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MICROWAVE INTEGRATED CIRCUITS FOR SPACE APPLICATIONS

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Monolithic microwave integrated circuits (MMICs), which incorporate all the elements of a microwave circuit on a single semiconductor substrate, offer the potential for drastic reductions in circuit weight and volume and increased reliability, all of which make many new concepts in electronic circuitry for space applications feasible, including phased array antennas.

Over the last ten years, NASA has undertaken an extensive program aimed at development of MMICs for space applications. The first such circuits targeted for development were an extension of work begun earlier in hybrid (discrete component) technology in support of the Advanced Communication Technology Satellite (ACTS). As a result it focused on power amplifiers, receivers and switches at ACTS frequencies. More recent work, however, has focused on frequencies appropriate for other NASA programs and emphasizes advanced materials in an effort to enhance efficiency, power handling capability, and frequency of operation or noise figure to meet the requirements of space systems.

MONOLITHIC MESFET CIRCUITS

Background

This work has been carried out under contract with Texas Instruments, Rockwell, and Minneapolis Honeywell and Hughes. It is aimed at ACTS-like applications, namely, communications satellites which feature multiple, electronically steerable beams. Such a system would ideally be implemented using phased array antennas with lightweight, low volume distributed transmitters and receivers and lightweight monolithic phase shifters rather than the extensive network of ferrite phase shifters and switches used by ACTS. The initial stages of development therefore were aimed at the development of the monolithic circuitry required for such a system. Carried out between approximately 1983 and 1987 and featuring transmitter frequencies of 20 GHz and receiver frequencies of 30 GHz, as required for the satellite portion of the system, the program utilized as a basic device the GaAs metal/semiconductor field effect transistor (MESFET). The program produced a number of developments, each of which consisted of one or more monolithic chips. Some of these are described here.

Ku-Band Amplifier

The space station proximity communications system is intended to provide communications within a radius of several 10's of kilometers of the space station. Users would include free flying experimental platforms, the orbital maneuvering vehicle (OMV), and astronauts in EVA. The original planning for this system utilized frequencies in Ku-band. It is not clear at this time whether that assignment will be maintained, inasmuch as there exists possible interference with commercial, fixed satellite services. Nevertheless, several chips have been developed at 13-15 GHz to accommodate this application. The most challenging of these was a variable power amplifier intended primarily for use by astronauts during EVA. The system design requires approximately 1 watt of output power. Power variability is necessary because of the wide variation in range experienced by the astronaut. Of course, high efficiency is also a prime consideration. The development of the chip was undertaken by Texas Instruments in January 1987. Their design is a four stage monolithic circuit using dual gate GaAs MESFET technology. The chip is shown in Figure 1.

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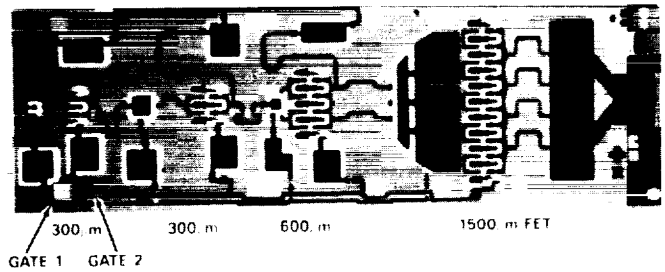

FIGURE 1. 15 GHz MONOLITHIC VARIABLE POWER AMPLIFIER

The performance of the amplifier, compared to the design goals, is shown in Table 1.

TABLE 1.
15 GHz HIGH EFFICIENCY VARIABLE POWER AMPLIFIER

	DESIGN GOAL	PERFORMANCE
CENTER FREQ./BANDWIDTH (GHz)	2.0/14.0	2.0/17.0
GAIN (dB)	15.0	29.6
MAX POWER OUTPUT (W)	1.0	.92
EFFICIENCY AT MAX POWER (%)	35	30
FINAL STAGE GATE WIDTH (MM)	---	1.5

20 GHz Variable Power Amplifier

Since, ideally, a phased-array antenna should be able to vary the phase and the amplitude of each antenna element independently, one desirable module for such a system would be a variable power amplifier. Because of the stringent limitations on power consumption imposed by a space system, it is desirable to maintain insofar as possible the efficiency of a power amplifier while adjusting output power. For this reason, the contractor (Texas Instruments) chose a dual gate FET as the basic device for design of this chip, and adjusted the device bias to obtain variable output. The topology of the amplifier closely resembles the Ku-band amplifier illustrated earlier. This was one of the earliest MMICs developed under the NASA program. A summary of its performance compared to design goals is shown in Table 2.

TABLE 2
TEXAS INSTRUMENTS 20 GHz VARIABLE POWER AMPLIFIER

	DESIGN GOAL	PERFORMANCE
BANDWIDTH (GHz)	2.5	2.5
MAX POWER OUTPUT (W)	0.5	0.25
EFFICIENCY AT MAX OUTPUT (%)	15	< 10
GAIN (dB)	20	20
4TH STAGE GATE WIDTH (MM)	----	1.2

High Power 20 GHz Amplifier

A second 20 GHz chip focussed entirely on the production of the maximum possible 20 GHz power in a monolithic chip. Once more the contractor was Texas Instruments. This effort resulted in a three stage amplifier using single gate FETs. In order to achieve the desired power output, each stage features multiple parallel gates (as many as 32 for the output stage). The chip performance is summarized in Table 3.

TABLE 3.
TEXAS INSTRUMENTS 20 GHZ HIGH POWER AMPLIFIER

	DESIGN GOAL	PERFORMANCE
BANDWIDTH	2.5	2.5
MAX POWER OUTPUT (W)	2.5	> 2.0
EFFICIENCY AT MAX POWER (%)	20	16
GAIN (dB)	15	18
LAST STAGE GATE WIDTH (MM)	----	3.6

20 GHz Integrated Transmitter Module

Ultimately, one desires to incorporate all the elements of a transmitter module (phase shifter, variable power amplifier, and power amplifier) on a single chip. The advantages of such high level integration include: improved reliability, compactness, potential performance enhancements, and reduced cost. Such a project was pursued under contract with Rockwell. The chip produced a 21 dBm output power with 15 dB gain. A picture of the module developed under this effort is shown in Figure 2.

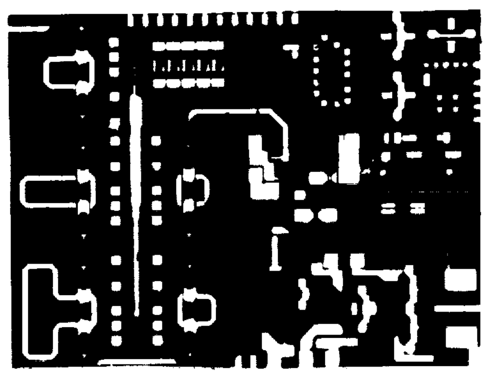

FIGURE 2. ROCKWELL 20 GHz TRANSMIT MODULE

30 GHz Integrated Receiver

Active phased arrays have been proposed for a number of NASA applications, including: array feeds for deep space communications, multiple-beam satellite communications, hemispherical coverage multiple access communications for Space Station Freedom, orbital debris tracking for Space Station Freedom, and adaptive arrays for distorted reflector compensation. To enable the practical implementation of scanning arrays, the complexities of device and antenna integration must be solved. As a preliminary step, prototype 30 GHz receiver modules were developed by Hughes and Honeywell. Honeywell developed an interconnected MMIC receiver for which all functions were performed at the RF frequency. The device consisted of a two-stage 0.25 by 100 micron gate FET low noise amplifier (LNA), a two-stage dual-gate gain control amplifier, and a four bit switched-line/loaded-line phase shifter. The receiver produced a noise figure of 14 dB at maximum gain (13 dB) and achieved full 360 degree phase coverage in nominally 11.25 degree increments. Ultimately, the LNA would require six stages of amplification, which would reduce the noise figure, in principle, to about 5 dB. Hughes was directed to implement phase shift control at the LO frequency and gain control at the IF. The advantage of this approach is that the array beam forming network can be implemented at lower frequencies, albeit the benefit could be offset by the need for a mixer at each antenna element. In fact, the mixer was perhaps the most troublesome component in both designs, providing a best case conversion loss of 8 dB.

HIGH PERFORMANCE MONOLITHIC CIRCUITS

Background

It is clear that all of the GaAs MESFET-based modules, although they constituted benchmark achievements at these frequencies, suffered from many of the same problems as the earlier hybrid implementations of solid state technology. For the power devices, their efficiencies make their use marginal for space applications, except in very limited numbers, such as would be required if they were used as a driver for a higher efficiency final stage. An attempt to use multiple chips with any kind of combining would lead to prohibitively large prime power requirements. For receiver modules, the noise figures obtained using MESFET technology are not competitive with that which can be attained using discrete devices and custom-tuned circuits. However, recent advances in semiconductor materials, enabled by the development of molecular beam epitaxy (MBE) techniques, have drastically improved the performance which basic devices can achieve. Typically, power-added efficiencies near 50% can be obtained for a single device at frequencies near 30 GHz. While device noise figures less than 1 dB are possible at 60 GHz.

At the present time NASA Lewis is sponsoring the development of monolithic chips based on heterojunction devices. Two of these at 32 GHz are for possible use in the space (transmitter) portion of the deep space communications network. The third and fourth at 60 GHz are intended for application to intersatellite communications, such as might be required by Advanced TDRSS or lunar/Mars exploration. A fifth chip will operate at 95 GHz, with potential applications in interplanetary communications, or in earth-observation systems.

<u>32 GHz Amplifiers</u>

In another application the NASA deep space communications network is considering a conversion to Ku-band. The primary motivation for such a change is the significant increase in antenna gain (for a fixed aperture size) and the corresponding decrease in power requirements (for a fixed data rate). Increased antenna gain, however, implies smaller beams and therefore more stringent pointing requirements. Such a situation, of course, is ideal for implementation of an electronically steerable phased array, which does not disturb other critically-pointed spacecraft instruments (experiments or sensors) in the way a mechanically steered antenna would. To support breadboard evaluations of such a system, 32 GHz power amplifier modules are under development. The contractors executing these efforts are Texas Instruments and Hughes Aircraft. The TI work has been under way since May, 1985, and is near completion, while the Hughes effort was initiated in June 1988.

TI proposed and originally designed amplifiers using GaAs MESFET technology, but was directed, after approximately 18 months work, to concentrate on heterojunction devices. Specifically, they have investigated AlGaAs/GaAs HEMT structures and pseudomorphic InGaAs/GaAs structures. At this point it is clear that the pseudomorphic technology outperforms both the AlGaAs HEMT and the GaAs MESFET technology by a significant margin at 32 GHz. The specific pseudomorphic structure which TI has adopted is shown in Figure 3.

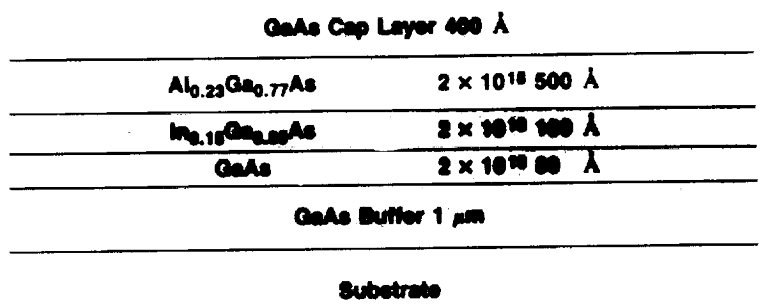

FIGURE 3. TEXAS INSTRUMENTS' PSEUDOMORPHIC POWER AMPLIFIER STRUCTURE

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The performance parameters for two of the pseudomorphic chips developed under this program are shown in Table 5.

TABLE 5.
TEXAS INSTRUMENTS 32 GHz MONOLITHIC POWER AMPLIFIER PERFORMANCE

	3-STAGE AMP	1-STAGE AMP
BANDWIDTH (GHz)	2.0	2.0
GAIN (dB)	23	4.6
GATE LENGTH (uM)	0.25	0.25
FINAL STAGE GATE WIDTH (MM)	.25	.25
POWER OUTPUT (mW)	190	460
EFFICIENCY (%)	30	24

The layout of the three-stage 2.6 mm by 1.2 mm MMIC amplifier is shown in figure 4.

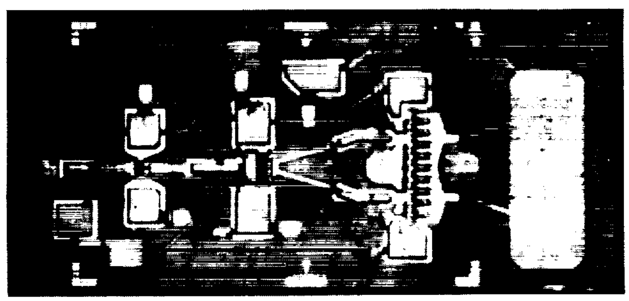

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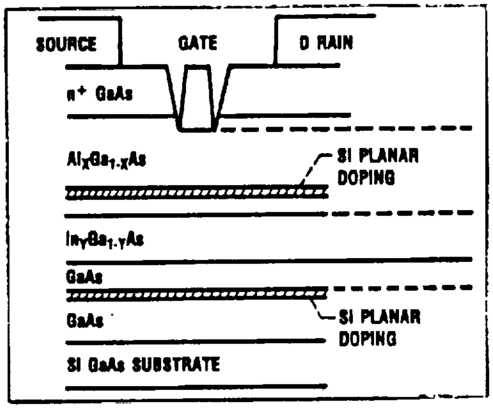
FIGURE 4. TI's 3-STAGE MONOLITHIC 32 GHz AMPLIFIER

In a parallel 32 GHz effort Hughes Aircraft Corporation's Microwave Products Division and Malibu Research Laboratories are collaborating on the development of a 32 GHz variable power amplifier. The design goals for this chip are shown in Table 6.

TABLE 6.
DESIGN GOALS FOR HUGHES 32 GHz VARIABLE POWER AMPLIFIER

BANDWIDTH (GHz)	2.0
MAX POWER OUTPUT (mW)	150
EFFICIENCY AT MAX POWER(%)	40
GAIN AT 1 DB COMP.(dB)	15.0

The Hughes contract, like most such developments at this time is to be carried out in several phases. These will consist of (1) the optimization of a single gate device design; (2) the development of a single stage amplifier; (3) the development of a dual gate device; (4) the design, fabrication, and test of a three-stage, single gate amplifier; and finally, (5) a three-stage dual gate amplifier. In the 16 months that the Hughes team has been under contract, they have carried out the first two phases. The epitaxy which they have selected for the basic device is similar to that utilized by TI, except that Hughes has elected not to dope the active layer. It does, however, utilize a single active InGaAs layer with donors on each side. The structure and performance parameters for the basic 32 GHz device are shown in Figure 5.



FREQUENCY	32.0
GAIN*	4(5) dB
POWER OUTPUT*	222(123)mW
EFFICIENCY*	23(41)%
GATE WIDTH	300 uM
GATE LENGTH	0.2 uM

*tuned for max power(eff)

FIGURE 5. STRUCTURE AND PERFORMANCE OF HUGHES 32 GHz POWER MODFET

This device has been incorporated into a single stage amplifier which exhibited an output power of 125 mW at 21% efficiency with 5.5 dB gain. This amplifier is intended as the third stage of the final monolithic module. These results represent the first iteration of this chip, and significant improvement is expected before the program ends.

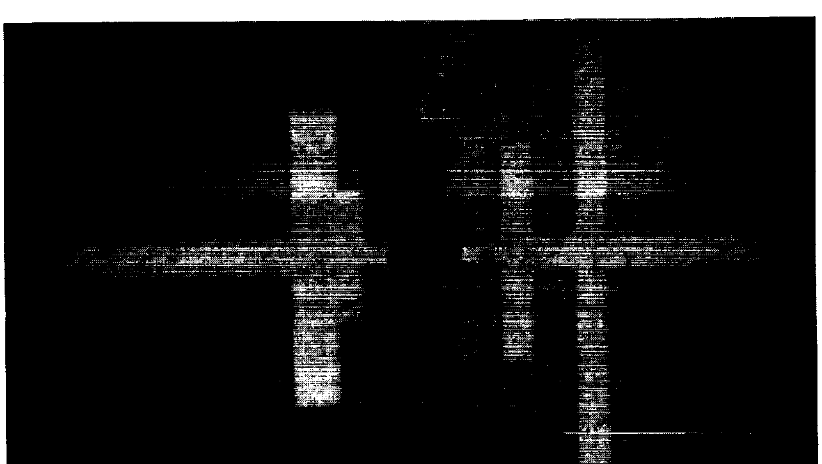
60 GHz Amplifiers

In addition, under the same contract, Hughes is developing a 60 GHz monolithic power amplifier. The justification for this program is eventual application in intersatellite links. Although NASA's plans for the Advanced Tracking and Data Relay Satellite (ATDRS) do not presently call for 60 GHz crosslinks, it seems likely that if such technology were available it would eventually find application in that area. The performance goals for the program, are shown below in Table 7.

TABLE 7.
Performance Goals for Hughes' Pseudomorphic 60 GHz

	Power Amplifier
BANDWIDTH (GHz)	2.0
MAX POWER OUTPUT (W)	0.1
GAIN (dB)	15
EFFICIENCY (%)	30.0

At 60 GHz Hughes is using the same basic pseudomorphic device structure as at 32 GHz, although the gate lengths have been shortened somewhat (0.1 to 0.15 uM). The layout and the performance achieved for a single stage amplifier are shown in Figure 6. The chip is approximately 1.5 mm long. As in the 32 GHz module, the amplifier shown is intended as the third (high power) stage of the completed monolithic amplifier.



POWER OUT	112 mW
GAIN	6 dB
EFFICIENCY	26%

FIGURE 6. HUGHES SINGLE STAGE MONOLITHIC 60 GHz AMPLIFIER

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FUTURE ACTIVITIES

Phased Array Development

The 32 GHz power amplifier modules developed by Texas Instruments and described here are scheduled to be incorporated into a breadboard transmitter array antenna which will also utilize phase shifters developed under NASA Lewis sponsorship. This work is being carried out at NASA's Jet Propulsion Laboratory, where a two-dimensional array is expected to be completed late in calendar year 1990.

The Hughes work at both 32 Ghz and 60 Ghz is probably at least a year away from being used even in a breadboard system. Although the contract is scheduled for completion in early 1991, it has yet to address what has been one of the major difficulties in the fabrication of a multistage power amplifier - inadequate large signal device models. It has been a common experience for a designer to develop excellent individual stage amplifiers, which meet all the requirements of the overall power and gain budget, only to find that the multistage module performance falls far short of the program requirements. Consequently, it appears optimistic to expect that Hughes will complete their development by 1991. 1992 would appear to be more realistic. At that time, it is anticipated that a 60 GHz breadboard array will be built, either at JPL or at NASA Lewis. As with the Ku-band array, it will utilize monolithic phase shifters which are being developed in parallel at Hughes.

W-Band Receiver

The most recent MMIC developmental effort is the production of a 94 GHz receiver. Potential applications include deep-space communications, radiometry, and orbital debris tracking radar. Goals of the program include a noise figure of 3.5 dB and a gain of 18 dB. It is anticipated that the ambitious goals of this program will necessitate a technology based on InP, rather than traditional GaAs.

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