Broadband Characterization of a 100 to 180 GHz Amplifier

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Abstract— Atmospheric science and weather forecasting require measurements of the temperature and humidity vs. altitude. These sounding measurements are obtained at frequencies close to the resonance frequencies of oxygen (118 GHz) and water (183 GHz) molecules. We have characterized a broadband amplifier that will increase the sensitivity of sounding and other instruments at these frequencies. This study demonstrated for the first time continuous low noise amplification from 100 to 180 GHz. The measured InP monolithic millimeter-wave integrated circuit (MMIC) amplifier had more than 18 dB of gain from 100 to 180 GHz and 15 dB of gain up to 220 GHz. This is the widest bandwidth low noise amplifier result at these frequencies to date. The circuit was fabricated in Northrop Grumman Corporation 35 nm InP high electron mobility transistor (HEMT) process.

Index Terms — high electron mobility transistors (HEMTs), indium phosphide, millimeter wave field-effect transistor (FET) amplifiers, monolithic millimeter wave integ low noise amplifier, MMIC.

TABLE OF CONTENTS

1. INTRODUCTION 1
2. MILLIMETER WAVE INSTRUMENTS 1
3. LNA TECHNOLOGY 3
4. ON-WAFER MEASUREMENTS 75-220 GHZ 3
5. CONCLUSIONS 5
REFERENCES 5
BIOGRAPHY 6

1. INTRODUCTION

The atmospheric sciences and weather forecasting have received significant attention in recent years due to hurricanes and predicted global climate change. These fields of research require continuous measurements that are obtained from both airplanes and satellites. The repeat rate of the full synthesized image is strongly dependent on the sensitivity of the instrumentation for the measurements. For this purpose we have characterized a recently developed InP LNA MMIC over a broad frequency range. Additionally, the InP LNA MMIC enables highly sensitive instruments for several other applications.

The MMIC characterization involved on-chip measurements at several waveguide bands from 75 GHz to 220 GHz. At these frequencies the measurement probes are only available with waveguide connections. We measured more than 80 GHz of bandwidth from 100 to 180 GHz from these LNAs. Several amplifiers at 100 to 200 GHz frequency range were reported previously [1]-[3], however, their usable operating frequency range was limited to 10 to 20 %. We demonstrate 60 % of operating frequency range. This is the widest bandwidth low noise amplifier result at these frequencies to date.

2. MILLIMETER WAVE INSTRUMENTS

The 100 to 180 GHz frequency range has a number of interesting applications for low noise amplifiers. These vary from remote sensing to astrophysics instrumentation, landing radars and imagers.

A. Geostationary Microwave Sounder

A geostationary microwave sounder is recommended in the NASA decadal survey of Earth science missions. This Precipitation and All-weather Temperature and Humidity (PATH) sensor will have a primary mission of observing hurricanes and severe storms. The Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR) concept developed under the Instrument Incubator Program of ESTO is the only sensor that can meet the PATH mission objectives. The sensor would operate in two spectral bands: near 50 GHz, with 4-6 channels, for temperature sounding and near 183 GHz, with 4-5 channels, for water vapor sounding. That would give the same functionality and capabilities as provided with current and future LEO sounders, such as the AMSU instruments. Table 1

summarizes the data products that can be generated with such a sensor system – this list corresponds to baseline capabilities equivalent to products generated with existing LEO systems (except for temporal and spatial characteristics)[4].

Table 1. Baseline capabilities [4]

BASELINE GEOSTAR DATA PRODUCTS

Parameter	Horiz. (km)	Vertical (km)	Temporal (min)	Accuracy
Tb (50 GHz)	50	N/A	3 per ch	< 1 K
Tb (183 GHz)	25	N/A	5 per ch	< 1 K
Temperature	50	2	~10	2 K
Water vapor	25	3	~20	25%
Liquid water	25	4	~20	40%
TPW	25	N/A	~20	10%
LWC	25	N/A	~20	20%
SST	50	N/A	~10	2 K
Stability index	50	N/A	~20	N/A

In addition, a number of experimental products are under development that will have particular applicability to hurricanes and severe storms. A selected list is shown in Table 2. These observations and derived products will be generated continuously, day and night, with a temporal resolution of 10-20 minutes in the central focus area. The "experimental" products include parameters that can currently only be produced from precipitation radar systems: rain rates, atmospheric ice content, convective intensity, but analysis of microwave sounder data from recent hurricane field campaigns indicate that the radiative effects of scattering from ice in deep convective systems is similar to the backscatter observed by radar – although with a lower vertical resolution.

Table 2. Experimental capabilities [4]

EXPERIMENTAL GEOSTAR DATA PRODUCTS

Parameter	Hor.res (km)	Vertical (km)	Temporal (min)	Accuracy
Rain rate	25	N/A (2)	20	TBD
Convective intensity	25	N/A (2)	20	TBD
IWC	25	N/A (2)	20	TBD
Wind vector	25	2	30	TBD

B. Radiometric Imaging of Tropospheric Temperature and Precipitation

The typical microwave sounding satellites use primarily the 60 GHz oxygen line for temperature sounding, however, there are several advantages to be gained from observations near the 118.75 GHz oxygen line. For fixed aperture dimensions, a diffraction-limited 118 GHz system will yield twice the spatial resolution of a similar 60 GHz system. Additionally the sensitivity to clouds and precipitation at 118 GHz is typically greater than at 60 GHz. This greater sensitivity to hydrometeors enables improved detection of regions of heavy cloud and precipitation relative to that available using 60 GHz frequency window or sounding channels. This feature, along with the higher spatial resolution available from diffraction-limited 118 GHz systems permits relatively weak precipitation cells to be remotely probed, particularly those over land [5].

When the 118 GHz observations are used in conjunction with 60 GHz oxygen channels, the differential hydrometeor sensitivity provides an additional degree of observational freedom related to liquid and frozen water density [5]. The 60 GHz and 118 GHz sounding channels provide more stable, more accurate, and less biased retrievals than window channels at e.g. 150 GHz – in particular, over land surfaces and with regard to snowfall. Average performance estimates show that if sounding channels are used, 80% of all retrievals are within 100% error limits and 60% of them are within 50% error limits with regard to rainfall. For snowfall, the sounding channels produce 60% of all retrievals with errors below 100% for rates smaller than 1 mm h^{-1}, and 50%-80% of the cases have errors below 50% for more intense snowfall. [6].

C. Cosmic Microwave Background Imagers

The cosmic microwave background (CMB), provides a wealth of information about the early universe and its constituents. Polarization of the CMB can trace the gravity wave history of the universe providing a glimpse into the first instants after the Big Bang. The polarization signals of gravity wave origin are expected to be at least 10 times dimmer than any presently detected CMB signal. Arrays of ultra-low-noise detectors are needed to measure these signals.

The CMB is brightest at frequencies 10 - 150 GHz, where amplifier technologies provide state-of-the-art performance. For ground based observations the window channels at 40, 90 and 140 GHz are optimum due to the low atmospheric attenuation at these frequencies. To this date the 40 and 90 GHz channels have been used in several LNA based experiments [7], however, the LNA technology has not been sufficiently low noise at 140 GHz range. Thus, by adding the 140 GHz LNA capability the complete CMB measurement can be carried out using cryogenically cooled (T=20 K) InP MMIC LNAs. This is a great advantage for space based measurements where the power for coolers is always limited.

D Millimeter Wave Imaging Systems

Passive millimeter wave cameras at 140 GHz provide advantages for real time imager of the observed scene. The 140 GHz InP MMIC LNAs make it feasible to build millimeter wave video cameras at the 140 GHz atmospheric transmission window. The 140 GHz would consume less power than 35 and 94 GHz cameras and would have either higher resolution for the same aperture, or the aperture could be 33% smaller (and the camera even smaller by volume) for the same resolution. A key disadvantage of the 140 GHz

camera is the reduced scene contrast due to the warmer sky temperature at 140 GHz, especially under cloudy skies. However, for some missions, in particular that of surveillance from an airborne (airplane or UAV) platform, the improved spatial resolution can offset this lower contrast through the improved beam fill factor resulting from the smaller beam footprint. [8].

E. Landing Radar

Safe, precise landing on planetary bodies requires knowledge of altitude and velocity, and may require active detection and avoidance of hazardous terrain. Radar offers a superior solution to both problems due to its ability to operate at any time of day, through dust and engine plumes, and ability to detect velocity coherently. Future space missions requiring high precision velocimetry must overcome problems of terrain interactions while maintaining a reasonable sensor footprint on the landing vehicle; for that reason G-band (160 GHz) radar velocimeters are advantageous. A G-band radar can achieve extremely high accuracy and precision (sub 10 cm/s) from a reasonable antenna size. Future hazard detection requirements of sub-degree resolution with nearly 30° field of view requirement also point to phase arrays at similar frequencies. [9]

3. LNA TECHNOLOGY

The LNA technology is based on devices with sufficiently high gain at the targeted operating frequency. The 35 nm InP device technology epi wafers were grown by MBE and employed a pseudomorphic $In_{0.75}Ga_{0.25}As$ channel, a silicon delta-doping layer as the electron supply, an $In_{0.52}Al_{0.48}As$ buffer layer and an InP substrate. Room temperature electron mobility over 12000 $cm^2/V.s$ was achieved with a sheet charge of $3.5x10^{12}$ cm-2 Excellent DC characteristic of the HEMTs included a peak Gm of 2000-mS/mm (Fig. 1) and a breakdown voltage over 2.5V. The output conductance is also well controlled by a carefully optimized gate recess etch and epitaxial structure design. The gate was formed with over 85% yield and excellent uniformity [10].

The result of combining the high performance epi profile and aggressive gate is a device with excellent RF characteristics. Shown in Fig 2 are the measured H21 and MAG for a two finger device with periphery of 30-μm. The measurements were taken on an unthinned substrate with the devices in a coplanar configuration. Measurements were taken with an on-wafer extended reference plane calibration with the reference planes of the measurement placed at the device feeds. Extrapolated f_T from the H21 trace is ~450-GHz using 20-dB slope/decade and the extrapolated MAG of the device at 180-GHz is ~10-dB.

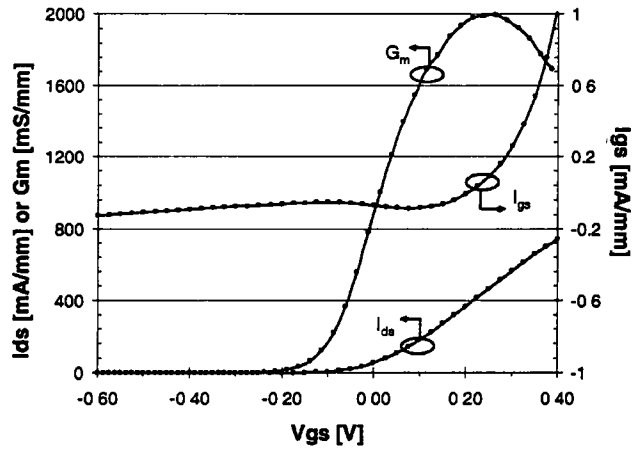

Fig. 1. The measured DC Gm, Ids and Igs for a 40 um InP HEMT device [10]

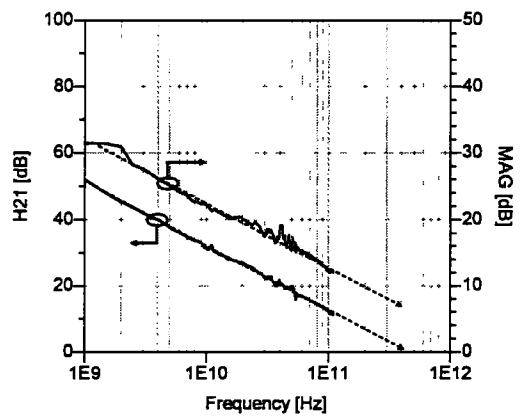

Fig 2 The measured 1 to 110 GHz S-parameters were used to calculate these H21 and MAG values for a 30 μm InP HEMT device at a drain bias of 1 V and Ids of 300 mA/mm [10]

The LNAs were developed based on this device technology with microstrip transmission lines on 2 mil thick substrate [11]. The design incorporated two-finger HEMT devices having gate widths of 15 μm each, for a total gate periphery of 30 μm. The simulated results for the three stage LNA indicate continuous gain from 60 GHz to 200 GHz at higher than 15 dB level and noise figure of 2.5 dB from 100 to 180 GHz. Each microstrip matching network was separately modeled using the ADS Momentum electromagnetic simulation tool.

4. ON-WAFER MEASUREMENTS 75-220 GHZ

Our S-parameter on-wafer measurement capability extends from DC to 340 GHz with dedicated extension modules for each frequency band [11]. These Oleson Microwave Labs (OML) vector network analyzer extension modules have a limited frequency range each, so to characterize a broadband

amplifier several separate measurement need to be carried out. We measured the response of the amplifier with WR-10, WR-08 and WR-05 extension modules that were interfaced to 100-μm, 100-μm and 80-μm pitch wafer probes, correspondingly, from GGB Industries. We used a short-open-load-thru (SOLT) calibration procedure with a standard GGB CS-15 alumina substrate for the two higher frequency ranges and SOLT calibration with GGB CS-05 at the lowest frequency band. The output power of the extender source at the LNA input side was reduced to avoid compressing the LNA. This reduced the available dynamic range at the lower and higher end of the extender frequency range.

The amplifier demonstrated over 18 dB of gain from 100 GHz to 180 GHz as is shown in Fig. 3. Furthermore, there is gain beyond 220 GHz at higher than 15 dB level. This measurement and the three other S-parameter results shown in Fig. 4 to Fig. 6 are composed of the WR-10 (75 to 110 GHz), WR-08 (90 to 140 GHz) and WR-05 (140 to 220 GHz) test results. The input return loss (Fig. 4.) is 4-12 dB, except for a 1.5 to 2 dB value at 105 GHz. The output return loss is 4 dB at 105 GHz, however, beyond that frequency it is better than 12 dB. The LNA has more than 30 dB reverse isolation over the whole frequency range (Fig 6)

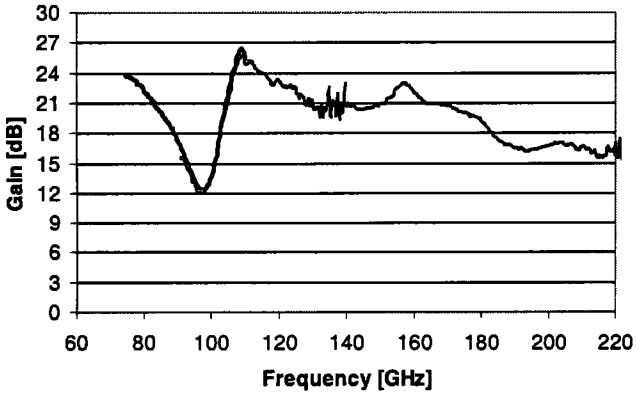

Fig 3 The measured gain of the broadband MMIC LNA at 75 to 220 GHz frequency range

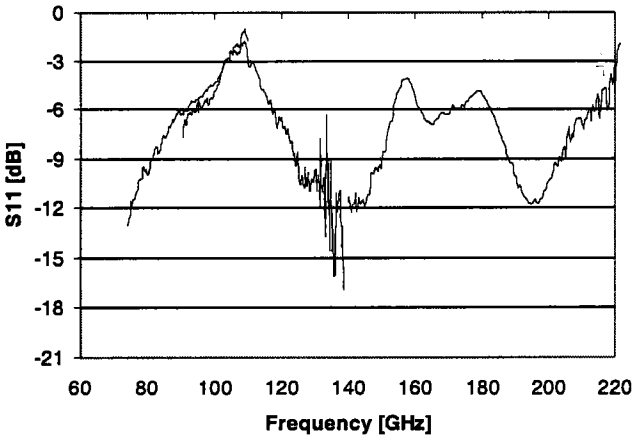

Fig 4. The measured input return loss of the broadband MMIC LNA at 75 to 220 GHz frequency range

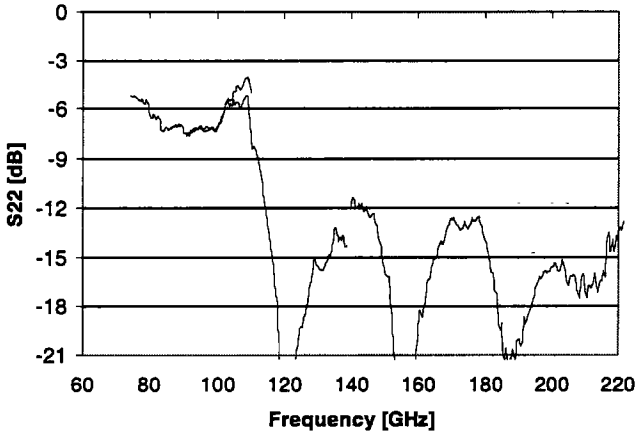

Fig 5 The measured output return loss of the broadband MMIC LNA at 75 to 220 GHz frequency range .

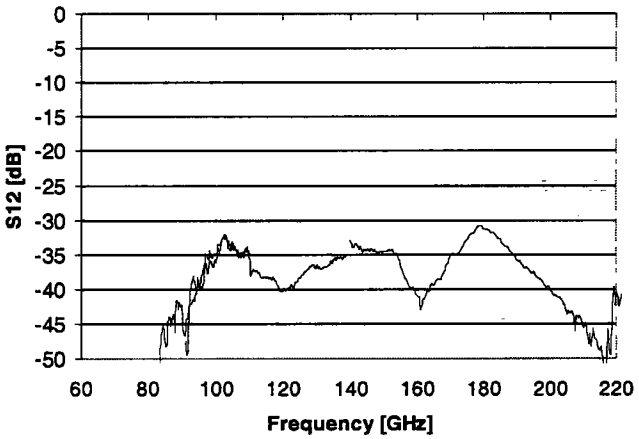

Fig 6 The measured reverse isolation of the broadband MMIC LNA at 75 to 220 GHz frequency range..

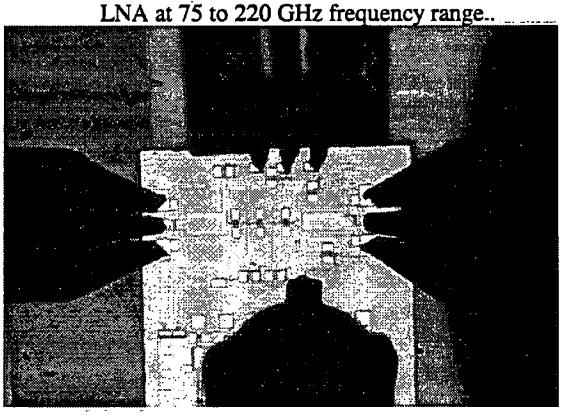

Fig. 7 Photograph of the measurement of the broadband MMIC LNA

These result were obtained with a total drain current of Id = 27 mA for the three stage amplifier. The drain voltage was Vd = 1 0 V. This power consumption of 27 mW was

reduced to 17 mW by reducing the drain voltage to 0.7 V and the drain current to 24 mA. The gain reduced only by 1-2 dB at this low power bias setting. Fig. 7 shows the measurement test set-up with the LNA under measurement. In order to suppress low-frequency (< 1 GHz) gain and potential oscillations which are commonly observed with very high frequency transistors, we had GGB industries mount bypass capacitors right at the tips of the gate DC needles. The first device in the LNA has a separate gate control and the second and third stage devices gates are connected together on the chip. The drains of all three devices are connected together, so for the drain biasing we used a single coaxial probe that has inherently low impedance (50 Ohm).

5. CONCLUSIONS

We have demonstrated the on-wafer characterization of a broadband millimeter wave InP MMIC LNA. For the first time continuous low noise amplification was shown from 100 GHz to 180 GHz. The amplifier had more than 10 dB gain over the whole measurement range from 75 to 220 GHz. Applications of this work include low noise receivers for atmospheric sounding and millimeter wave imaging and radars. Future work will involve on-wafer characterization of its noise figure.

ACKNOWLEDGEMENT

This work was supported by the by the NASA ESTO Advanced Component Technologies ACT-05 program and DARPA SWIFT Program and Army Research Laboratory under the DARPA MIPR no 06-U037 and ARL Contract no. W911QX-06-C-0050.

This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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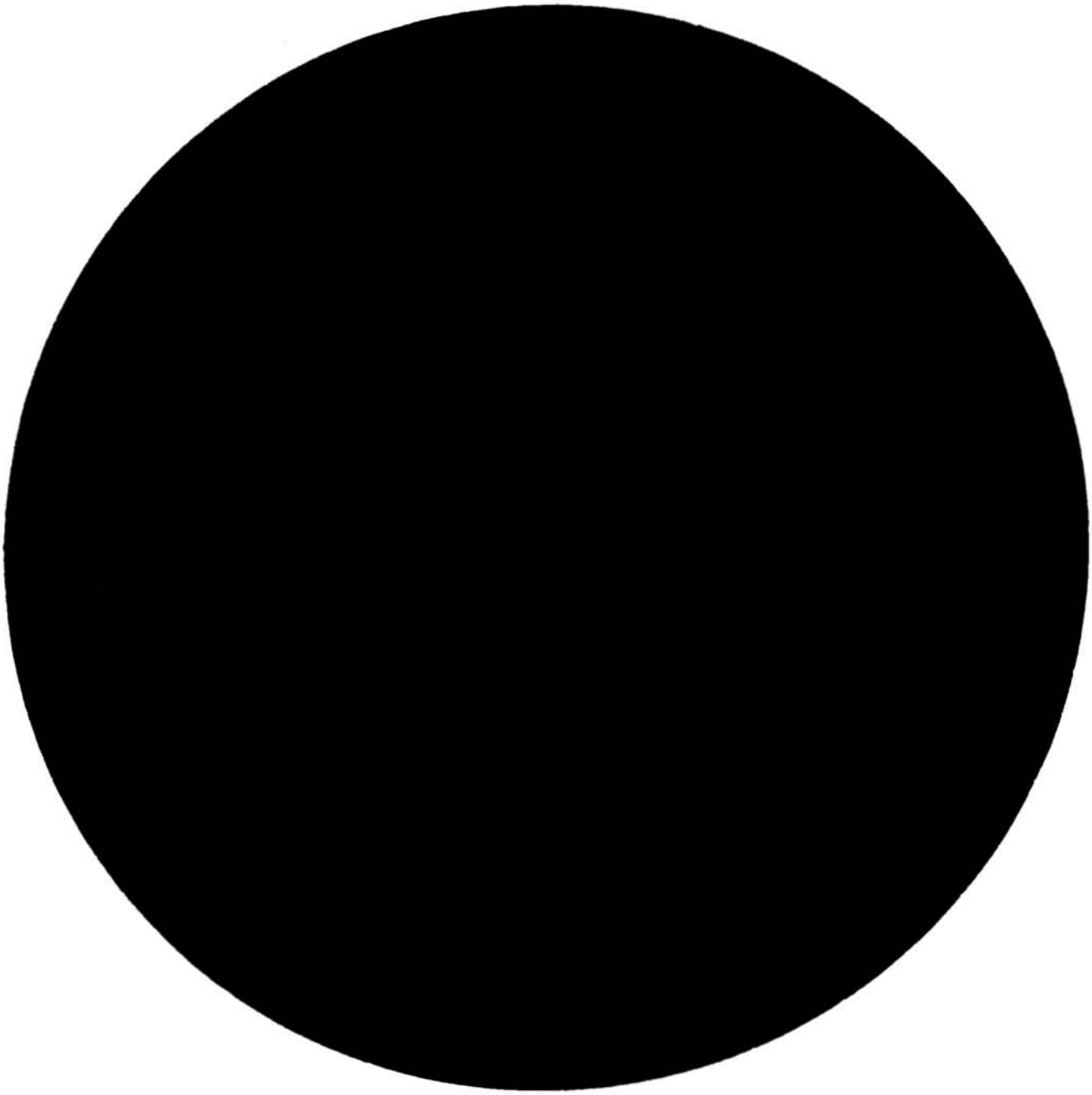
BIOGRAPHY

Pekka Kangaslahti (S'94-M'98) received the M. Sc and Ph.D. degrees from the Helsinki University of Technology, Espoo, Finland, in 1992 and 1999, respectively. He is currently a Senior Engineer with the Microwave Systems Section, Jet Propulsion Laboratory, Pasadena. His current interest is in the development of the millimeter-wave and submillimeter-wave MMICs and modules for large arrays.

William Deal (M'96–SM'06) received the B.S. degree in electrical engineering from the University of Virginia, Charlottesville, in 1996, and the M.S. and Ph.D. degrees from the University of California, Los Angeles, in 1998 and 2000, respectively. Currently, he is a Senior Staff Engineer at Northrop Grumman's RF Product Center in Redondo Beach, CA. He leads several MMIC development efforts, as well as developing his own MMIC designs. Previously, he worked at Lucix Corporation and Malibu Networks. He is developing electronics in GaAs, InP, ABCS, and GaN technologies and has developed the first MMIC amplifiers working at sub-millimeter wave frequencies (> 300 GHz). He has authored and co-authored more than 50 journal and conference papers and four book chapters.

Gerry Mei

Richard Lai (M'85–SM'01) received the Ph.D. degree from the University of Michigan, Ann Arbor, in 1991. He has 20 years of experience in the research, development, and production of advanced GaAs-based and InP-based HEMT device and MMIC RF technologies. Since 1994, he has been the principal investigator for advanced HEMT research and development at Northrop Grumman (formerly TRW). He has authored and co-authored over 150 total papers, patents, and conference presentations in the area of advanced GaAs and InP-based device and circuit technology, establishing world-record performance for the lowest noise amplifiers, highest frequency amplifiers, and highest power amplifiers.

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