Cryogenic Characteristics of Wide-Band Pseudomorphic HEMT MMIC Low-Noise Amplifiers

Cheng Chih Yang, *Member, IEEE,* Brad L. Nelson, *Member, IEEE,* Barry R. Allen, *Member, IEEE,* William L. Jones, *Member, IEEE,* and John B. Horton, *Fellow, IEEE*

***Abstract*—Two wide-band (8–18 GHz) single-stage MMIC low-noise amplifiers (LNA's) using 0.2-μm T-gate InGaAs pseudomorphic HEMT technology, designed and fabricated for room-temperature operation, were evaluated and compared at cryogenic temperatures below 20 K. One is a balanced design using 3-dB Lange couplers, and the other is a feedback design using a series RLC parallel feedback network. The gain flatness over the 8–18 GHz frequency band was maintained for both amplifiers at room and cryogenic temperatures, indicating that the topology for wide-band designs is insensitive to temperature of operation. As the physical temperature decreased from 297 K to below 20 K, the balanced LNA exhibited an average gain increase of 2 dB and as much as an eightfold reduction of noise temperature to 20 K, while the feedback LNA exhibited an average gain increase of less than 1 dB and an average fourfold reduction of noise temperature to 50 K. The negative feedback network of the feedback LNA resulted in less gain increase and less noise temperature reduction at cryogenic temperatures. The MMIC LNA's remained electrically and physically stable without adverse effects, such as breakage, at all test temperatures, and the measured results were repeatable.**

I. Introduction

The low-noise amplifier (LNA) usually determines system sensitivity and, as such, is one of the most critical components in receivers used in communication systems. The high electron mobility transistor (HEMT), because of its inherently low-noise characteristics, has been utilized widely for LNA designs. Cryogenic LNA's with even lower noise figure (or noise temperature) are used in many applications such as satellite receiving systems, radio astronomy, remote sensing, and so on, where maximum signal sensitivity is the major requirement. System noise can be greatly reduced when the LNA operating temperature is lowered. Because of this, there is a growing demand for cryogenic microwave LNA's when a lower noise temperature can be used to reduce the size of the receiver antenna and/or the transmitter power. In addition, recent advances in high-temperature superconductors (HTS) have provided a need for low-temperature amplifiers in the HTS electronics. The progress in developing more efficient and reliable cryogenic cooling systems has made it feasible to integrate HTS components, cryogenic amplifiers, and cryogenic coolers into a high-performance microwave system.

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The authors are with TRW, Inc.,Space and Electronics Group,One Space Park, Redondo Beach, CA 90278, USA.
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The InGaAs pseudomorphic HEMT, which utilizes an undoped InGaAs layer as a conducting channel, has demonstrated excellent noise performance and high cutoff frequency at room temperature [1]. When the operating temperature decreases, it has also demonstrated a much lower noise figure and higher cutoff frequency than the conventional AlGaAs HEMT [2], showing its greater potential for low-temperature applications. At cryogenic temperatures, the reduced phonon and impurity scattering leads to a lower device noise figure, and the improved effective electron saturation velocity in the channel results in higher device cutoff frequency. The cryogenic characteristics, including dc and RF, of the pseudomorphic HEMT's have been studied extensively [3], [4]. Also, the accurate cryogenic device small-signal model [5] and noise model [6] have been derived for circuit designs. Although many cryogenic hybrid HEMT LNA's were designed and published [7], [8], little data have been reported on the cryogenic performance of HEMT MMIC LNA's [9].

Advanced fabrication technology has made HEMT MMIC LNA's available for cryogenic tests [9]. In this paper, two wide-band (8–18 GHz) single-stage MMIC LNA's using 0.2-μm T-gate InGaAs pseudomorphic HEMT technology, designed and fabricated for room-temperature operation, are evaluated and compared at cryogenic temperatures below 20 K. One is a balanced design using 3-dB Lange couplers [10], and the other is a feedback design using a series RLC network as a parallel feedback element [11]. Both design topologies provide an octave band performance. In Section II, a linear circuit and noise model of the HEMT device for room-temperature MMIC LNA designs is briefly described. The MMIC LNA designs for room-temperature operation and the assembly techniques for cryogenic operation are presented in Section III. In Section IV, the cryogenic measurements and results are shown and discussed. The conclusions and paper summary are given in Section V.

II. Device Model

An accurate linear circuit and noise model of the 0.2-μm gate-width InGaAs pseudomorphic HEMT was developed for room-temperature MMIC LNA designs [10]. For example, a typical linear circuit and noise model for a 4-finger 200-μm gate-length device at room temperature is illustrated in Fig. 1. The value of each circuit element is shown. The linear circuit model was derived from 1–26.5 GHz on-wafer S-parameter measurements, and the noise model was derived from 2–18 GHz on-wafer noise parameter measurements. The linear

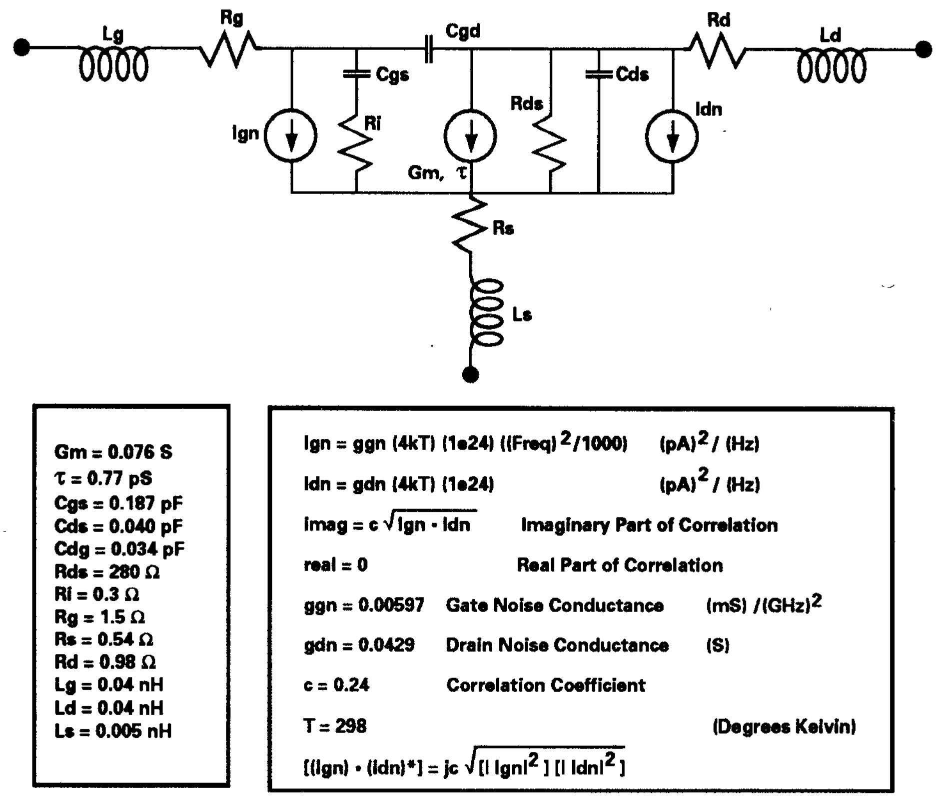

Fig. 1. A 200-μm gate-width InGaAs pseudomorphic HEMT device model with intrinsically correlated noise sources. Drain voltage is 2 V, and drain current is 16 mA.

circuit model allows accurate determination of the parasitic gate and source resistances, which are a major contributor to the device noise figure. The noise model of the intrinsic device uses two correlated gate and drain noise current sources. The correlation of the gate and drain noise currents is due to modulation of the channel by the drain current fluctuations. The modeling was done using Libra's nodal noise analysis capability, which offers correlated noise sources as standard circuit elements. The drain noise current source in the model is independent of frequency, and the gate current source mean square magnitude is proportional to frequency squared. The mean square of the drain noise current source is approximately linear with the drain current.

Both gain and noise figure parameters at room temperature have been verified through measurement and simulation of MMIC LNA's [10], [11]. At cryogenic temperatures, the HEMT exhibits higher transconductance (Gm), faster transit time (τ), and lower output resistance (Rds), resulting in higher gain and cutoff frequency [5]. The HEMT linear circuit model at low temperatures is similar to that at room temperature, except the element values change at low temperatures [5]. The room-temperature noise model in [6] is applicable at cryogenic temperatures. The room-temperature noise model used for our MMIC LNA designs should also be applicable at low temperatures because of the similar modeling concept. Nevertheless, the improved device noise temperature at low temperatures is partly due to the decrease in gate and source resistance thermal noise as well as gate and drain noise conductance (ggn and gdn). Thus, the performance improvement of the MMIC LNA's at low temperature operations can be projected somewhat by the HEMT linear circuit and noise model.

III. MMIC LNA Design and Assembly

The balanced amplifier design incorporating 3-dB Lange couplers at the input and output ports is suitable for octave band performance. It provides design flexibility in achieving optimum noise match and broad-band gain flatness without degrading VSWR. The circuit photograph with chip size of 2.76 mm × 3.0 mm is shown in Fig. 2. The input noise matching network employs a three-section impedance transformer for broad-band device noise matching. Series inductive feedback in the source is used to improve the broad-band input noise match as well as the stability. The active devices are two HEMT's that have 0.2-μm gate length and four gate fingers with a total gate width of 150 μm.

The feedback design uses a series RLC feedback network between the drain and gate of the device to maintain the octave-band gain flatness response. The input matching network is designed for optimum noise performance with low VSWR. The output matching network is designed to achieve the low VSWR. Stability and input matching are enhanced by the addition of series source inductance. The design parameters were selected to insure unconditional stability. The active device is a single 0.2-μm gate-length, four-finger 200-μm gate-width HEMT. The circuit photograph with chip size of 2.45 mm × 1.3 mm is shown in Fig. 3.

The MMIC LNA's were designed to be on-wafer testable. They were fabricated on a 3-in GaAs substrate with the active

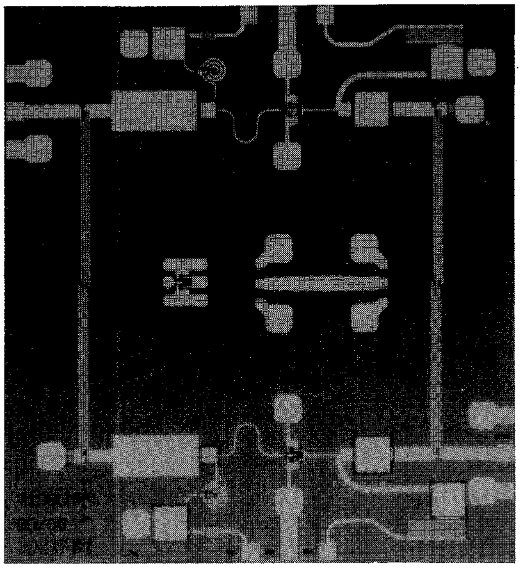

Fig. 2. Single-stage balanced pseudomorphic HEMT MMIC LNA. The chip size is 2.76 mm × 3.0 mm.

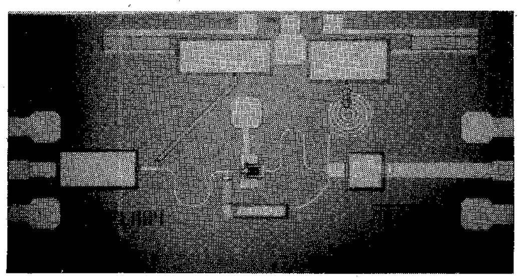

Fig. 3. Single-stage feedback pseudomorphic HEMT MMIC LNA. The chip size is 2.45 mm × 1.3 mm.

layers grown in a Varian Generation II MBE system. The detailed MMIC fabrication process was reported previously in [9]–[11]. Automatic on-wafer S-parameter and noise figure measurements were performed at room temperature for circuit functionality and selection. The HEMT MMIC LNA's were then diced and mounted on the center block of a test fixture, made of Kovar. Both the MMIC LNA and alumina substrate interconnects were mounted on the test fixture using silver epoxy, and cured for 60 minutes at 125°C. A 0.7-mil-diameter gold bonding wire was used to connect the MMIC chip to a 50 Ω transmission line on the 10-mil-thick alumina substrate. The dc bias wires were bonded to the designated bias pads on the chip through a shunt chip capacitor of 50 pF to insure an unconditionally stable cryogenic operation. The K connectors were installed at input and output blocks of the test fixture. The measured back-to-back insertion loss of the test fixture was less than 0.5 dB up to 20 GHz. The test-fixtured amplifier was then placed in a vacuum dewar for cryogenic evaluation.

IV. Measurement and Results

A wide-band cryogenic measurement test set, capable of being operated up to 20 GHz, is shown schematically in Fig. 4. As shown, the device under test (DUT), when placed inside the vacuum dewar, is covered by a radiation shield to

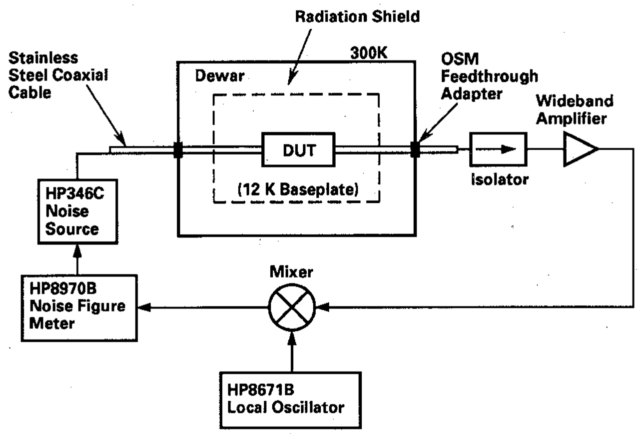

Fig. 4. Wide-band cryogenic noise temperature measurement setup.

reduce the radiation loading from the ambient environment. The dewar is cooled by a CTI 1020 closed-cycle helium refrigerator. To minimize the thermal resistance, a copper block is sandwiched between the DUT and the baseplate. The thermal isolation at the input and output is preserved by 0.141-inch-diameter stainless steel semirigid coaxial cables. Hermetically-sealed OSM feedthrough adapters are installed in the walls of the dewar to provide a vacuum seal for the semirigid coaxial cables. A calibrated HP 346C noise source and HP 8970B noise figure meter are used for gain and noise figure measurements. An isolator is used at the output for improved matching, and a wide-band amplifier is used prior to the mixer to improve the wide-band measurement accuracy. Temperature sensors are mounted on the baseplate and DUT to monitor critical temperatures. Without a heat load, the baseplate in the vacuum Dewar can be cooled down to 12 K.

Fig. 5 shows the noise temperature and gain of the balanced HEMT MMIC LNA measured at room and 19 K operating temperature over the 8–18 GHz frequency band at 0.5 GHz increments. The data have been corrected for the test fixture and semirigid coaxial cable losses. Drain current was set to 13 mA for the optimum room-temperature performance, and reset by gate voltage adjustment to 9 mA for the optimum cryogenic noise performance. The drain voltage was kept at 2.6 volts. Therefore, the total dc power consumption was 68 mW at room temperature and reduced to 47 mW at 19 K. The amplifier gain was flat over the frequency band at both room and cryogenic temperatures, indicating that the broad-band design topology is relatively insensitive to operating temperature changes. This also means that the broad-band MMIC design topology is insensitive to device, resistor, capacitor, and inductor variations, as was shown by the simulations and room-temperature measurements [10]. The measured amplifier gain increased an average of 2 dB at 19 K, equivalent to an average gain increase of 20%, mainly due to the device transconductance (Gm) enhancement. The lowest noise temperature was less than 160 K at room temperature, and reduced to less than 20 K at a physical temperature of 19 K, exhibiting an eightfold reduction in noise temperature. An average of better than fourfold reduction in noise temperature was measured across the 8–18 GHz frequency band. At cryogenic temperatures, the decrease in gate resistance and drain noise current as well

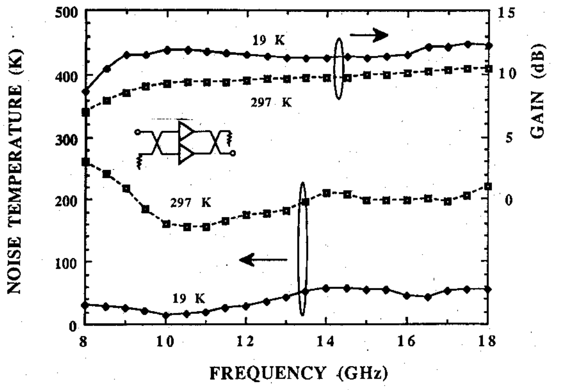

Fig. 5. Measured noise temperature and gain of an 8–18 GHz balanced MMIC LNA at 19 K and room temperature.

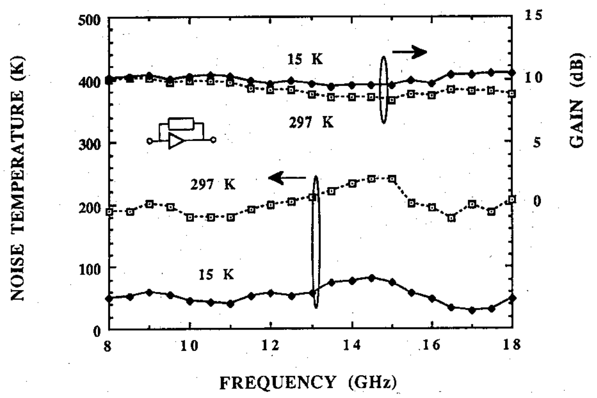

Fig. 6. Measured noise temperature and gain of an 8–18 GHz feedback MMIC LNA at 15 K and room temperature.

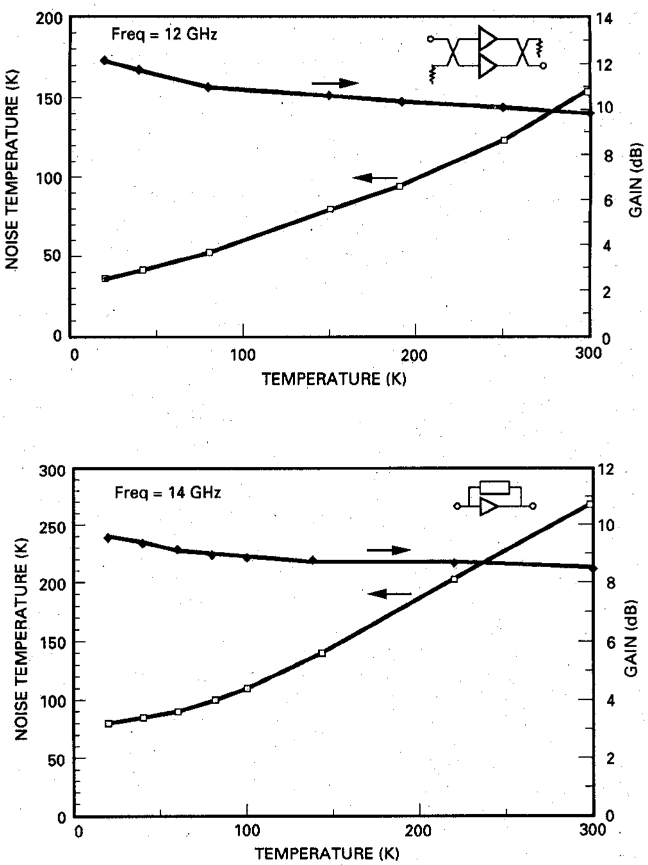

Fig. 7. Noise temperature and gain as a function of operating temperature for (a) balanced MMIC LNA at 12 GHz, and (b) feedback MMIC LNA at 14 GHz.

as the increase in device transconductance contribute to the reduced noise performance.

The feedback HEMT MMIC LNA was evaluated at room and 15 K operating temperatures over the 8–18 GHz frequency band at 0.5 GHz increments. The measured noise temperature and gain are plotted in Fig. 6. The drain current was set to 16 mA for the optimum room-temperature performance, and reset by gate voltage adjustment to 10 mA for the optimum cryogenic noise performance. The drain voltage was also kept at 2.6 volts. The higher optimal drain biasing current resulted from the larger HEMT device geometry in the feedback LNA. The total dc power consumption was 42 mW at room temperature, and reduced to 26 mW at 15 K. The lower heat load from the feedback LNA resulted in a lower cryogenic operating temperature. The average noise temperature across the 8–18 GHz frequency band was approximately 200 K at room temperature, and dropped to 50 K at 15 K operating temperature, exhibiting a fourfold reduction in noise temperature. The impedance in the RLC feedback loop limited the noise temperature reduction of the feedback LNA at low temperatures. At the physical temperature of 15 K, the average gain increase was less than 1 dB, equivalent to less than 10% gain increase, but the gain flatness was improved. The smaller gain increase for the feedback LNA, compared to the balanced design at cryogenic temperatures, is mainly due to the negative-feedback loop, which tends to minimize variations in amplifier gain caused by variations in device transconductance (Gm). As shown in Fig. 6, very little gain variation was measured at the low end of the 8–18 GHz frequency band. This was caused by the high loop gain at the lower frequencies.

TABLE I

	BLNA*	FLNA**
Size	2.76 x 3.0 mm²	2.45 x 1.3 mm²
HEMT Device(s)	2	1
Lange Coupler(s)	2	0
Via Hole(s)	10	2
Thin Film Resistor(s)	8	3
MIM Capacitor(s)	8	5
Spiral Inductor(s)	2	1

* BLNA = Balanced Low Noise Amplifier
** FLNA = Feedback Low Noise Amplifier

For a wide-band amplifier application, the noise temperature of the feedback LNA is generally higher than that of the balanced LNA, due to the resistor inserted in the negative-feedback network. The input matching network contributed 0.5 dB to the noise figure of both circuits. A 0.5-dB insertion loss was measured from the 3-dB Lange coupler, while a 0.7-dB noise figure was estimated from the negative-feedback loop. In this case, the larger device (200-μm versus 150-μm gate width) also contributed more noise to the feedback LNA. At 12 GHz, the measured minimum noise figure (Fmin) average was 0.87 dB (or 64 K noise temperature) for the 150-μm device, and 0.95 dB (or 71 K noise temperature) for the 200-μm device at room temperature. Thus, the noise figure of the balanced LNA is at least 1 dB higher than Fmin of the 150-μm gate-width device, and the noise figure of the feedback LNA is at least 1.2 dB higher than Fmin of the 200-μm gate-width device. The balanced design tends to be more stable than the feedback design. To improve stability, the feedback is increased. Thus, the gain of the feedback LNA is generally lower than that of the balanced LNA. Although a 200-μm gate-width device was implemented in the feedback LNA, its overall gain was still slightly lower than the balanced LNA. As shown in Figs. 5 and 6, the general features of these two amplifiers, when cryogenically cooled, remain the same as they are at room temperature. In other words, at cryogenic temperatures the noise temperature of the balanced LNA remains lower than that of the feedback LNA, and the gain of the balanced LNA remains higher than that of the feedback LNA.

Fig. 7 shows the noise temperature and gain of the balanced and feedback MMIC LNA's as a function of operating temperature. Both LNA's exhibited smooth changes in noise temperature and gain as the temperature was lowered from room temperature to below 20 K. The temperature performance of the balanced LNA at 12 GHz is plotted in Fig. 7(a), showing a gain increase of more than 2 dB and a noise temperature drop of more than four fourfold to 35 K. The drain bias was set at 2.6 volts, and the drain current of each device was kept at 13 mA. In Fig. 7(b), the temperature performance of the feedback LNA at 14 GHz showed a similar trend with a gain increase of 1 dB and a noise temperature reduction to 80 K. The feedback LNA was biased at 2.6 volts at drain with 16 mA drain current.

Both balanced and feedback MMIC LNA's were fabricated using pseudomorphic HEMT devices, via holes, thin film resistors, MIM capacitors, and spiral inductors. The component complexity comparison between these two LNA's is summarized in Table I. In addition to these active and passive devices, a number of air bridges were used for connections and crossovers. The thermal resistance of the MMIC LNA to baseplate was low because the wafer was thinned to 4 mils. The heat dissipation per chip area, which was 5.7 mW/mm^2 and 8.2 mW/mm^2 for the balanced LNA and the feedback LNA, respectively, was moderately low. Therefore, thermal cycling did not cause cracking or collapse of any of the component structures of the MMIC's. Performance measurements were repeated after the dewar was cycled several times, indicating that HEMT MMIC LNA's were not damaged during cryogenic operation. It should be pointed out that no illumination was used in any of the tests when lowering the dewar temperature.

V. Conclusions

Advanced fabrication technology has made single-stage balanced and feedback MMIC LNA's, using 0.2-μm T-gate InGaAs pseudomorphic HEMT's, available for evaluation at cryogenic temperatures below 20 K. The cryogenic performance of the two designs was compared. The gain flatness over the 8–18 GHz frequency band was maintained for both amplifiers at room and cryogenic temperatures, indicating that the broad-band design topology is insensitive to temperature of operation. As the physical temperature decreased from 297 K to below 20 K, the balanced LNA exhibited a higher gain increase and a higher noise temperature reduction than the feedback design. The negative feedback network of the feedback LNA resulted in less gain increase and less noise temperature reduction at low temperatures. At cryogenic temperatures, the noise temperature of the balanced LNA remains lower than that of the feedback LNA, while the gain of the balanced LNA remains higher than that of the feedback LNA. Although the balanced topology consumes more dc power and requires more components, it seems a better approach for a cryogenic wide-band MMIC LNA design.

The MMIC LNA's remained electrically and physically stable without adverse effects, such as breakage, at all test temperatures, showing the thermal rigidity of the MMIC chips. The measured results were repeated after the Dewar was cycled several times. These unique features make HEMT MMIC LNA's very attractive for cryogenic receiver systems and HTS electronics.

Acknowledgment

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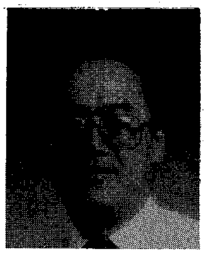
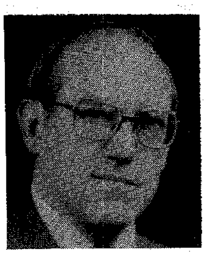


Cheng Chih Yang was born in Taiwan, Republic of China, on September 25, 1955. He received the B.S. degree in physics from National Cheng Kung University, Tainan, Taiwan, Republic of China in 1977, and the M.S., Engineer, and Ph.D. degrees in electrical engineering from the University of California, Los Angeles.

From 1977 to 1979 he served as an infantry platoon leader in the Chinese Army. From 1979 to 1983 he was a research and teaching assistant at UCLA, where he conducted research in the area of microwave electronics. In 1983, he joined Commodore MOS Technology, Costa Mesa, CA, where he worked on SPICE modeling and CMOS logic circuits. In 1984, he joined the Electronic Systems Group of TRW Inc., Redondo Beach, CA, where he has been an IR&D principal investigator and a project manager responsible for developing microwave and millimeter-wave circuits and subsystems, such as low-noise amplifiers, mixers, multipliers, downconverters, detectors, and frequency synthesizers. Currently, he is responsible for the development of low-noise millimeter-wave monolithic integrated circuits and receivers for space communication. He is also developing millimeter-wave phased arrey electronics and packaging. His interests include device characterization and modeling, microwave and millimeter-wave integrated circuits designs, and communication system integrations.

Brad L. Nelson was born in San Diego, CA in February 1962. In 1985 he received the B.S. degree in engineering physics from the University of the Pacific, Stockton, CA. He is currently working on an M.S. degree in electrical engineering at the University of Southern California.

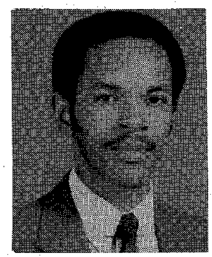
From 1983 to 1984 he worked at Naval Ocean Systems Center, San Diego, CA on ocean sensor arrays. In 1984 he joined TRW, Redondo Beach, CA. At TRW he has been developing microwave circuits with an emphasis on monolithic low noise HEMT amplifiers, low intermodulation distortion HBT amplifiers, and MESFET and HEMT phase shifters. Currently he is developing phased array electronics at TRW.



Barry R. Allen (S'82–M'83) was born in Cadiz, KY, on November 5, 1947. He received the B.S. degree in Physics and the M.S. and Sc.D. degrees in electrical engineering from the Massachusetts Institute of Technology, Cambridge, MA in 1976, 1979, and 1984, respectively.

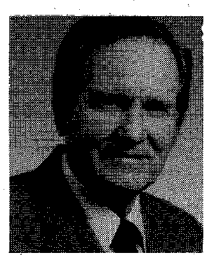
From 1970 to 1975, he was with the Chesapeake and Potomac Telephone Company of Virginia working on microwave and radio telecommunications equipment. From 1975 to 1983, he was a member of the Research Laboratory of Electronics at MIT both as an undergraduate and as a Research Assistant in radio astronomy. While at MIT he was responsible for the development of room temperature and cryogenic low noise receiving systems spanning 300 MHz to 43 GHz. He joined TRW in 1983 as a Senior Staff member and has held a number of positions since then. Since 1983 he has been involved in all aspects of MMIC design and modeling. His main interests are low noise receiving systems, millimeter wave circuits, and accurate circuit modeling. From 1985 to 1992 he was principal investigator for GaAs MMIC IR&D project, which resulted in several system insertions of MMIC. His current interests are accurate nonlinear models for improved distortion analysis of microwave and millimeter wave circuits.

In 1991, Dr. Allen became a TRW Technical Fellow in the Space and Defense Sector. For contributions to the application of GaAs MMIC in spacecraft payloads, he was awarded TRW's 1992 Chairman's Award for Innovation. He has published several papers on circuit applications of devices and MMIC's. Dr. Allen is currently assistant program manager for design and advanced technology on the ARPA funded MIMIC Phase 2 Program.



William L. Jones (S'80–M'81) was born in Harlem, NY. He did his undergraduate B.S. thesis research at the Massachusetts Institute of Technology under Professor C. Warde on the optical applications of crystals and lasers. He received the B.S. degree from M.I.T. in electrical engineering in 1980. He received the Masters and Ph.D. degrees, both in electrical engineering, in 1981 and 1984, respectively, from Cornell University, Ithaca, NY. His doctoral thesis was done with Professor L. F. Eastman, while an IBM Fellow, and dealt with the design, fabrication, and testing of GaAs MESFET's and AlGaAs/GaAs MODFET's for high-speed logic applications using an all direct-write electron-beam lithography process.

He worked as part of an informal summer co-op/scholarship program with the Electro-Optical and Data Systems Group at Hughes Aircraft Company of Culver City, CA, from 1977 to 1980, as a circuit designer. Prior to starting graduate school, he worked at the Western Electric/Bell Labs Engineering Research Center in Princeton, NJ as a Special Member of the Research Staff in the Optical Studies Group. Immediately after graduate school, he joined AT&T Bell Laboratories' Heterojunction IC and Material Department in Murray Hill, NJ, as a Member of the Technical Staff. He was responsible for research and process development of AlGaAs/GaAs heterojunction devices, device fabrication, improvements in ohmic contact formation and reactive ion etching for uniform threshold voltage control. He later joined TRW's Electronic Systems Group where he has performed research activities in the area of process development related to the design and fabrication of GaAs heterostructures for HEMT microwave devices and MMIC's. He is currently Section Head for Advanced Technologies, responsible for the supervision of research and process development of AlGaAs, InGaAs, and InP devices and MMIC's.



John B. Horton (S'55–M'57–SM'68–F'86) received the B.S.E.E. degree from George Washington University and the M.S.E.E. degree from the University of Pennsylvania.

He is a Project Manager, Systems Engineering in TRW's Space and Technology Group, Redondo Beach, CA. He is on special assignment for new business in satellite communications systems. His experience includes work on the Navy EHF Satcom Program, the NASA 30/20 GHz System Study, TDRSS, several military satellite systems, Shuttle payload studies, missile guidance, and airborne and large ground-based radars.

Mr. Horton is a member of AIAA. He served on the IEEE Microwave Theory and Techniques Society (MTT) Administrative Committee from 1969 through 1979 and was president of the society in 1973. He is currently Associate Editor for Microwave Systems and Applications for the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES and a member of the MTT-16 Technical Committee on Microwave Systems.