Ultra-Low-Noise Indium–Phosphide MMIC Amplifiers for 85–115 GHz

John W. Archer, *Fellow, IEEE*, Richard Lai, *Member, IEEE*, and Russell Gough, *Member, IEEE*

***Abstract*—This paper describes a high-performance indium–phosphide monolithic microwave integrated circuit (MMIC) amplifier, which has been developed for cooled application in ultra-low-noise imaging-array receivers. At 300 K, the four-stage amplifier exhibits more than 15-dB gain and better than 10-dB input and output return loss from 80 to 110 GHz. The room-temperature noise figure is typically 3.2 dB, measured between 90–98 GHz. When cooled to 15 K, the gain increases to more than 18 dB and the noise figure decreases to 0.5 dB. Only one design pass was required to obtain very good agreement between the predicted and measured characteristics of the circuit. The overall amplifier performance is comparable to the best ever reported for MMIC amplifiers in this frequency band.**

***Index Terms*—Indium phosphide, low-noise amplifiers, millimeter-wave amplifiers, MMICs.**

I. Introduction

INDIUM–PHOSPHIDE (InP)-based high electron-mobility transistors (HEMTs) have demonstrated the highest gain, lowest noise figure, and highest frequency capability of any three terminal transistor [1],[2] and are attractive for next-generation satellite communication system, wireless local area network (LAN) and high-frequency remote-sensing applications. This paper describes the design and performance of an 85–115-GHz low-noise amplifier monolithic microwave integrated circuit (MMIC). Only a single design pass was required to achieve performance comparable with the best reported elsewhere [3],[4]. This MMIC was developed for a demonstration millimeter-wave imaging-array receiver with potential application in passive radiometric imaging for commercial remote sensing and radio astronomy. The millimeter-wave MMICs, designed and tested at the Commonwealth Scientific and Industrial Research Organization (CSIRO), Epping, N.S.W., Australia, were fabricated under contract by TRW, Redondo Beach, CA, using a state-of-the-art 0.1-μm InP HEMT process [5]. CSIRO's unique opportunity for early access to this leading-edge InP technology is helping TRW expedite InP's maturity and commercial availability.

Manuscript received February 26, 2001.

J. W. Archer is with Telecommunications and Industrial Physics, Commonwealth Scientific and Industrial Research Organization, Epping, N.S.W. 1710, Australia.

R. Lai is with the Telecommunication Programs Division, TRW, Redondo Beach, CA 90278 USA.

R. Gough is with the Australia Telescope National Facility, Commonwealth Scientific and Industrial Research Organization, Epping, N.S.W. 1710, Australia.

Publisher Item Identifier S 0018-9480(01)09377-2.

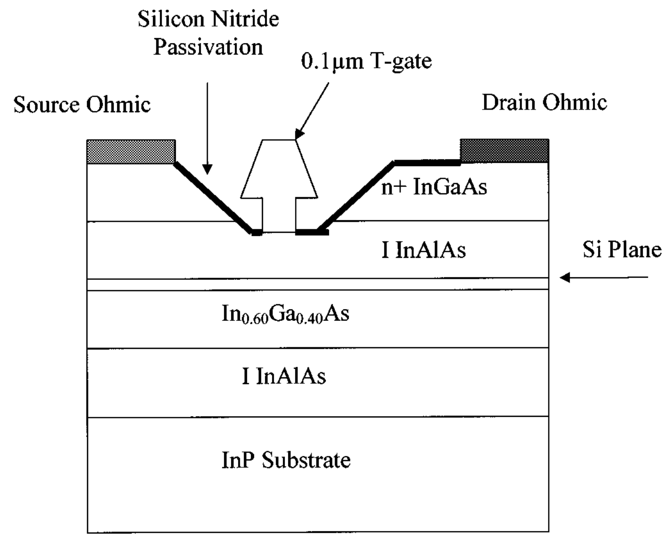

Fig. 1. Cross section of layers in the TRW InGaAs/InAlAs/InP HEMT device.

II. Fabrication Process

TRW's InP HEMT MMIC process evolved from an existing space-qualified GaAs HEMT MMIC process, taking advantage of an established knowledge base in this more mature technology [6]. For the MMICs discussed in this paper, the wafers were grown by molecular-beam epitaxy (MBE) on 75-mm-diameter Fe-doped semi-insulating substrates. The epitaxial structure is illustrated in Fig. 1, and uses a 200-Å pseudomorphic InGaAs channel with 60% indium. The main features of the process are 0.1-μm gates defined by electron-beam lithography, 750-Å plasma-enhanced chemical vapor deposited silicon nitride for device passivation, 100-$\Omega/\square$ nichrome thin-film resistors, and 300-pF/mm^2 silicon–nitride metal–insulator–metal capacitors. The wafers are thinned to 75 μm. Via-holes, with a diameter of 40 μm, are then etched through the substrate using a dry process. Ti/Au backside metallization is sputtered/plated to a thickness of 3.5 μm. For the four production wafers fabricated for CSIRO, typical 0.1-μm InP HEMT devices exhibited f_t in the 184–196-GHz range at 1-V drain bias (test device geometry was two-finger 200-μm total gatewidth). The peak transconductance for the test devices across these four wafers varied from 986 to 1049 mS/mm. This data highlights the high gain, high-frequency performance, and excellent wafer-to-wafer device uniformity achieved by TRW's process.

III. Amplifiers

The 85–115-GHz HEMT amplifier reported in this paper was a four-stage design, implemented in microstrip on the semi-in-

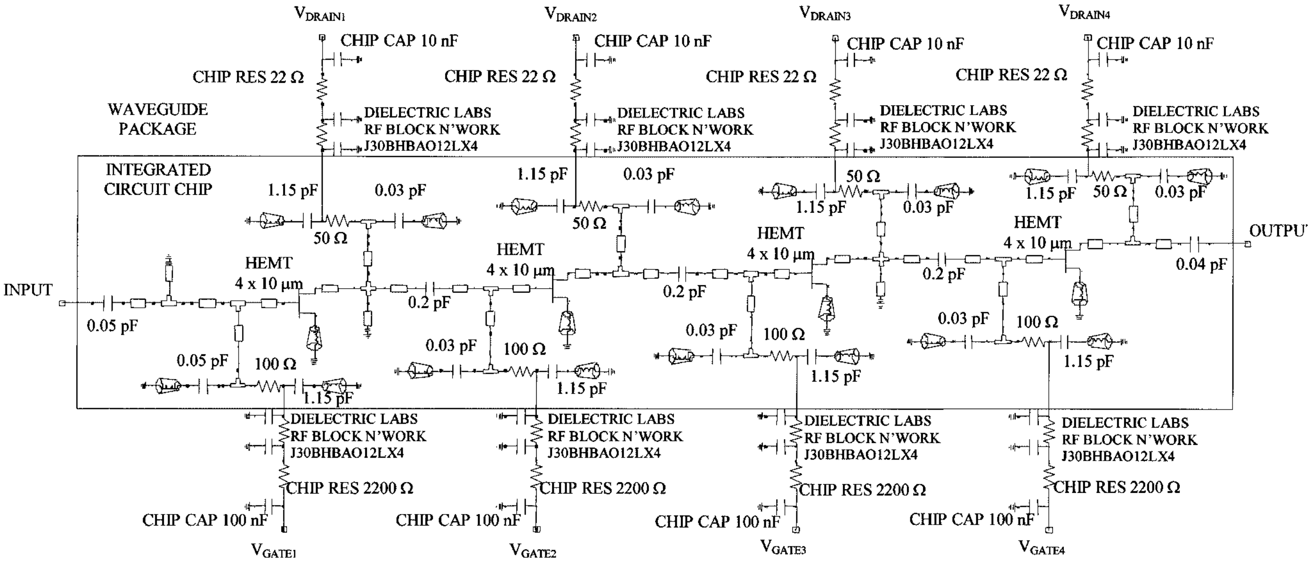

Fig. 2. Circuit schematic for 85–115-GHz four-stage InP HEMT MMIC amplifier including package components.

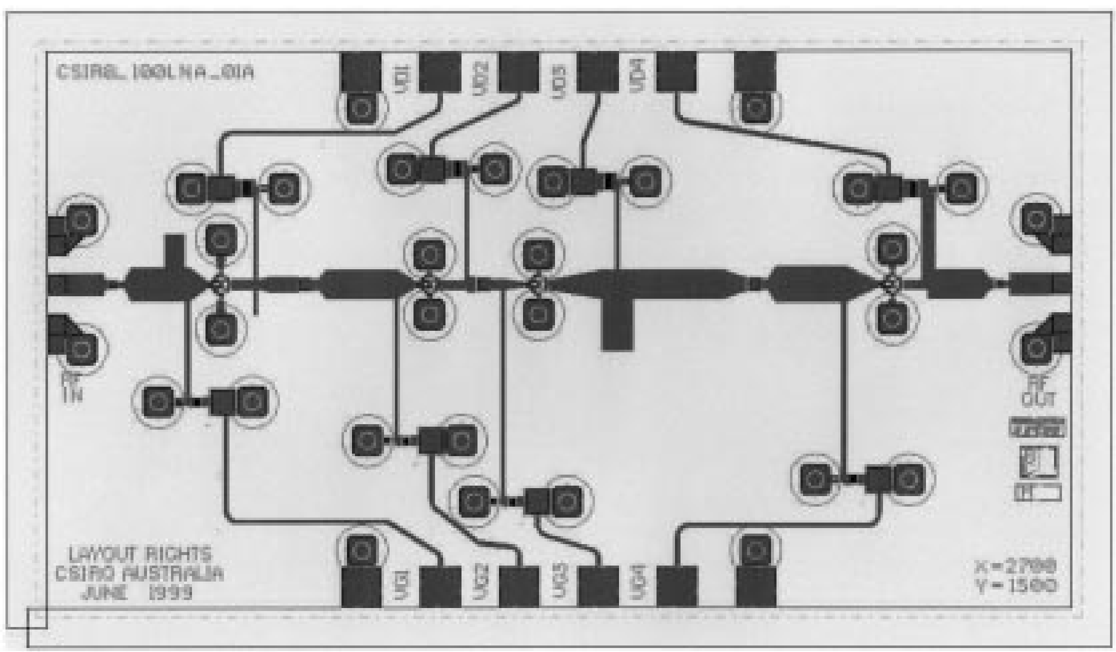

Fig. 3. Circuit layout for 85–115-GHz four-stage InP HEMT MMIC amplifier (chip size 1.5 × 2.7 mm).

sulating InP substrate, with vias for circuit grounding. Fig. 2 shows a schematic diagram of the amplifier and Fig. 3 shows the circuit layout. The InP HEMT devices had a gate length of 0.1 μm and a four-finger interdigitated geometry with a total width of 40 μm. Small-signal HEMT models were developed by TRW using carefully designed on-wafer calibration and device embedding circuits. The models have been verified and optimized to frequencies above 120 GHz through design and evaluation of a range of amplifier circuits [7],[8].

CSIRO has found that careful evaluation of the accuracy of the Agilent–EEsof Libra simulator models for the passive elements in the circuit is important for first-pass design success in millimeter-wave circuits. In particular, the standard simulator models for the passive elements have been found to be of restricted validity because either the dimensions of the element, or the operating frequency, are often outside acceptable limits. In this paper, S-parameter matrices for the elements of interest were derived using electromagnetic simulator software. This information was then used to restrict the application of these elements in the design of the 85–115-GHz circuit to frequencies and dimensions where the Libra models provided reasonable accuracy.

The predicted performance of the amplifier is shown in Figs. 4 and 5. The amplifier was expected to have a gain of 15 dB and noise figure of less than 5 dB when operating at room temperature. Input and output return losses were expected to be better than 10 dB over the entire design band and better than 15 dB in the center of the 85–115-GHz range. For this first-pass design, excellent agreement has been achieved between the predicted characteristics and measured results.

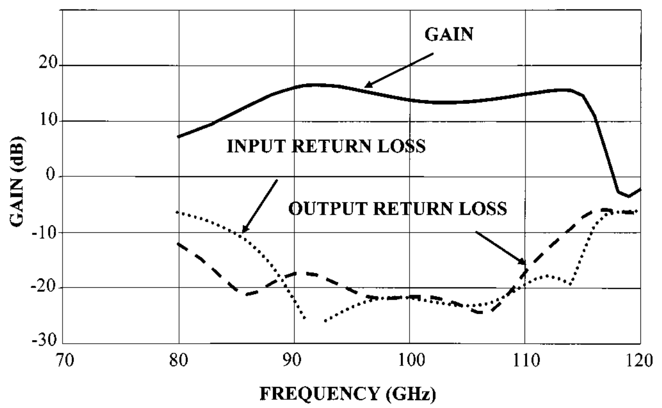

Fig. 4. Predicted performance of the 85–115-GHz MMIC amplifier (at 300 K).

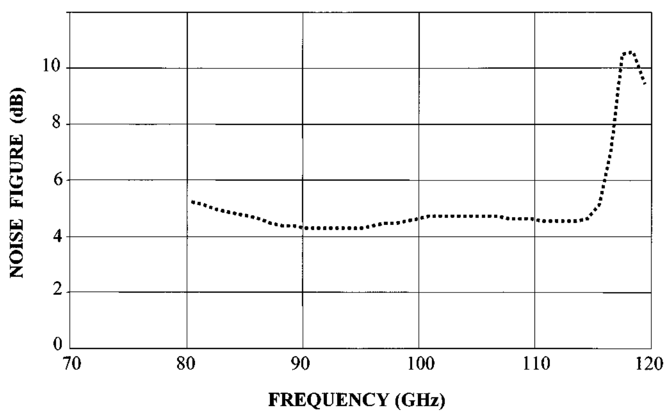

Fig. 5. Predicted noise figure of the 85–115-GHz InP MMIC amplifier for 300-K operation.

The measurements were made on-wafer for the four production wafers delivered to CSIRO. Each wafer contains about 40 85–115-GHz amplifier chips of this design. All of the circuits on the four wafers have been characterized using the wafer prober, with the functional circuit yield observed to be about 50%. Scattering parameter measurements were made using an HP8510C network analyzer system and coaxial on-wafer probes manufactured by GGB Industries, Naples, FL. Typical measured performance of one of the amplifiers is shown in Fig. 6, with each stage of the amplifier biased at 1.1-V drain supply voltage and with drain current in the range of 5–9 mA, optimized to give the best frequency response.

The agreement between the predicted response and measurements verifies that standard simulator microstrip passive element models can be used to accurately design amplifiers in the 85–115-GHz band provided their range of validity is carefully assessed. For this amplifier, the gain is 15.5 dB$\pm$1.5 dB over the 82-112-GHz range. The input return loss is better than 10 dB over the same range and is close to 20 dB between 85–105 GHz. The output return loss is also better than 10 dB between 80-112 GHz, and better than 20 dB between 90–103 GHz.

The noise figure of a sample of the amplifiers on the four wafers, operating at room-temperature, was also measured. These measurements were made directly at the wafer level using a switched solid-state noise source and a low-noise downconverter covering the 90–98-GHz range, which provided an output to an HP noise-figure meter. The system was carefully

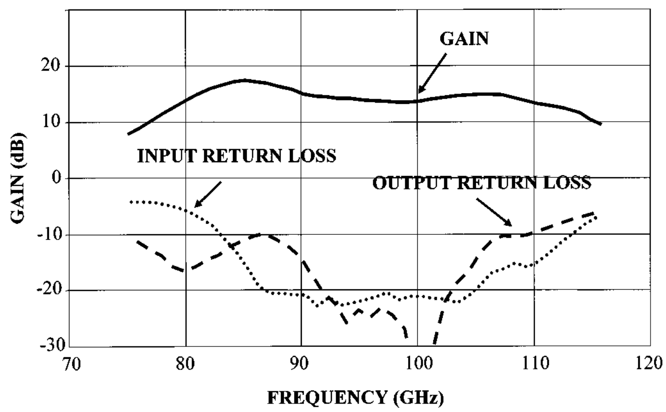

Fig. 6. Measured performance of a typical 85–115-GHz MMIC amplifier (at 300 K).

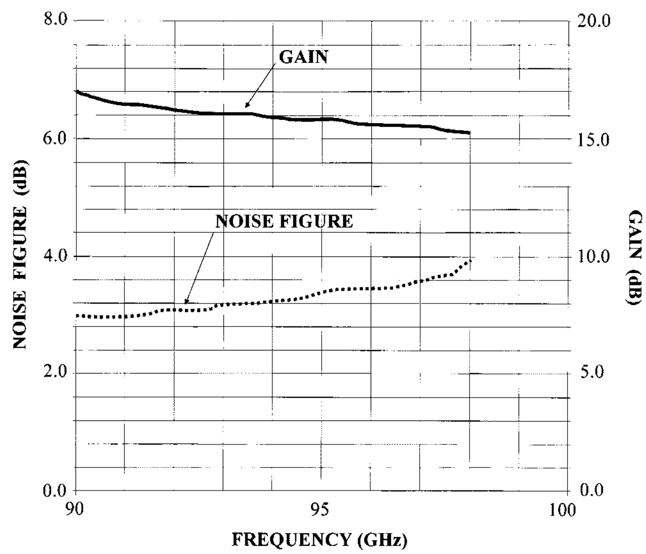

Fig. 7. Noise figure of a typical 85–115-GHz InP MMIC amplifier measured on-wafer at 300 K.

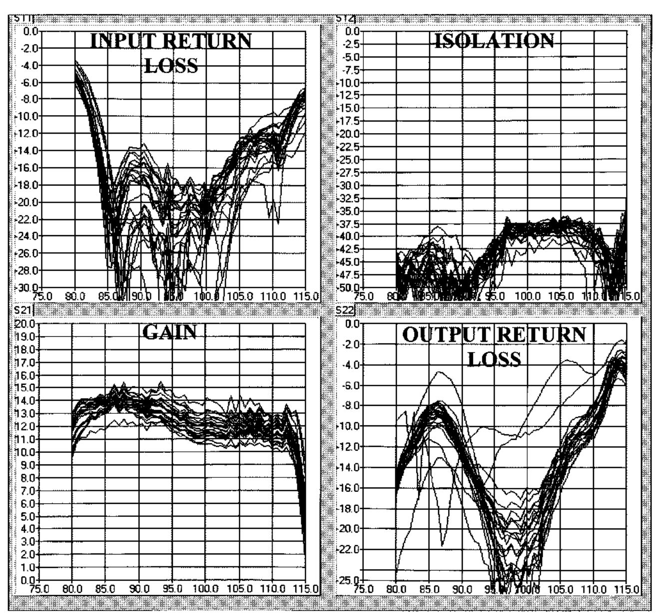

Fig. 8. Measured S-parameters of 30 amplifiers from two of the four InP wafers.

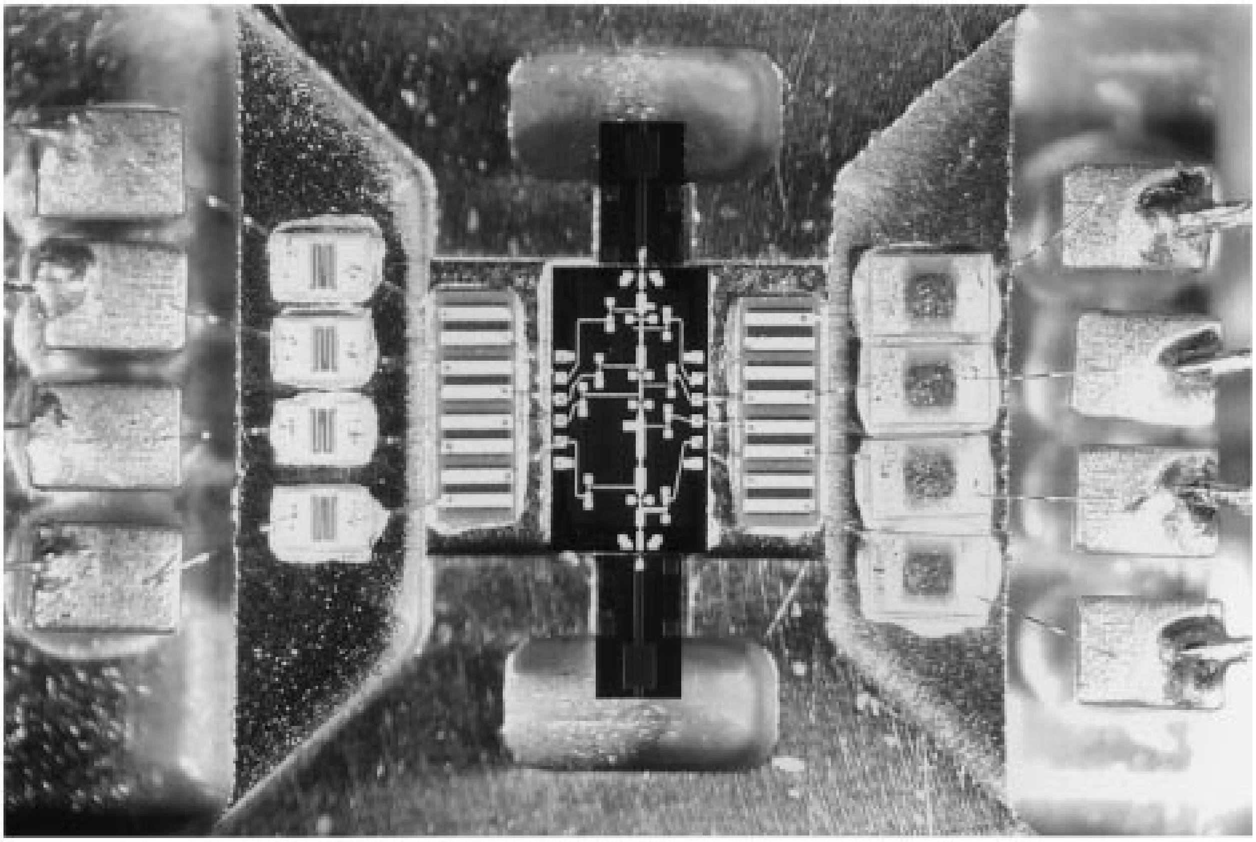

Fig. 9. 85–115-GHz InP MMIC amplifier mounted in the waveguide package.

calibrated to account for losses in the probes and waveguide assemblies. Waveguide full-band isolators were used between on-wafer probes and the measurement system to minimize errors due to reflections. The performance of the test setup was verified by measurements on wafer-level 6- and 10-dB attenuators. The measured noise figure of the test amplifier (measured S-parameters given in Fig. 4) is shown in Fig. 7, under the same bias conditions as before. It is estimated that the measured noise figure is accurate to within ± 0.5 dB.

Fig. 8 illustrates the range of measured performance for 30 amplifiers from two of the four wafers. This data was taken for all amplifier stages biased at 1.1-V drain supply voltage and 6-mA drain current, different conditions from those used for the optimized characteristics shown in Fig. 6. The data provides a measure of the uniformity of amplifier characteristics across a wafer, and from wafer to wafer, which can currently be achieved in the 100-GHz band with TRW's InP HEMT MMIC process. It can be seen that the spread in device performance is acceptably small. Most devices exhibit nominal gain within the 12–14-dB range, flat to within ± 1 dB over the 80-112-GHz range. The input return loss for all amplifiers tested was better than 12 dB between 85-112 GHz, whereas the output return loss was better than 10 dB between 90-110 GHz.

IV. Packaged Amplifier Performance

MMIC amplifiers have been mounted in three individual metal packages (an example, see Fig. 9), which incorporate WR10 (75–110 GHz) waveguides for signal input and output. The packaged amplifiers were intended for installation in receivers of the CSIRO Australia Telescope National Facility Compact Array (ATNFCA), Narrabri, Australia. The mounting block was machined from gold-plated tellurium copper and incorporated a silvar chip carrier. Silvar is an alloy of silver and invar, which has a coefficient of thermal expansion that approximates the coefficient of the InP substrate. This choice of material for the chip carrier is important to avoid mechanical damage to the mounted chip, due to stresses created by differential contraction, when the assembly is cooled to cryogenic temperatures. The amplifiers were connected to the input and output waveguides via wide-band E-plane probe-type waveguide-to-microstrip transitions fabricated on metalized 75-μm-thick GaAs substrates. The performance of the transition was simulated using Agilent's HFSS software and the probe geometry was optimized using Agilent's Empipe optimizer. Package manufacture and amplifier operation is simplified by fixing the position of the waveguide backshort relative to the plane of the probe when the mounting block is machined.

Probe performance has not yet been measured directly. However, return loss of better than 20 dB for either the waveguide or microstrip port was predicted across the 75–110-GHz waveguide band. Measurements on the packaged amplifiers show good input and output return loss at the waveguide flanges, suggesting that probe performance is acceptable. In order to verify the simulations and optimize transition performance, a pair of

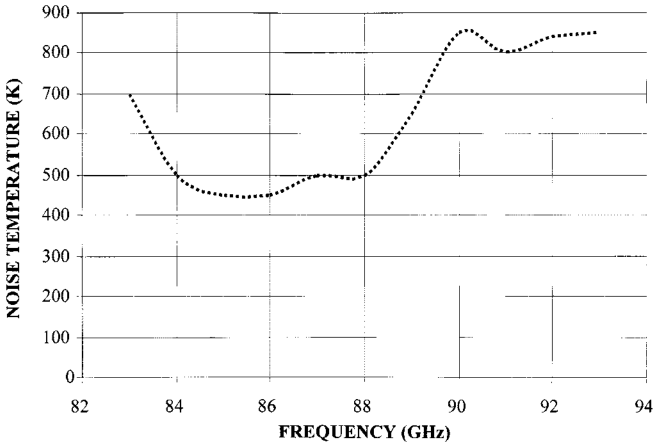

Fig. 10. Measured noise temperature of a typical packaged 85–115-GHz InP MMIC amplifier operating at a physical temperature of 300 K.

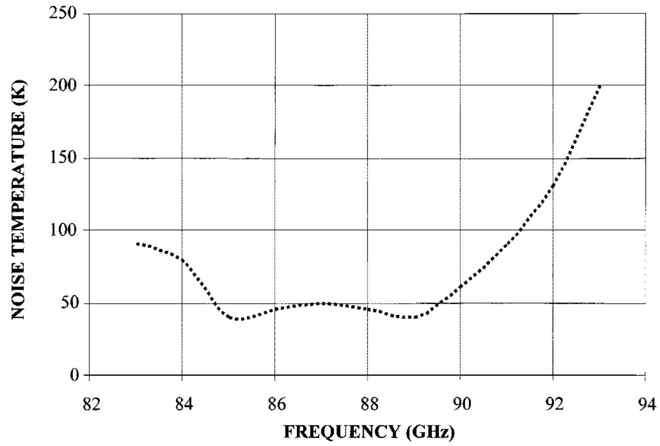

Fig. 12. Measured noise temperature of a typical packaged 85–115-GHz InP MMIC amplifier, operating at a physical temperature of 15 K.

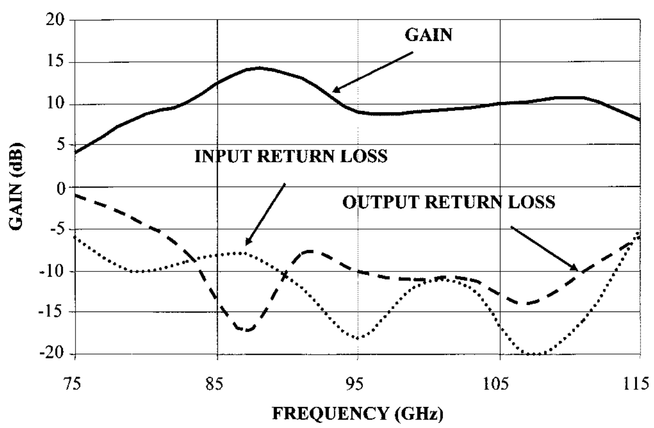

Fig. 11. Measured gain and return loss of a typical packaged 85–115-GHz InP MMIC amplifier operating at a physical temperature of 300 K.

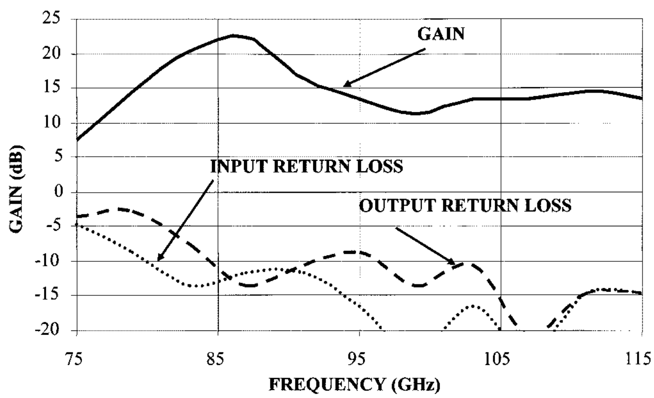

Fig. 13. Measured gain and return loss of a typical packaged 85–115-GHz InP MMIC amplifier operating at a physical temperature of 15 K.

probes connected back-to-back will be characterized independently in the near future.

The amplifier chip and coupling probes are attached to the chip carrier using electrically conductive epoxy. The coupling probe conductors and dc-bias circuitry are connected to the amplifier terminals using thermocompression-bonded 25-μm-diameter gold wire. Off-chip RF bypassing is implemented in the package using Dielectric Labs RF filters and low-pass RC networks, as shown in Fig. 2. The selection of the bypassing networks is critical in eliminating low-frequency bias circuit oscillations that can occur when the amplifier is cooled to cryogenic temperatures.

The performance of the packaged amplifiers was measured at 300 K using the test equipment described previously in Section III. The room-temperature performance of the packaged amplifier is shown in Figs. 10 and 11. It can be seen that the coupling probes and waveguide connections result in a reduction in overall gain of about 4 dB compared to the on-wafer results.

A special cryogenic test system was constructed so that the characteristics of the amplifier could also be determined at 15 K. Careful determination of the waveguide losses in this system enabled the cooled behavior of the packaged amplifiers to be determined accurately. As can be seen from Figs. 12 and 13, the amplifiers cooled successfully, achieving a very good noise temperature between 40–50 K (a noise figure between 0.5–0.7 dB) over the 85–92-GHz band, with more than 18-dB associated gain. These amplifiers were installed on two telescopes of the ATNFCA during the last week of November 2000, and successful two-element interferometer observations were made of SiO maser spectral line sources at 86 GHz. An overall receiver noise temperature of 150 K (including feed-horn and polarizer losses) was measured for a receiver configuration with a single cryogenically cooled amplifier stage before the mixer. This is believed to be the first time that cooled MMIC amplifiers have been successfully installed and used for astronomical observations in an interferometer system in the 3-mm-wavelength band.

V. Summary

This paper has described the successful first-pass design, fabrication, and test of a very high-performance InP-based HEMT MMIC amplifier for the 85–115-GHz band. The combination of wide bandwidth, high gain, good gain flatness, very low noise figure, and excellent input and output match mean that this MMIC is very competitive with other designs that have been reported in the literature in this frequency range [3]–[5]. More than 100 identical circuits have been fabricated on four 75-mm-diameter wafers. The circuit-to-circuit and wafer-to-wafer uniformity has been shown to be excellent. Several amplifiers, packaged in waveguide mounts, have performed well at cryogenic temperatures. A minimum noise temperature of 40 K has been achieved over the 85–89-GHz band with 18-dB associated gain.

ACKNOWLEDGMENT

The authors are indebted to many people, both at the Commonwealth Scientific and Industrial Research Organization (CSIRO), Epping, N.S.W., Australia, and TRW, Redondo Beach, CA, for their support, which underpinned the results reported in this paper. The following staff at CSIRO contributed to this paper: X. Wang, who designed the transitions, H. Kanoniuk, who carried out the package assembly, and S. Mahon, O. Sevimli, and M. Sinclair. The following staff at TRW made the MMIC design and fabrication possible: R. Grundbacher, M. Barsky, R. Tsai, P. Reid, the InP pilot line engineers and laboratory, D. Streit, T. Block and the staff from the MBE area, P. Hsin and the electron beam lithography (EBL) staff, R. Elmajarian, R. Rodriguez, and the InP backside people.

REFERENCES

[1] P. D. Chow *et al.*, "W-band and D-band low noise amplifiers using pseudomorphic InAlAs/InGaAs/InP HEMT's," in *Proc. IEEE Int. Microwave Symp. Dig.*, Albuquerque, NM, June 1992, pp. 807–807.

[2] M. Wojtowicz *et al.*, "305 GHz f_t using 0.1 μm gate-length graded channel pseudomorphic InAlGaAs/InAlAs HEMT's," *IEEE Electron Device Lett.*, vol. 16, pp. 477–477, Nov. 1994.

[3] S. Weinreb *et al.*, "W-band InP wideband MMIC LNA with 30 K noise temperature," in *Proc. IEEE Int. Microwave Symp. Dig.*, Anaheim, CA, June 1999, pp. 101–101.

[4] H. Wang *et al.*, "Fully passivated W-band InGaAs/InAlAs/InP monolithic low noise amplifiers," *Proc. Inst. Elect. Eng.*, pt. 5, vol. 143, pp. 361–366, Oct. 1996.

[5] R. Lai *et al.*, "0.1 μm InGaAs/InAlAs/InP HEMT production process for high performance and high volume mm-wave applications," in *Proc. GaAs Mantechnol.*, Vancouver, BC, Canada, 1999, pp. 249–252.

[6] ——, "0.15 μm InGaAs/AlGaAs/GaAs HEMT production process for high performance V-band power MMIC's," in *GaAs IC Symp. Dig.*, San Diego, CA, Oct. 1995, pp. 105–105.

[7] ——, "D-band MMIC LNA's with 12 dB gain at 155 GHz fabricated on a high yield InP HEMT production process," *Microwave J.*, vol. 40, pp. 166–166, Sept. 1997.

[8] H. Wang *et al.*, "A 140 GHz monolithic low noise amplifier," *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 150–152, May 1995.

John W. Archer (M'82–SM'83–F'90) was born in Sydney, N.S.W., Australia, in 1950. He received the B.Sc., B.E. (Hons. I), and Ph.D. degrees from The University of Sydney, Sydney, N.S.W., Australia, in 1970, 1972, and 1977, respectively.

His professional career has been distinguished by sustained contributions to the development of millimeter-wave components and systems. His doctoral research led to the world's first 100-GHz variable-baseline two-element coherent interferometer for radio astronomy. From 1977 to 1984, he was with the National Radio Astronomy Observatory, where his research focused on millimeter-wave systems for radio astronomy, particularly component design and receiver construction. During this period, he gained international recognition for his work on the development of frequency multipliers, fixed-tuned mixers, and novel cryogenic receivers. In 1984, he was appointed to head a new research effort at the Commonwealth Scientific and Industrial Research Organization (CSIRO), Marsfield, N.S.W., Australia. Over the last 17 years at CSIRO, he has successfully established an Australian resource base in gallium arsenide (GaAs) and InP MMIC technology, which has lead to the application of these circuits in the Australian defence and telecommunications industries. In parallel with his leadership role, he has continued to contribute to the development of new millimeter-wave MMIC components. Highlights of this research include the development of unique planar Schottky diodes and MMICs, incorporating them, as well as low-noise and medium power InP and GaAs MMIC amplifiers of novel design, for frequencies from 2 to 205 GHz, including a patented new class of bidirectional amplifiers. His research has also led to the development of MMIC voltage-controlled oscillators realized by combining planar diodes and HEMTs on a single wafer. He has achieved wide international recognition for his contributions to millimeter-wave receiver technology. He is an Editorial Board member of *Microwave and Optical Technology Letters*.

Richard Lai (M'99) was born in Evanston, IL, in 1964. He received the B.S.E.E. degree from the University of Illinois 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 the Advanced Microelectronics Laboratory, TRW, Redondo Beach, CA, where he was a Product Engineer involved in the research, development, and production of advanced GaAs- and InP-based HEMT device and MMIC technologies into various military and commercial millimeter-wave (MMW) applications. Since 1994, he has been the Principal Investigator for an advanced HEMT research and development project at TRW. Since 1997, he has been the Manager for the HEMT MMIC Products Section. He has authored and co-authored over 100 papers and conference presentations in the area of advanced GaAs and InP-based device and circuit technology, establishing world-record performance for low-noise amplifiers, high-frequency amplifiers and power amplifiers. He also holds numerous patents.

Russell Gough (M'85) was born in Rockhampton, Australia, in 1951. He received the B.Sc., B.E. (Hons. I), and M.Eng.Sc. degrees from The University of Sydney, Sydney, N.S.W., Australia, in 1973, 1975, and 1980, respectively.

In 1981, he joined the Max-Plank Institut for Radioastronomie, Bonn, Germany, where he was involved with a number of projects, including a 30-GHz dual-beam radiometer for the 100-m-diameter Effelsberg radio telescope. In 1983, he joined the Commonwealth Scientific and Industrial Research Organization (CSIRO), Epping, N.S.W., where he was primarily responsible for the design and construction of cryogenically coolable low-noise amplifiers for the Australia Telescope. From 1989 to 1993, he worked in an operational capacity at the Australia Telescope Compact Array, Narrabri, N.S.W., Australia. Since 1993 he has been involved in the design and construction of several new centimeter and millimeter-wave receiver systems for Australian and international telescopes.