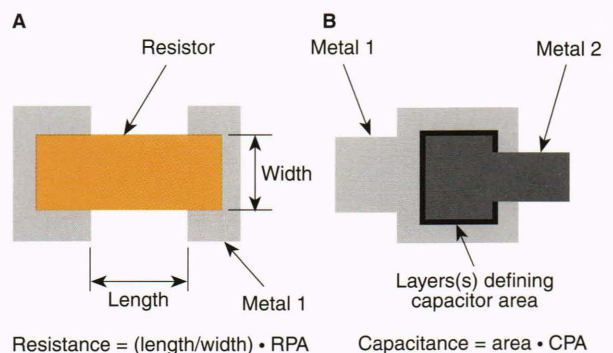


Figure 1. Example of typical macro elements for monolithic microwave integrated circuits. **A.** Thin-film resistor. RPA = resistance/area. **B.** Capacitor. CPA = capacitance/area.

amplifier at 30 GHz was designed (but has not yet been fabricated) using Westinghouse high-electron-mobility transistors (HEMT's).

The Applied Physics Laboratory created a third MMIC library for the GaAs pseudomorphic HEMT (PHEMT) process used by Martin Marietta Laboratories. A fixed set of PHEMT transistors and diodes was used with programmable macros for resistors, capacitors, and microstrip elements. We used the library to design several low-noise amplifiers and some Schottky diode mixers at 37 GHz for a radiometer design for the Geosat advanced technology model. The library was also used to design a 200- to 250-mW amplifier at 29 to 33 GHz for the ultra-small-aperture terminal (USAT) program.

Linear and Nonlinear Simulation

The simulation engine in EEsof's software is known as Libra and is accessible within the Academy framework. Both linear and nonlinear simulations can be performed within Libra with some minor constraints to the simulation file. Simulations in the linear region generally use transistors as the active elements where one is concerned with small signal gain, phase, impedance match, and so on. Amplifiers, phase shifters, switching devices, couplers, and the like undergo linear analysis, whereas nonlinear analysis is used for RF power, transients, harmonic response, power efficiency, mixers, oscillators, transistor current-vs.-voltage curves, and the like. A high-level simulation at the system level could be considered as a third level of simulation where both linear and nonlinear devices are simulated at a basic building-block level. An example of a system-level simulator is EEsof's Omnisys program, which can use data derived from linear or nonlinear simulations or measurements. Ideally, a single integrated simulation tool would perform linear, nonlinear, or system simulations.

Electromagnetic Analysis

Another useful analytical tool is the high-frequency structure simulator, which is a three-dimensional electromagnetic simulator. Reference 1 describes this tool using design examples.*

Design-Rule Checking

Design-rule checking is needed for any type of integrated circuit design, including MMIC's. The DRACULA program is the industry standard for design-rule checking and has been used for verifying MMIC designs at APL. Design rules were written by using DRACULA's programming language and are based on TriQuint's guidelines for the process. In recent years, design-rule checking has been added to the relatively inexpensive PC-based Integrated Circuit Editor layout tool, which can check relatively small designs such as most MMIC's. Design rules for TriQuint's process were created for the Integrated Circuit Editor and tested on APL designs and on student designs at JHU.

*Further description and examples will be given in an article by Jablon, Moore, and Penn to be published in the next *Digest*, which continues the advanced microwave technology theme.

Plotting

Calma is the most widely used standard for integrated circuit mask descriptions. Using this format, one can easily transfer integrated circuit designs between tools for additional modifications or design checking. This feature has been advantageous for obtaining large color plots from a 36-in. Versatec plotter on the computer-aided engineering network. Calma descriptions of MMIC's are transferred to the Mentor Graphics network and then translated into the Chipgraph integrated circuit layout software for plotting. Large color plots are very useful for locating subtle design flaws through visual verification and for improving layouts.

Measurement

An essential part of design is measurement of the fabricated MMIC's to verify that the devices operate correctly and that the simulation models and design methodology are correct. Extra effort to isolate differences between the simulation and measurements will ensure that future designs can be improved to guarantee first-pass success. Differences can result from variations in device processing, which can be simulated statistically or by using best-/worst-case values before sending the designs to the foundry for fabrication. Measurements of MMIC components (e.g., transistors, capacitors) for resimulation of the fabricated designs can determine whether differences are due to processing changes. Limitations in certain simulation models or the use of models beyond their specified range can also explain some differences. Omitting parasitic capacitances or coupling from elements spaced closely on the MMIC should be explored,

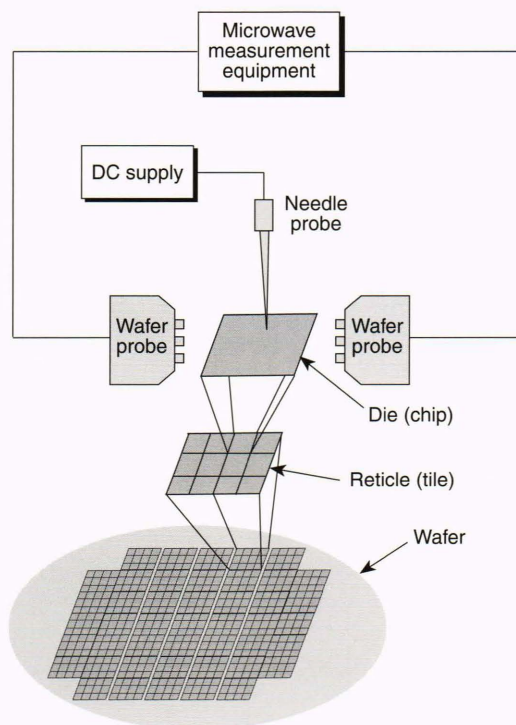


Figure 2. Wafer probing of monolithic microwave integrated circuits.

although parasitics have been found to cause only minor effects on several past APL MMIC designs up to 37 GHz. Being able to resimulate a design to obtain a correct simulation file that correlates with the measurement is an important learning experience that ensures future success and yields confidence in the design tools and methods.

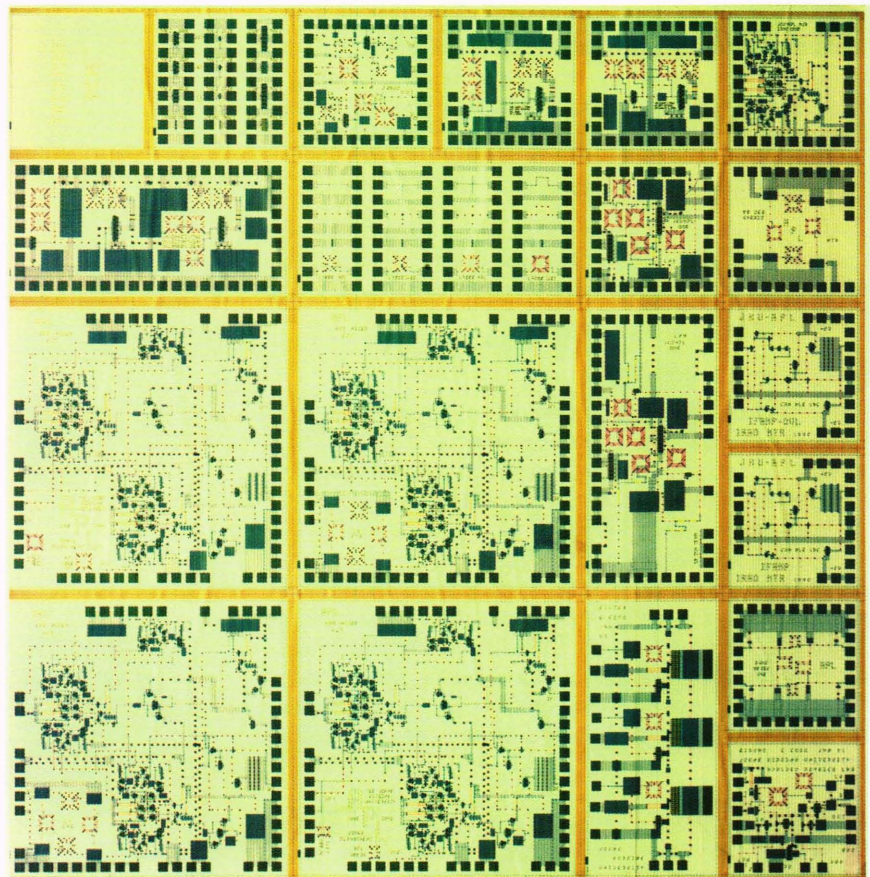
MMIC's are fabricated in large quantities on thin circular disks of GaAs called "wafers" before they are diced into individual units and assembled in high-frequency packages. A microwave probe station allows testing and verification of MMIC designs on the wafer before the expensive dicing and assembly stages (Fig. 2). Testing reduces costs by allowing only "good" devices to be packaged, but it requires sophisticated equipment and techniques. Clever measurement tricks can be used such as adding capacitors to the DC bias needle probes of the probe station to eliminate low-frequency oscillations when probing amplifiers. We used this technique to probe amplifiers up to 50 GHz. The technique has also been used to probe amplifiers that were considered a failure because they oscillated in previous probe measurements that did not use the capacitors. For unstable amplifiers where a capacitor at the needle probes for bias is not enough, amplifiers have been mounted on a small piece of metal with chip capacitors wire-bonded to the bias pads on the MMIC to allow successful probe testing.

Consistent, precise measurements are as important to designing MMIC's as the design tools. We have used vari-

ous calibration schemes to understand measurement accuracies and the benefits and limitations of the different calibration techniques. On-chip and off-chip wafer calibrations have been compared and shown good agreement up to 26 GHz.² Off-chip standards are known high-quality impedance standards usually purchased from a microwave probe manufacturer. On-chip wafer standards are impedance standards included on the wafer being fabricated that can be used to track processing variations when compared with known off-chip standards or to perform calibrations for probe measurement. Additional measurements were attempted up to 50 GHz, but a distinct divergence of the various calibration techniques occurred at about 30 GHz and could not be isolated. Some additional insight was gained into the coplanar probe to microstrip launches, but it was unclear how much error might have been due to measurement equipment, calibration techniques, or assumptions about the coplanar-to-microstrip launches. Cascade Microtech, the probe station manufacturer, has recently recommended a calibration technique for measurements above 26 GHz. If additional funding becomes available, we hope to explore measurements up to 50 GHz.[†]

[†]In their upcoming *Digest* article, mentioned in the previous footnote, Jablon et al. will discuss the use of a three-dimensional electromagnetic field solver to provide insight into the on-wafer MMIC calibration standards.

Figure 3. Multichip wafer reticle of a monolithic microwave integrated circuit tracking receiver. The entire 360 × 360 mil tile was reproduced seventy-six times on a 4-in. GaAs wafer.



APL MMIC DESIGNS

S-Band MMIC Tracking Receiver

The MMIC tracking receiver program produced the first full custom GaAs multichip microwave wafer designed at APL. Using the TriQuint macro library described earlier, all of the designs were simulated and physically laid out on PC's using EEsof software. The designs were also checked for violations at APL by using the DRACULA program. Nineteen unique MMIC's were fabricated, including amplifiers, mixers, hybrids, and active filters from 300 MHz to 13.6 GHz. A large MMIC supercomponent was included that contained a complete image-rejection (I and Q) mixer at 2.3 GHz RF and 300 MHz IF. Figure 3 is a plot of the entire 360×360 mil tile, which was reproduced seventy-six times on a 4-in. GaAs wafer.

K-Band Microwave Remote Sensing Element

Another multichip wafer was fabricated for an active-element array sensor. Amplifiers, phase shifters, attenuators, mixers, transmit/receive switches, and power amplifiers were designed to create a transmit/receive module for the active-element phased array. Test structures for measurement were included in unused space across the wafer. All of the devices except the power amplifier were fabricated by TriQuint on a single multichip wafer.

One of the designs was a five-stage high-gain amplifier for transmit and receive. One of the authors of this article, Craig Moore, designed a simple driver that took in standard digital control signals that were transistor-transistor logic compatible and created appropriate analog voltages to turn the amplifier gate bias on or off, depending on whether the module was transmitting or receiving. A single transmit/receive digital control signal replaces two control signals, since each amplifier is configured for either the transmit or receive function by breaking one of two air-bridge metal structures. With each amplifier modified in this way, the transmit amplifier will be off when the receive amplifier is on and vice versa. In the amplifier state, there is 35 dB of gain (Fig. 4), and in the off state there is over 70 dB of isolation! During probe

testing of the amplifier, it was initially oscillating and thought to be unstable despite the previous simulations. Because of the long bias wires and artificially high inductances created in the test configuration, an amplifier may oscillate at low frequencies. Stable probing of the amplifier was achieved by adding bypass capacitors at the needle probes used to apply DC bias to the device being tested.

Westinghouse's power GaAs process was used to create multiple versions of a 0.5-W power amplifier for the microwave remote sensing element program. Some of the devices included switches to shunt the outputs when the module was in a receive mode, thus performing the transmit/receive switch function. All of the fabricated devices were functional. Two power amplifier versions, one with a switch and one without, were measured by bonding the devices to a piece of metal and wire-bonding bypass chip capacitors to the supply pads to stabilize the devices. A probe station was used to measure the amplifiers, and DC bias was provided by needle probes touching the tops of the chip capacitors. The losses in the test setup were subtracted to determine the large signal power out of the devices. Although slightly below the design frequency, the measured peak output power curves closely matched the shape of the simulations. One power amplifier that contained switches and was expected to achieve about 400 mW of output power (+26 dBm) did so, as shown in Figure 5. Another design variation, which had about one-third more output MESFET periphery and no output switches, was expected to achieve over 630 mW (+28 dBm). It also met or exceeded the expected output power with an overall efficiency of about 25% for the three-stage amplifier.

Several test structures, such as capacitors, inductors, resistors, FET's, and microstrip structures, were included on these wafers for calibration and verification. Measurement and calibration techniques using the impedance standard substrate from Cascade Microtech, Inc., and "on-wafer" structures allowed us to measure the devices accurately up to 26.5 GHz. The good agreement of the measurements using various calibration techniques gave

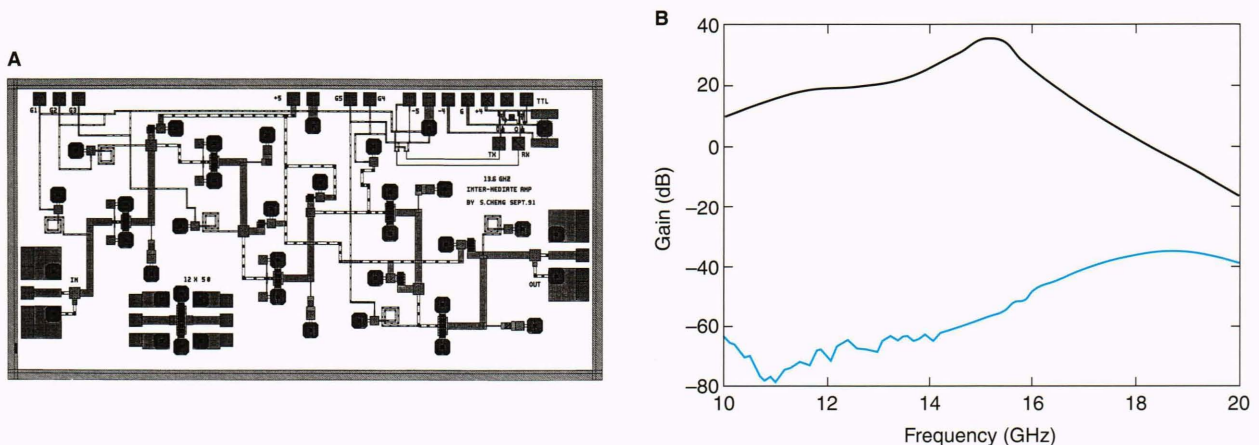


Figure 4. A. Photograph of a K-band microwave remote sensing element (MRSE) amplifier. B. K-band MRSE amplifier gain in the on (black) and off (blue) states.

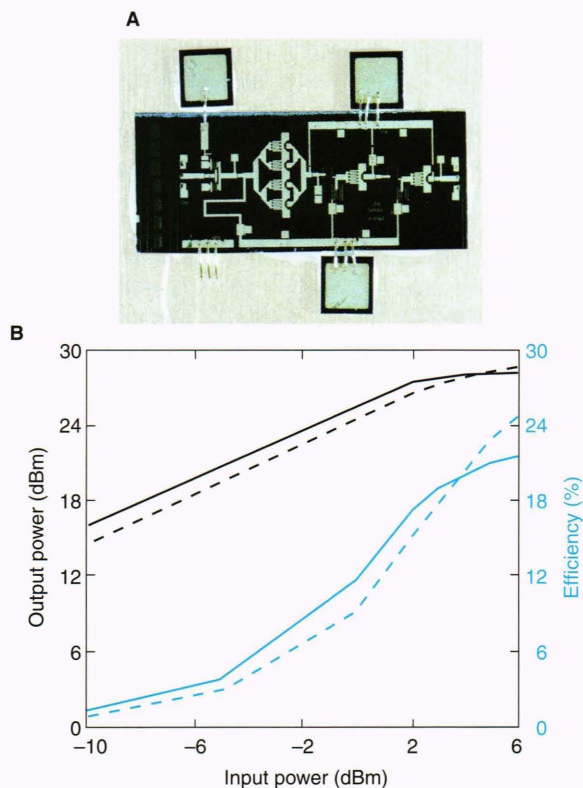


Figure 5. A. Photograph of a typical amplifier. B. Output power (black) and efficiency (blue) of a typical amplifier. The solid curves are the simulated values, and the dashed curves are the measured values.

us a standard with which to compare the simulation models. As a result, some of the foundry-supplied models were improved. Also, the MESFET measurements allowed resimulation of the designs to see whether differences between the original simulations and the measured devices were due to wafer processing variations or to errors in the simulation models.²

Ka-Band Radiometer

Using a simple macro library for the Martin Marietta GaAs process, amplifiers and mixers were designed and fabricated for the Geosat Advanced Technology Model program. Martin Marietta has a very low-noise, high-frequency PHEMT GaAs process used for designs at 94 GHz and above. Programmable macros for microstrip elements, resistors, capacitors, and spiral inductors were created for their process. The PHEMT's and diodes were added using a small library of fixed, active-component layouts. Several low-noise amplifiers were designed for 37-GHz operation. One was designed for lowest noise figure, another for moderate noise figure with good input and output match (voltage standing-wave ratio), and a third for high gain with moderate noise figure. Also, several variations in the bias supply methods were tried on a single amplifier design to see which technique worked best at 37 GHz. Another new concept used in these amplifier designs was "wafer tuning," introduced to

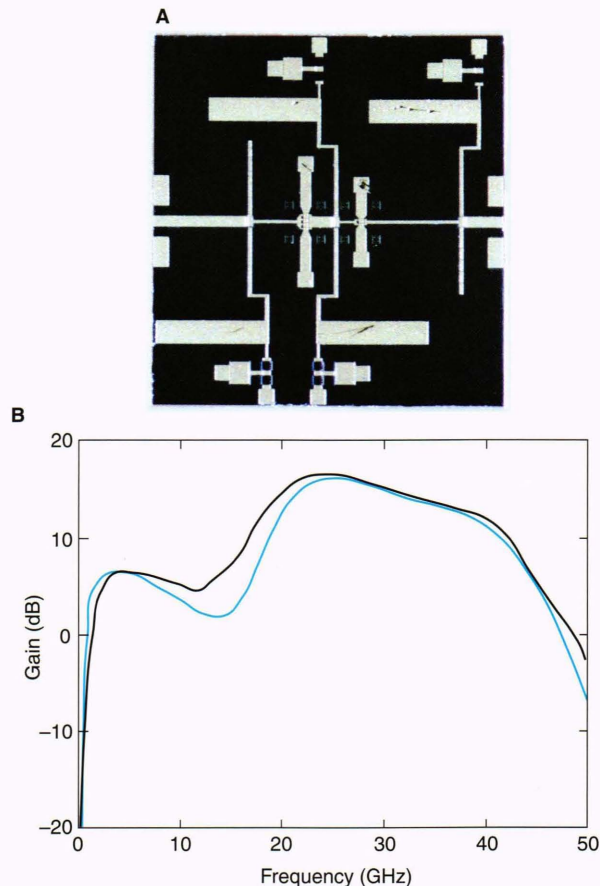


Figure 6. A. Photograph of a radiometer amplifier. B. Simulated gain (black) versus measured gain (blue) for a radiometer amplifier.

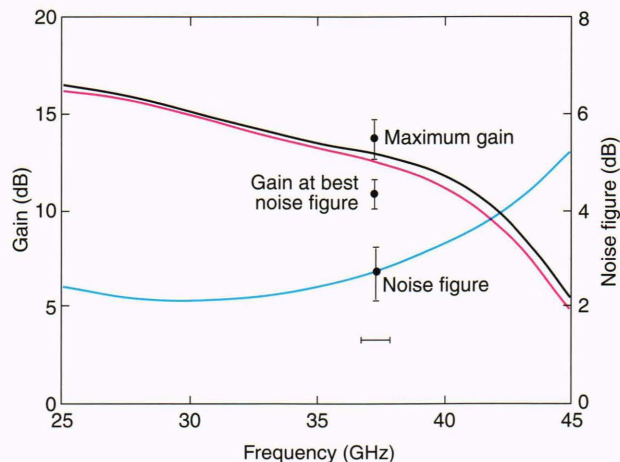


Figure 7. Gain and noise figure of a Ka-band low-noise amplifier. Simulated gain (black), simulated noise figure (blue), and measured gain using an HP 8510 probe (red). The circles refer to measured noise figure and gain using an HP 8970 probe. The vertical ranges around the circles indicate the scatter of the measurements, and the horizontal range centered at 37 GHz is the frequency range of the measurements.

us by Martin Marietta; it provides a means of tuning the MMIC's. Two microstrip stubs with several breakable air bridges spaced $75 \mu\text{m}$ apart were used to tune each amplifier. Although the tuning and testing of the first device may be tedious, the other devices on the wafer can be expected to operate similarly. One need only tune the first device or two, then set all the devices from that wafer to the same tune point for similar operation. Generally, the devices operated fairly well without any tuning. Figure 6 shows the measured and simulated gain versus frequency of one of the amplifiers. Note the wide bandwidth of the 20- to 40-GHz operation. The noise figure was measured for some devices and compared favorably with the simulations (Fig. 7). When testing for noise figure, one must adjust the MESFET bias point for lowest noise, since the transistor performance is sensitive to the DC operating point.

A diode mixer operating at 37 GHz was designed using the Martin Marietta Schottky diode GaAs process. The same macro library was used, but the actual GaAs process was slightly different for the diode process and the PHEMT process. Several mixer variations were fabricated using hybrid branch-line couplers and Lange couplers. The Lange couplers were smaller but have higher loss than the

branch-line couplers. The mixers should be tested in the near future.

Ka-Band Power Amplifier

A power amplifier was needed for a small, low-cost USAT. A 0.25-W amplifier at 30 GHz was designed using MMIC's. A first iteration employed the Westinghouse process for GaAs HEMT's. About 200 to 250 mW of output power was expected at 30 GHz with about 20 dB of gain in the three-stage amplifier. An alternative design used the Martin Marietta PHEMT GaAs process; for this design, several PHEMT's were measured, and a nonlinear model was extracted using a probe station, network analyzer, and Hewlett Packard IC-CAP software. Since the gain of the transistors was higher in the Martin Marietta process, only two stages were required to achieve about 20 dB of small signal gain. Wilkinson couplers were used as power dividers/combiners so that maximum gain with good matching could be obtained in the final stage. As in the previous Westinghouse design, four PHEMT's were combined in the output stage to achieve 200 to 250 mW of power at 29 to 33 GHz. The layout and simulations of the Martin Marietta power amplifier, currently in fabrication, are shown in Figure 8.

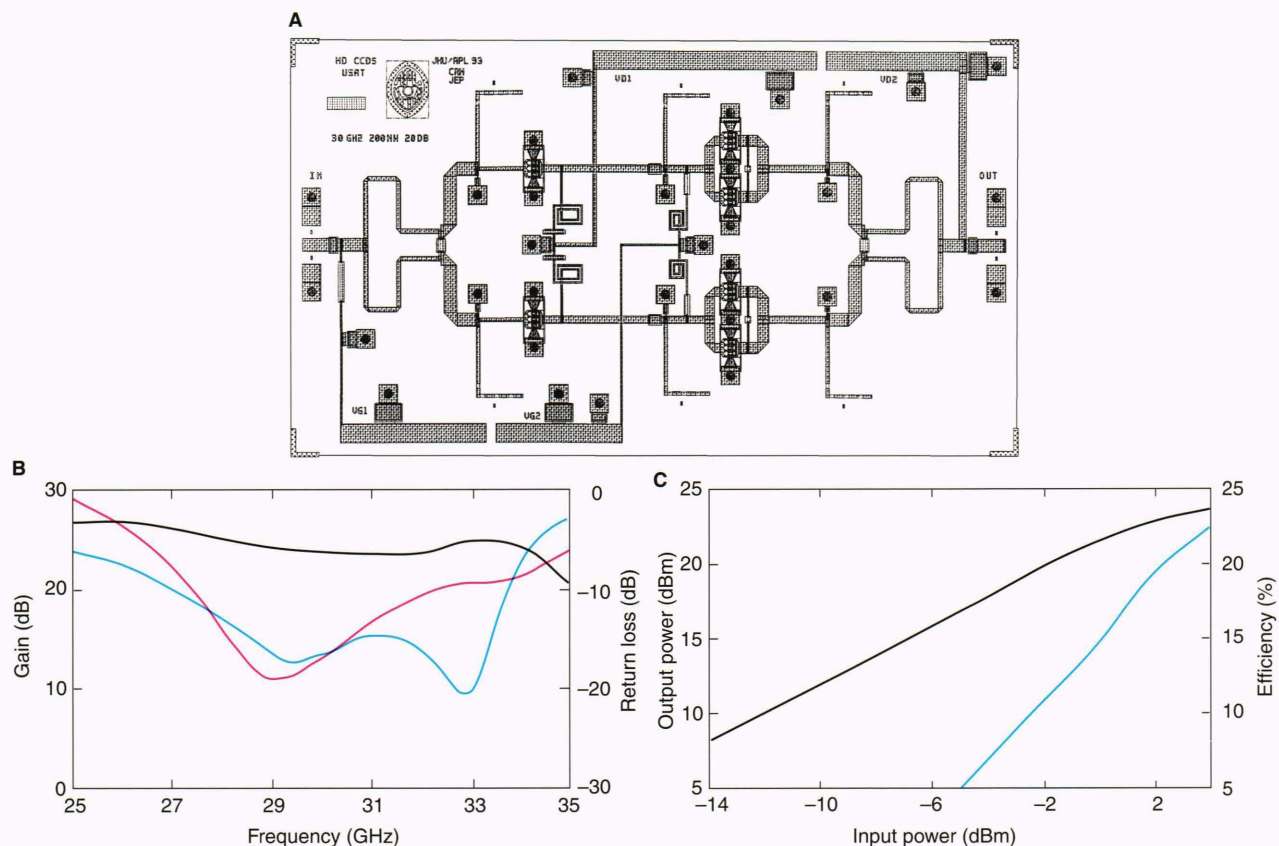
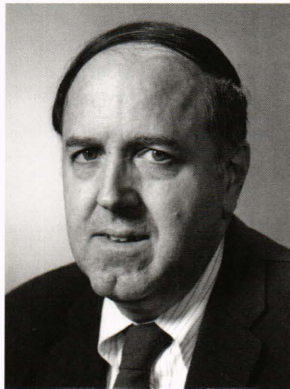


Figure 8. A. Layout of a 30-GHz amplifier. B. Simulated small-signal S-parameters of a 30-GHz amplifier. Gain (black), output return loss (blue), and input return loss (red). C. Output power (black) and efficiency (blue) versus input power of a 30-GHz amplifier.

CONCLUSION

The Laboratory has significantly advanced MMIC design, testing, and modeling during the past few years. Future work will continue to push higher frequencies of operation that will challenge both the design and testing of MMIC's. The goal is to build on previous work by compiling a computer library of component designs that can be used at the system-design level.

THE AUTHORS



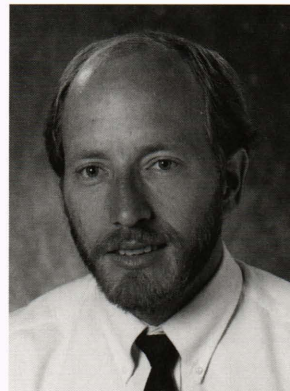
CRAIG R. MOORE is a member of APL's Principal Staff. He received B.E.E. and M.S. degrees from Cornell University in 1962 and 1964. He previously served as associate division head at the National Radio Astronomy Observatory, principal research associate for the Australian government, and group manager at Bendix Field Engineering Corporation, before joining APL in 1987. His work at the Laboratory has involved improvements to the hydrogen maser, work on ultra-high-Q cryogenic microwave resonators, and MMIC design and testing. He is currently

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