A High-Power and High-Efficiency Monolithic Power Amplifier at 28 GHz for LMDS Applications

Mansoor K. Siddiqui, Arvind K. Sharma, *Senior Member, IEEE,* Leonardo G. Callejo, and Richard Lai

***Abstract*— A high-power and high-efficiency monolithic power amplifier operating from 27.5 to 29.5 GHz is presented for local multipoint distribution service. Using 0.15-μm InGaAs/AlGaAs/GaAs pseudomorphic high electron-mobility transistor devices, the two-stage power amplifier on 4-mil GaAs substrate demonstrated greater than 16-dB small-signal gain, 32-dBm (1.6 W) power with 35% power-added efficiency. The amplifier attained peak output power of 33.9 dBm (2.4 W) and peak power-added efficiency of 37%. At the peak power level, the amplifier exhibited power densities in excess of 640 mW/mm, which is the highest output power density attained by Ka-band monolithic power amplifiers. At lower drain voltage, the amplifier attained 43% power-added efficiency with 30-dBm output power.**

***Index Terms*— Millimeter-wave transmitters, MMIC power amplifiers, MMIC transmitters.**

I. Introduction

WITH THE emergence of local multipoint communication service (LMDS), there is now considerable activity in Ka-band. In order to provide communication services such as television, video-on-demand, distance learning, Internet access, interactive games, as well as a host of other services to homes, various system architectures are being implemented.

In a typical analog FM system operating in 27.5–29.5 GHz, 20-MHz-wide FM channels are used to broadcast video. A LMDS system in a cellular network consisting of low-power transmitters operating in 1-GHz bandwidth, provide transmission to the subscribers, as shown in Fig. 1.[1] Newer digital quaternary phase-shift keying (QPSK) systems use typically 40-MHz channels to provide high-capacity data transfer.

This tremendous need has created considerable interest in the development of Ka-band high-power and high-efficiency amplifiers. Transmit power of 1 W is required for various system implementations.

Solid-state discrete devices in a microwave integrated circuit (MIC) amplifier can be used to achieve the desired power level. The large periphery devices used in high-power amplifiers present very low impedance levels. The variations in assembly fabrication process invariably require extensive assembly, test, and tune operations, which result in modules with high cost. The power monolithic microwave integrated circuits (MMIC's), on the other hand, offer small size, reproducible performance, and high reliability. They are also highly cost effective due to minimum or no tuning requirements in module fabrication process.

For LMDS applications, Siddiqui *et al.* [1] presented a hybrid power amplifier, which produced 8.75-dB small-signal gain, 39.6% power-added efficiency, and 37 dBm (5.0 W) from 27.5 to 29.5 GHz. At this power level, amplifier power density was 780 mW/mm. This is the best power density achieved using high electron-mobility transistors (HEMT's) on a 1.2-mil GaAs substrate.

Recently, Yarborough *et al.* [2] presented performance comparison of 1-W Ka-band MMIC amplifiers realized using pseudomorphic HEMT's (pHEMT's) and ion-implanted MESFET's. The power amplifier using pHEMT's achieved greater than 20-dB gain, 35% power-added efficiency from 26.5 to 28 GHz. It utilized four 600-μm cells, to achieve 1-W power level and exhibited power density of 417 mW/mm. The power amplifier using 0.2-μm MESFET also achieved 1-W power with 18-dB gain and 24% power-added efficiency.

Ingram *et al.* [3] also presented a 6-W power amplifier utilizing monolithic amplifiers on 2-mil GaAs substrate producing 35.4 dBm (3.47 W) output power with 11.5-dB gain and 28% power-added efficiency. The power density of the output devices was 516 mW/mm.

A comparison of various Ka-band power amplifiers in terms of output power density is provided in Table I. It is clearly seen that the power density of 780 mW/mm, presented in [1], is still the best power density achieved by a hybrid MIC amplifier.

In general, it is possible to attain high-efficiency and high-power density with smaller periphery devices. However, the power-amplifier design challenge is to achieve high efficiency at high output power levels. An additional challenge in the design of monolithic power amplifiers is to achieve power densities somewhat closer to that achieved by MIC power amplifiers, which are usually tuned to get the best performance from devices.

With that objective in mind, we designed a power amplifier operating in 27.5–29-GHz band. This power amplifier demonstrated greater than 16-dB small-signal gain, 32-dBm power with 35% power-added efficiency. The amplifier attained peak output power of 33.9 dBm (2.4 W) and peak power-added efficiency of 37%. At peak power level, the amplifier exhibited power densities in excess of 640 mW/mm, which is closer to

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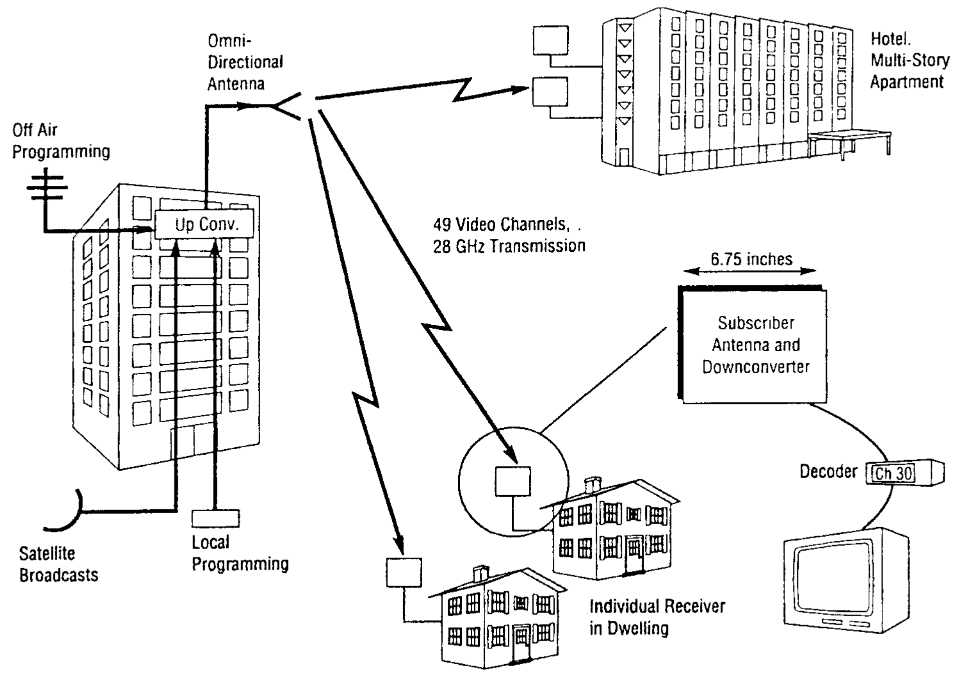


Fig. 1. LMDS system.

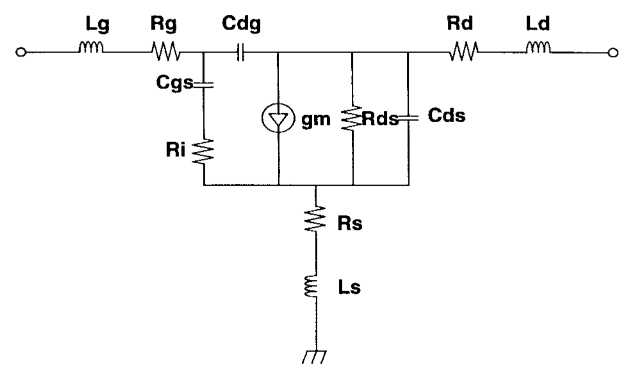
TABLE I
COMPARISON OF Ka-BAND POWER AMPLIFIERS

Frequency Range (GHz)	Output Power dBm (Watts)	Power density (mW/mm)	Reference
18-19	37.2 (5.248)	540	5
27-30	37.0 (5.000)	783	2
27-30	30.0 (1.000)	417	3
27-30	33.9 (2.454)	640	This Paper
34-36	30.0 (1.000)	312	6
34-36	35.4 (3.467)	516	4
34-36	37.8 (6.025)	448	4

the earlier results of 780 mW/mm [1]. This paper will present details of design approach, process, and measured performance of this monolithic power amplifier.

II. DEVICE AND PROCESS TECHNOLOGY

The pseudomorphic InGaAs/AlGaAs/GaAs HEMT devices have been engineered to provide high breakdown voltage and high current densities. They also provide high gain and power-added efficiency at millimeter-wave frequencies. To improve the breakdown voltage, the AlGaAs layer is left undoped and the Schottky gate is recessed to this undoped region. To increase the current density, an additional planar doping is employed, increasing the amount of charge in the two-dimensional electron gas. The device optimization was performed to ensure high aspect ratio, which is defined as the ratio of gate length to the gate-to-channel separation. This enables the device to provide high gain, high efficiency, as well as high cutoff frequency for millimeter-wave operation. Typically, for a 0.15-μm gate-length devices, gate-to-drain



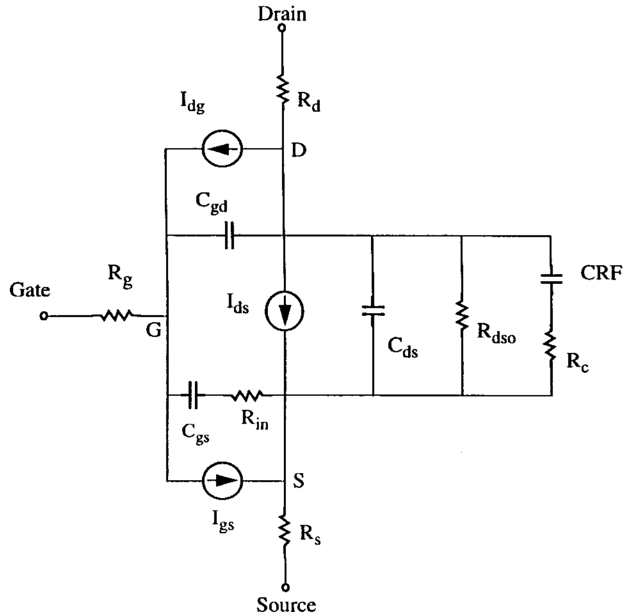
(a)

Parameter Description	Parameter	Units	Parameter Value
Transconductance	Gm	mho	0.078052
Delay	T	ps	1.653155
Gate to Source Capacitance	Cgs	pF	0.175070
Gate to Drain Capacitance	Cdg	pF	0.021008
Drain to Source Capacitance	Cds	pF	0.048216
Drain to Source Resistance	Rds	ohm	273.7828
Channel Resistance	Ri	ohm	2.969488
Gate Contact Resistance	Rg	ohm	0.408305
Drain Contact Resistance	Rd	ohm	0.600000
Source Contact Resistance	Rs	ohm	0.400000
Gate Contact Inductance	Lg	nH	0.014466
Drain Contact Inductance	Ld	nH	0.033161
Source Contact Inductance	Ls	nH	0.001015

(b)

Fig. 2. (a) HEMT linear model. (b) Equivalent-circuit parameters.

voltage of up to 12 V (measured at 0.1 ma/mm), maximum channel current of 500 ma/mm, transconductance of 550 mS/mm, and f_t greater than 75 GHz is obtained. TRW's



(a)

HEMT	GAS	MODEL=2		
A0=0.058410	A1=0.10341	A2=-0.0092479	A3==-0.048684	
BETA=0.021295	GAMMA=2.3457	CGS=0.048216 pF	CGD=0.021008 mho	CDS= 0.048216 pF
RDSO=273.7828 ohm	RIN= ohm	R1=140 ohm	R2=-74 ohm	RF=48.3 ohm
TAU=1.653155 ns	VBI=0.76 volt	VBR=11 volt	VDSO=5.0 volt	VDSDC=5.0 volt
RC=-941 ohm	CRF=10000 pF	VTO=-1.2 volt		

(b)

Fig. 3. (a) Asymmetric Curtice nonlinear model. (b) Device model at 50% gmpeak I_{ds}. Parameter values.

power HEMT process is capable of providing better than 800 mW/mm, as documented in [1].

III. HEMT Device Model

The development of an accurate small- and large-signal model is extremely critical in the design of power amplifiers [6]. Accurate small-signal models were developed using measured S-parameter data. Extensive dc and RF measurements over different bias conditions were made to develop accurate linear and nonlinear device models. S-parameter measurements were performed at 50% and 100% I_{ds}, at peak conductance, at $V_{ds} = 3.0$ and 5.0 V (active conditions), at $V_{ds} = 0$ V and $V_{gs} = -2.0$ and 0.0 V (passive conditions), and $V_{ds} = 0.0$ V with V_{gs} forward biased. A nonlinear model was developed for 0.15 μm $\times$ 200 μm device, which was scaled and used as a cell for the 0.15 μm $\times$ 320 μm and 0.15 μm $\times$ 480 μm. The small-signal model parameters were obtained for all the bias conditions simultaneously using the measured S-parameter data. Fig. 2 presents the linear model and its equivalent-circuit parameter values. A large-signal Curtice asymmetric model, using dc I–V data, is shown in Fig. 3 with the parameter values. Fig. 4 shows the verification between the small-signal S-parameter, measured at $V_{ds} = 5$ V and 50% I_{ds} at peak conductance, and the power-dependent S-parameters obtained from the large-signal model. Using the procedure described by Sharma [7], the load–pull data on Ka-band prematched structures were obtained. Since these structures use transmission lines only, it is easy to deembed these transforming network from the on-wafer measurements to obtain device load–pull impedance information. This procedure is accurate and useful in the verification of the large-signal model.

IV. Power-Amplifier Design

The amplifier uses 0.15 μm $\times$ 320 μm and 0.15 μm $\times$ 480 μm devices as a basic cell for use in in-phase multicell matching. The first stage uses 1.36-mm periphery devices to drive 3.84-mm output stage devices. The amplifier is developed on 4-mil GaAs substrate. The design employed simple transmission-line elements to transform the device optimum load to moderate impedance level. We used a Curtice nonlinear model to design this amplifier. Fig. 5 shows the photograph of the amplifier. The amplifier provides unconditional stability under all load conditions.

V. Power-Amplifier Performance

The amplifiers were initially tested for output power as a function of frequency at a given input power using an on-wafer pulse power test set. The test data show consistent 1-W performance with RF functional yield greater than 70%. Several amplifiers were then assembled in a test fixture and they also achieved consistent performance.

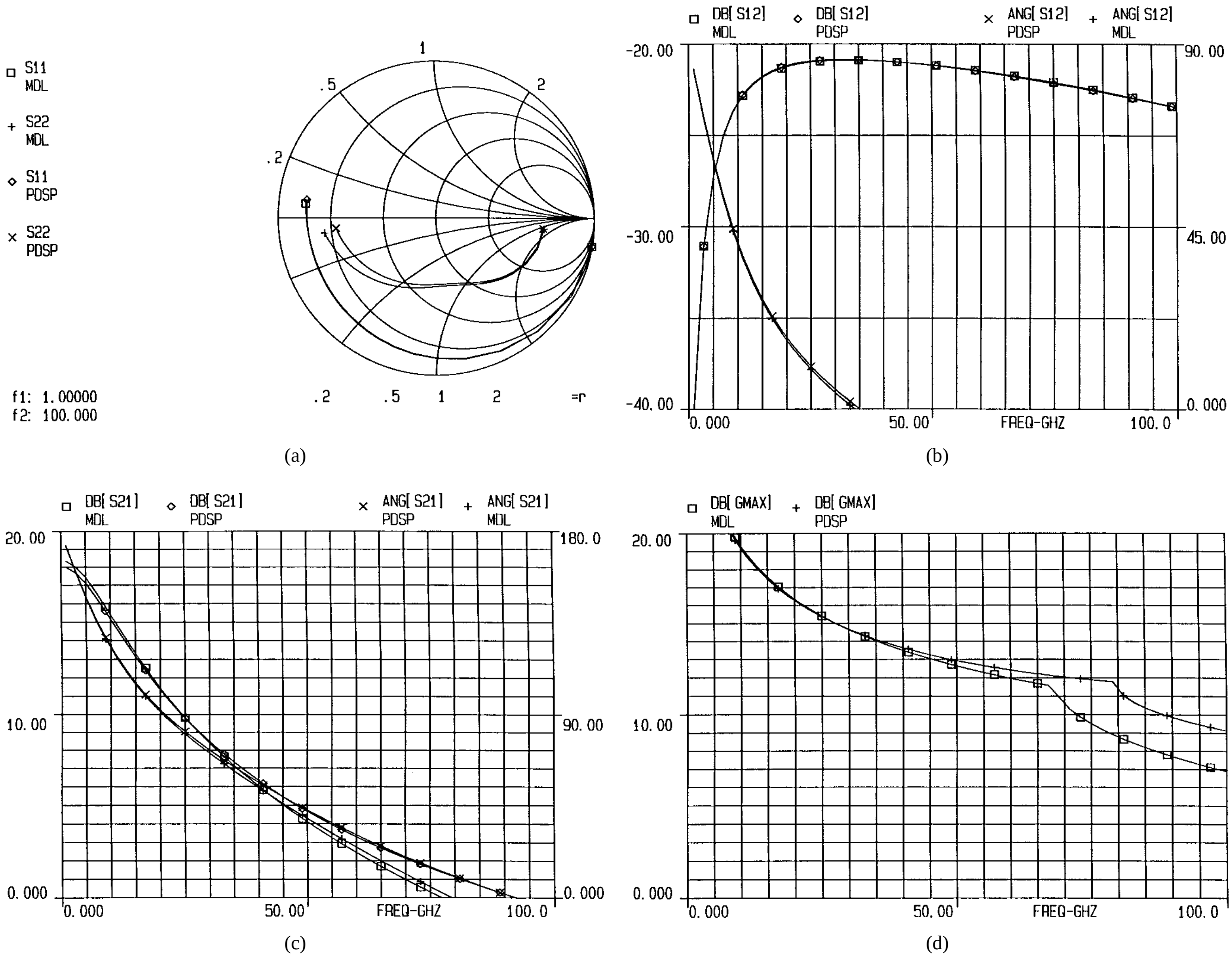


Fig. 4. Comparison between small-signal parameters and power-dependent S-parameters obtained from the large-signal model.

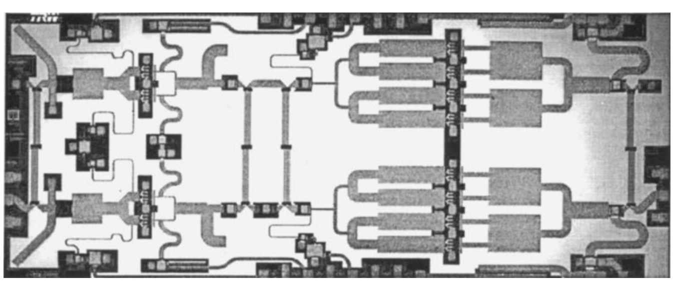


Fig. 5. Photograph of 28-GHz monolithic power amplifier.

The performance of the amplifier is shown in Fig. 6. It shows output power, gain, and power-added-efficiency performances of the amplifier at 27.5 GHz, biased for high-efficiency operation. The small-signal gain is about 19 dB. When the amplifier is about 5 dB in compression, the output power of 33 dBm and 37.2% power-added efficiency is obtained.

Fig. 7(a) shows the same performance parameters at 29 GHz for high-power operation. At 22 dBm of input power, the amplifier was capable of producing 33.59 dBm of output power. The power-added efficiency was 30% and is slightly lower than the high-efficiency operation. Fig. 7(b) shows the gate currents as a function of drive power. It can be seen that both first and second stages show a gradual increase in gate currents. This shows that both the first and second stages are reasonably in compression.

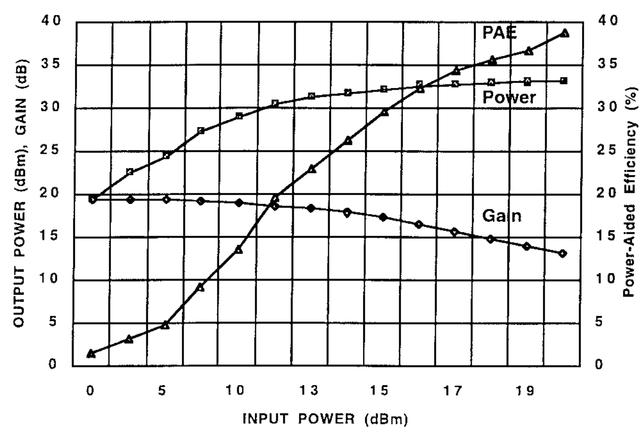
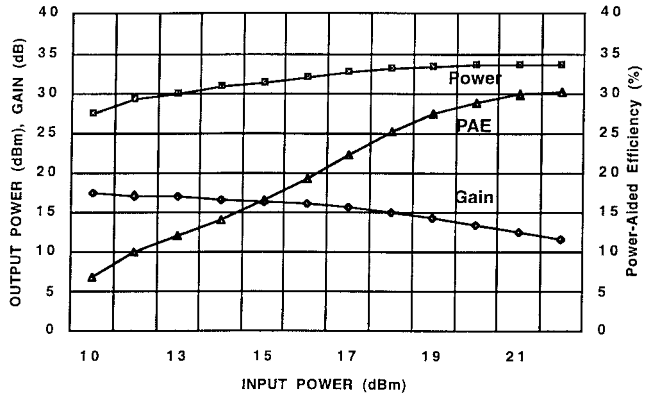
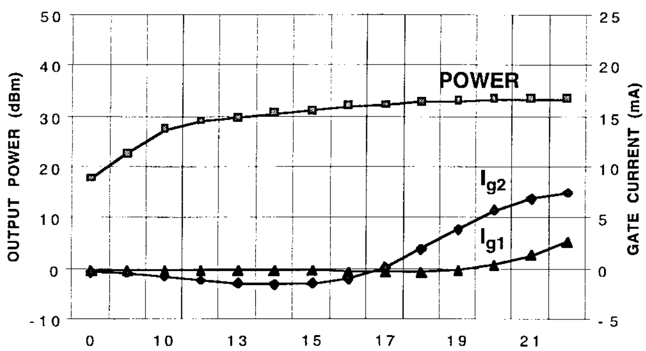


Fig. 6. Measured performance of the amplifier at 27.5 GHz for high-efficiency operation.

A typical power-added efficiency and output power as a function of frequency is shown in Fig. 8. At 21 dBm of input power, the output power variation is less than 0.25 dBm over



(a)



(b)

Fig. 7. (a) Measured performance of the amplifier at 29 GHz for high-power operation. (b) Gate current as a function of input drive power.

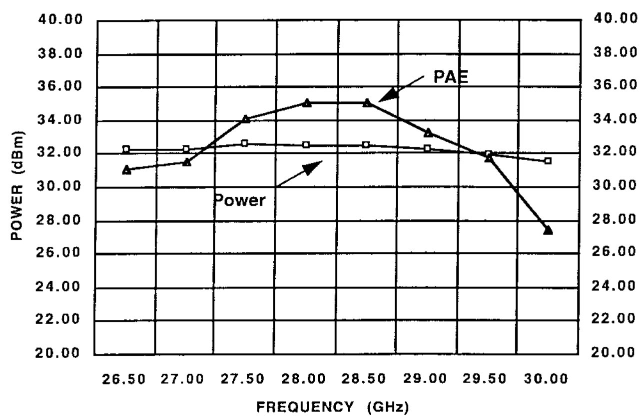


Fig. 8. Measured output power and power-added efficiency of the amplifier as a function of frequency. Input power = 21 dBm.

26.5–29.5 GHz. Fig. 9 shows maximum output power that can be achieved at an input power level of 22 dBm. The output power density of the output devices ranges from 570 mW/mm at band edges to 700 mW/mm at 29.5 GHz.

It is interesting to observe the behavior of this power amplifier as a function of drain voltage, as shown in Fig. 10. The output power and gain are plotted as a function of input power for various drain voltages. At lower drain voltage, the gain and output power is lower. As the drain voltage is increased, both the gain and output power increases. As shown in Fig. 11, the power-added efficiency, on the other hand, is best at lower drain voltage, and a peak value of 43% was

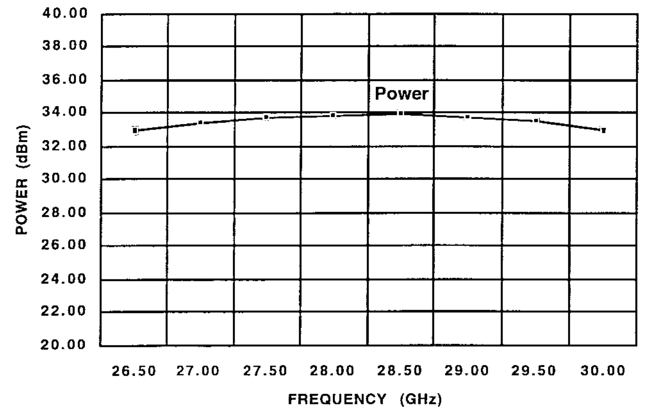


Fig. 9. Measured output power as a function of frequency. Input power = 22 dBm.

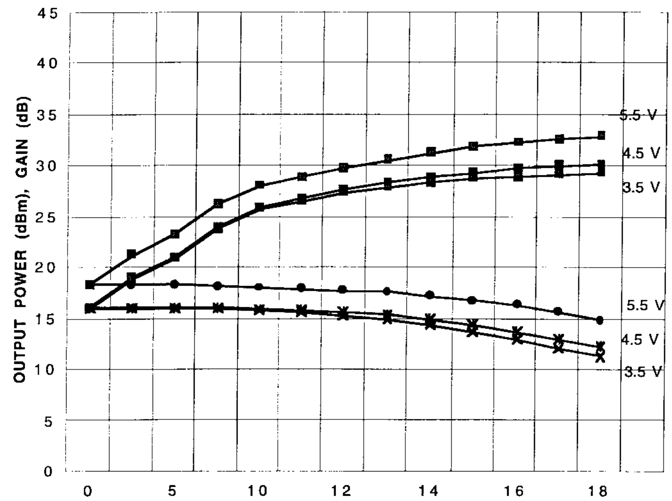


Fig. 10. Output power and gain as a function of input power for various drain bias voltages.

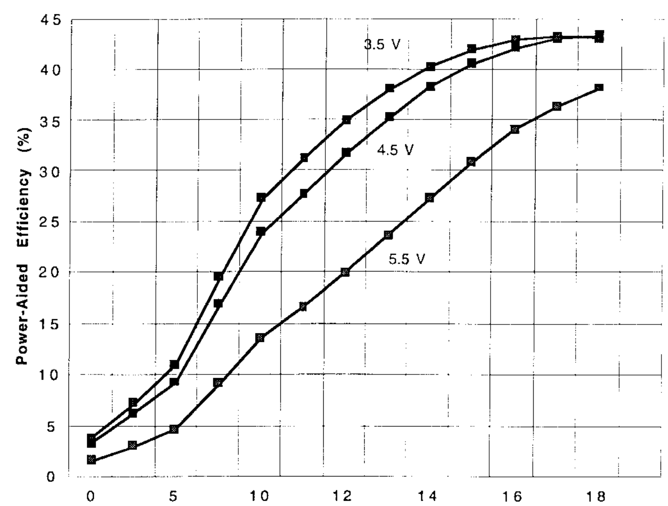


Fig. 11. Power-added efficiency as a function of input power for various drain bias voltages.

achieved. The power-added efficiency degrades as the output power and drain bias is increased. This demonstrates that the amplifier output power and efficiency can be adjusted to some extent to achieve desired system performance. It is important

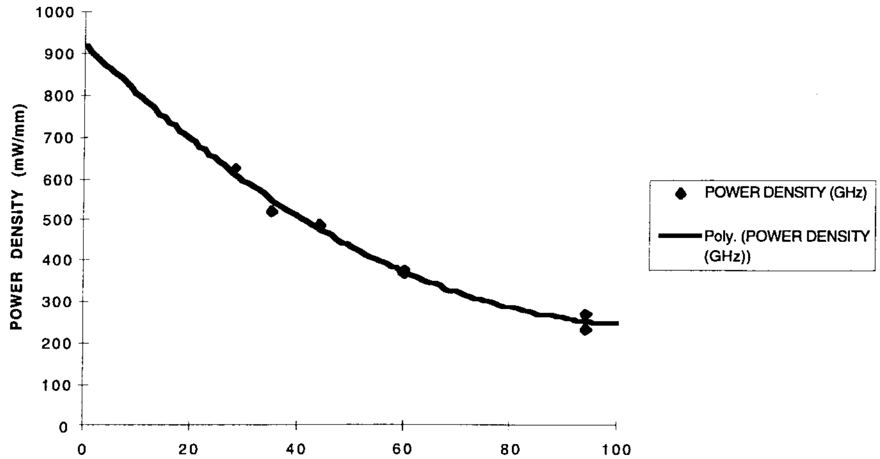


Fig. 12. Power density as a function of frequency for various millimeter-wave power amplifiers processed at TRW.

to note that the power amplifier was designed to operate in a saturated mode with the drain bias voltage between 5.0–6.0 V.

To our knowledge, this is the first time that the performance of a monolithic power amplifier, in terms of power density, is close to that achieved by hybrid MIC amplifiers and is approaching that of HEMT devices. The results are consistent since our 2- and 4-mil GaAs MMIC's and 1.2-mil GaAs discrete devices use the same process and device structure. In order to document this, the output power density as a function of frequency is plotted in Fig. 12 for various millimeter-wave monolithic power amplifiers developed at TRW using the same process. Published results at 28 GHz (this paper), 35 [9], 44 [10], [11], 60 [6], [12], and 94 GHz [13], [14] were used to determine the power densities. Also shown is a polynomial curve-fitted line to understand the trend on achievable power densities at different frequencies.

VI. Conclusion

In this paper, we have presented a high-power and high-efficiency monolithic power amplifier operating from 27.5 to 29.5 GHz for LMDS. The amplifier demonstrated greater than 16-dB small-signal gain, 32-dBm (1.6 W) power with 35% power-added efficiency. It also attained peak output power of 33.9 dBm (2.4 W) and peak power-added efficiency of 37%. At the peak power level, the amplifier exhibited power densities in excess of 640 mW/mm, which is the highest output power density attained by Ka-band monolithic power amplifiers. At lower operating voltage, this amplifier attained 43% power-added efficiency with 30-dBm output power. The results of this paper as well as the other published results on monolithic power amplifiers on 2- and 4-mil substrates using TRW's 0.15-μm InGaAs/AlGaAs/GaAs pHEMT process are documented to benchmark and demonstrate process and circuit design capability at these frequencies.

Acknowledgment

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Richard Lai was born in Evanston, IL, in 1964. He received the B.S.E.E. degree from the University of Illinois at Urbana-Champaign in 1986, and the M.S.E.E. and Ph.D. degrees from the University of Michigan at Ann Arbor, in 1988 and 1991, respectively.

In 1991, he joined TRW's Advanced Microelectronics Laboratory, Redondo Beach, CA, as a Product Engineer, where he is involved in the research, development, and production of advanced GaAs-based and InP-based HEMT device and MMIC technologies into various military and commercial millimeter-wave (MMW) applications. Since 1994, he has become the Principal Investigator for an advanced HEMT research and development project at TRW, and is currently the Product Engineering Manager for HEMT MMIC products. He has authored or co-authored over 60 papers and conference presentations in the area of advanced GaAs and InP-based device and circuit technology.