Low-Noise Amplifiers—Then and Now

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Invited Paper

***Abstract*—The evolution in the performance of low-noise amplifiers (LNAs) has been dynamic over the past years. From the early LNAs that were complex, large, and heavy, to the present day InP high electron-mobility transistors that have virtually transformed the industry by their performance and extension into frequency bands that were not even considered in the past. This paper will hopefully summarize the transformation that has occurred in the LNA field, viewing where they were in the past, and where they are now.**

***Index Terms*—Cryogenics, FETs, masers, parametric amplifiers, transistors.**

I. Introduction

OVER THE past number of years, the advances made in low-noise technology have been dynamic. From the early 1980s, the technological innovations achieved in this expanding field not only resulted in improved devices, subsystems, and systems, but also enabled new markets to be developed such as the cellular market, Direct TV, satellite communications, Internet communications, etc. We are now accustomed to a brand new vocabulary that has been ingrained in us. The vocabulary of the 1980s for low-noise front-ends and, in particular, low-noise amplifiers (LNAs), was parametric amplifiers (paramps), field-effect transistors (FETs), microwave amplification by stimulated emission of radiation (MASERS), cryogenically cooled amplifiers, thermoelectrically cooled (TE) amplifiers, bipolar transistors, etc. Fig. 1 shows the state-of-the-art noise performance of these LNAs [1]. While the low-noise performance of the LNAs were extremely good then, the design engineer still had to make some very complex system trades. Many LNAs were large, heavy, and consumed a lot of power. Satellite ground terminals were one application where low-noise performance, light weight, low power, and high reliability were simultaneously required, but not always achieved. In many cases, the LNAs were designed for lower noise figures than required since the amplifiers and their ancillary support equipment could not be located in very close proximity to the antenna. Relatively long interconnecting lines that could have substantial loss were used between them. Consequently, higher cost LNAs with noise performance lower than was really required were necessary to meet the system requirements. With the development of three-terminal devices that has continually lowered the noise threshold coupled with a significant reduction in size, weight, and power, system performance and capability has been vastly improved. We see LNAs now being used in systems well beyond the traditional boundaries that were considered their role in the past. LNA technology has expanded into the millimeter-wave frequency band and is now approaching the submillimeter-wave portion of the frequency spectrum. Expanded bandwidths across the entire frequency spectrum have been obtained and are now commonly included in our designs. We now have a new vocabulary that includes as a minimum high electron-mobility transistors (HEMTs), pseudomorphic high electron-mobility transistors (p-HEMTs), indium phosphide high electron-mobility transistors (InP HEMTs), microwave/millimeter-wave integrated circuits (MMICs), high-temperature superconductivity (HTSC), and expanding. We anticipate newer and more advanced devices to be developed to meet the needs of tomorrow's systems. We have already witnessed the explosive growth in wireless and satellite communication systems.

But first, let use consider where we started. In the 1980s, LNAs were developed for the microwave and low millimeter-wave region. Mixers were generally the front-end component of choice in the millimeter- and submillimeter-wave region. We now have practical low-noise millimeter-wave satellite systems operating around 30 GHz (TDRS H, I, J) and above, collision-avoidance systems used on buses and cars that operate around 77 GHz [2]. LNAs for remotely sensing the Earth's environment from a satellite platform have been developed at 200 GHz. Significant progress to improve low-noise performance, enhance system capability while simultaneously making the systems smaller, lighter weight, lower power, broader bandwidth, and increasing the frequency of operation has been made. Multichip module (MCM) millimeter-wave modules (Fig. 2) have been developed for space applications using MMIC amplifiers. With these new technologies, phased arrays with their unique capability are becoming more practical and affordable. HTSC is an area that has tremendous promise if higher temperature material could be developed beyond the present 100-K threshold. Low noise has been and still is a multidimensional growth area. We will explore a few of the paths taken by LNAs from the 1980s to today. We will consider some of the new developments that have been made, and ponder where we are heading and how these low-noise developments will impact future applications and the new system architectures.

II. MASERS

The technological advances, particularly in LNAs, that we had seen from the end of World War II were dynamic and

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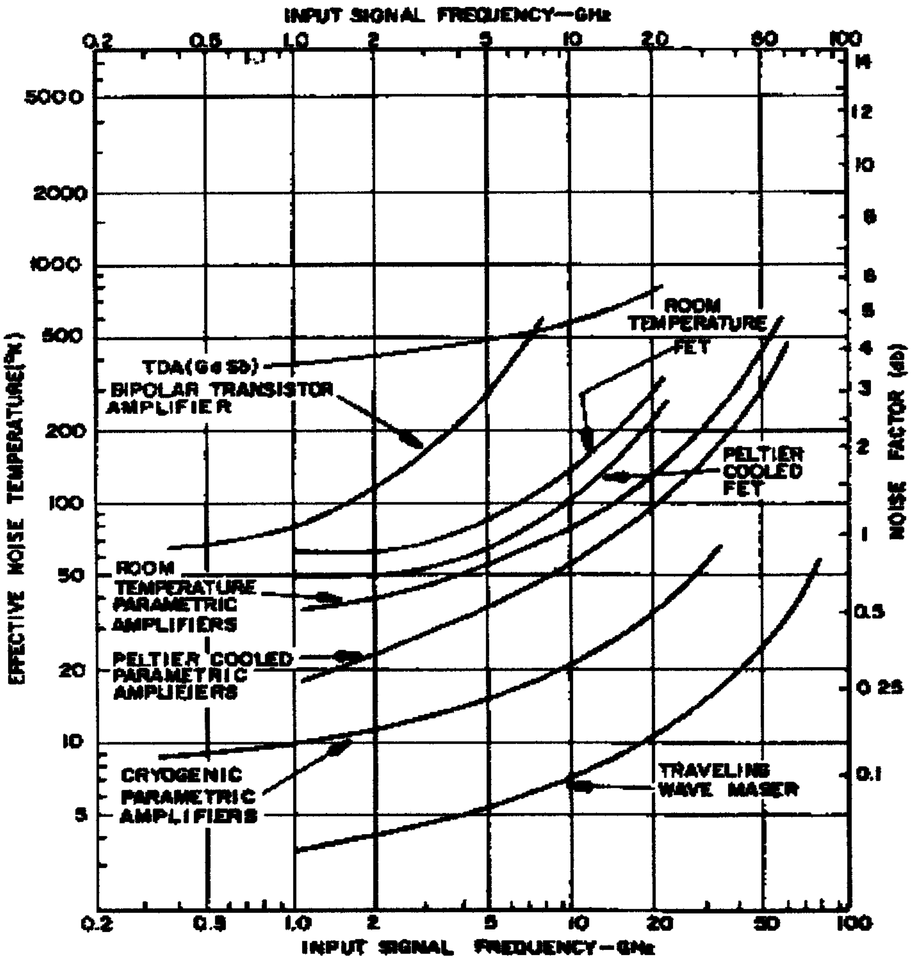

Fig. 1. State-of-the-art performance of LNAs.

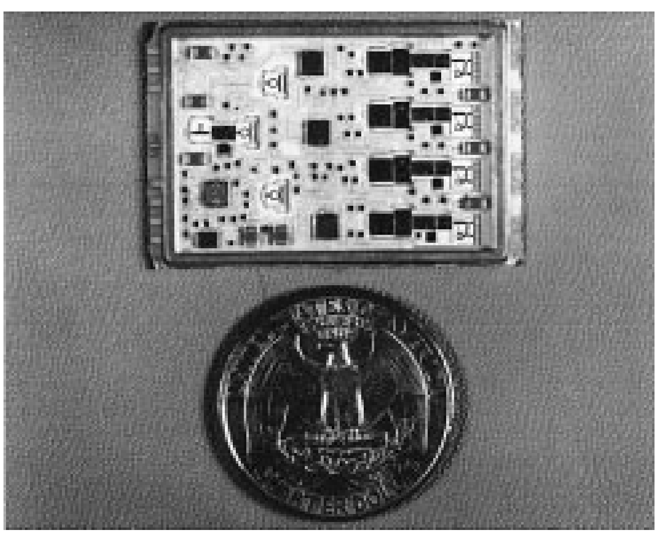

Fig. 2. Millimeter-wave MCM module (courtesy of the EDO Corporation).

enabled us to design systems that were only speculative in the past. In the early 1980s, ultra-low-noise performance generally required amplifiers to be cryogenically cooled to liquid nitrogen temperatures (77 K) and even lower temperatures (4 K). Cryogenically cooled amplifiers were extensively used in satellite communication ground terminals due to the limited transmitter power available in the spacecraft, and by the radio astronomers who required highly sensitive receivers to explore the wonders of the universe. They were also developed for the Jet Propulsion Laboratory (JPL) deep space network (DSN) to maintain the long communication links with the spacecraft that were being launched to explore the solar system. Most of the LNAs had relatively narrow bandwidths (about 5%–15%). However, when the ultimate in low-noise performance was required, the only LNA that could satisfy these demands was the MASER, a narrow-band LNA ($\sim$5%-10%). However, this LNA had to be cryogenically cooled to liquid-helium temperatures ($\approx$4 K). Both traveling-wave masers (TWM) and cavity masers were originally developed. However, the instantaneous bandwidth of the TWM was broader and became the MASER of choice in most cases. Some of the early MASERs were physically immersed in a bath of liquid helium, but the operational duty cycle was very limited. With the availability of closed-cycle refrigerators, the MASER became more acceptable. A MASER is a very complex amplifier that is large, heavy, and consumed lots of power (kilowatts). Most of this power was used for the cryogenic refrigerator that cooled the maser structure to 4.5 K. The TWM MASER amplifies microwave signals that are propagating along the length of a tuned ruby crystal (other crystals were also used) in a slow-wave structure. The ruby crystal is cooled to a bath temperature of about 4.5 K. The

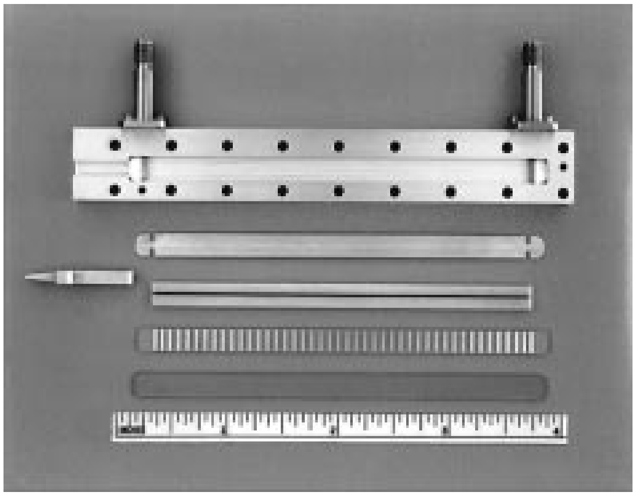

Fig. 3. X-band TWM assembly (courtesy of the Jet Propulsion Laboratory, California Institute of Technology).

physical details of an X-band TWM structure are shown in Fig. 3 [3]. The noise temperature (Te) of the MASER structure is directly proportional to its operating temperature, as shown by the following equation [4]:

$$Te = T_B/I$$

where

- Te noise temperature of the TWM;
- T_B physical temperature of the ruby crystal;
- I inversion ratio-constant determined by the material.

The noise temperature of a cavity maser and the TWM MASER are essentially the same for a high gain case when a relatively low-loss slow-wave structure is used. An X-band MASER structure that operates at a bath temperature of 4.5 K, with an inversion ratio of approximately 2.8, has a theoretical noise temperature of 1.6 K. The noise temperature of the LNA measured at the room-temperature flange is approximately 3.5 K. As the bath temperature of the MASER structure is raised or lowered, the noise temperature is raised or lowered proportionally. Since the MASER structure is mounted on a cold station at 4.5 K, low-loss input and output lines coupled with high thermal isolation were required to achieve the low-noise temperature at the room-temperature input flange. Many innovative low-noise techniques were used over the years to minimize the input line loss, such as gold flashed stainless-steel lines, gapped waveguide structures in the cryogenic environment, antenna horns attached to the intermediate cold station (77 K), etc. In addition, ancillary lines that included the waveguide for the pump source, bias lines for the magnet, etc. were also required. The entire structure was enclosed in a vacuum chamber to minimize the heat load. A photograph of an X-band MASER [5] without the compressor and ancillary equipment box is shown in Fig. 4 and demonstrates the complexity of this LNA. An S-band MASER operating at 2.2 GHz had a noise temperature of approximately 2 K at its input terminal, a gain of 30 dB, with a bandwidth of 20 MHz. An X-band MASER had a noise temperature of 3.5 K at the feedhorn aperture, a gain of 40 dB, and a bandwidth of 100 MHz. As the technology has progressed, Ka-band cavity masers are becoming the preferred design approach because of lower pump power requirements and smaller volume when compared to the TWM. For these units, noise temperatures of 5 K with a gain of 35 dB and a bandwidth of 85 MHz have been achieved in an open-cycle liquid-helium system. For future systems, it appears that cavity masers could be the preferred choice over TWMs for future DSN applications [5].

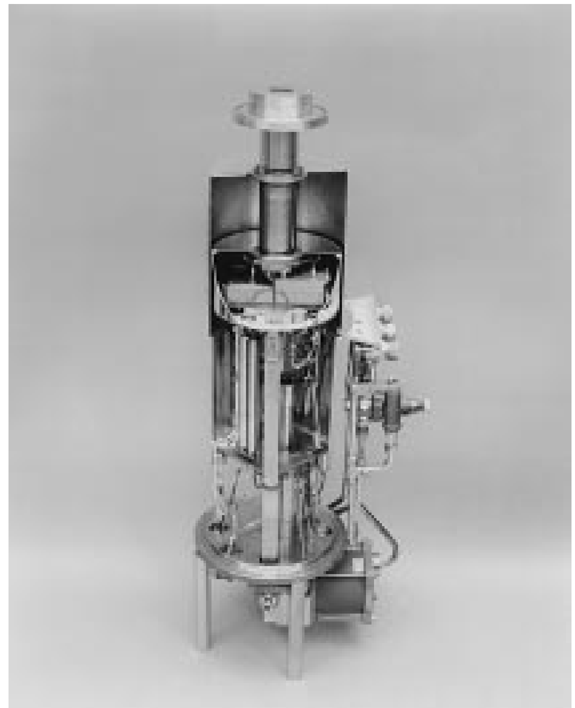

Fig. 4. X-band TWM internal cryogenic structure (courtesy of the Jet Propulsion Laboratory, California Institute of Technology).

The active element for the maser was a ruby crystal, although other crystals were also used, that was placed in a very high magnetic field, normally provided by a superconducting magnet that was also operated at 4.5 K. The superconducting magnet was used to minimize the thermal load on the refrigerator. It normally was an air-core solenoid made of niobium–zirconium wire. Some of the magnets were as large as 7.5 in in diameter, 5 in in length, and weighed about 3 lb. The magnet generated a magnetic field of about 4500 G with a current of 6.5 A.

Improvements in MASER technology that improved RF performance and its size has been achieved over the years. However, new technologies have started to compete successfully with it. Some of the MASER amplifiers are being supplemented by cryogenically cooled HEMTs that operate at 12 K and lower. While still having the complexity of cryogenic cooling, these refrigerators are less expensive, much smaller, and consume a lot less power. Cryogenically cooled HEMTs have been developed that are now being used in the JPL's DSN. For example, an X-band InP HEMT operating in a 6-K refrigerator achieved a noise temperature of 4.5 K. The DSN is now using both MASERs and cryogenically cooled HEMTs in their ground terminals. While the physical structure of the HEMT cryogenically cooled amplifier is still complex, broader instantaneous bandwidths and almost comparable noise

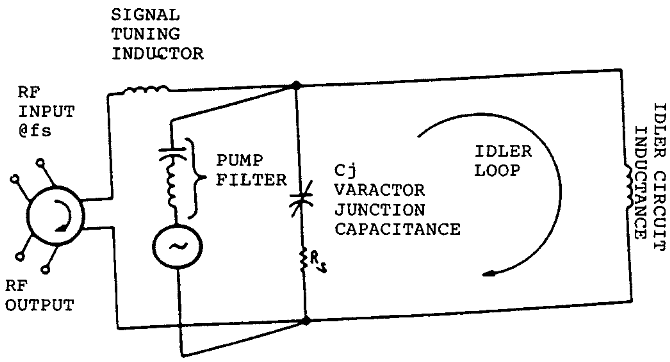

Fig. 5. Paramp circuit diagram.

performance can be obtained. At Ka-band, a noise temperature of 16 K has been achieved with an InP HEMT cooled to 6 K. However, further improvements for the HEMTs are anticipated, and, in the future, cryogenically cooled HEMTs may come very close to the noise performance that is now obtained only with the MASER.

III. Paramps

In addition to the MASER, the paramp became the amplifier of choice for many low-noise applications. The paramp not only provided extremely good low-noise performance at room temperature, but gave excellent performance when cooled to cryogenic temperatures. Two basic types of paramps were used, i.e., the nondegenerate and degenerate amplifier. The nondegenerate amplifier, a single-sideband amplifier, was commonly used for communication and radar applications. The degenerate amplifier was used in double-sideband applications where the signal was broad-band noise used in radio astronomy applications. Paramps maintained their LNA lead position until the FETs, HEMTs, etc., excelled in their low-noise performance and other attributes. However, the paramp did serve a very unique low-noise market that could not have been served by any other amplifier at the time.

Paramps use the nonlinear capacitance variation of a reverse-biased varactor diode to provide the basic amplification mechanism. As shown in Fig. 5, the varactor is "pumped" at a frequency fp, which is usually an order of magnitude higher than the signal frequency fs (for a nondegenerate amplifier). The paramp requires an "idler" circuit that allows current to flow at the difference frequency that is generated by mixing the pump and the signal frequency in the nonlinear capacitance. Through this mechanism, energy from the pump circuit is transferred to the signal frequency, thereby providing gain. Actually, the pumped varactor appears as a negative resistance at the signal frequency. A nonreciprocal three-port ferrite isolator with good isolation shown in Fig. 5 is used to separate the input signal from the output signal.

The noise temperature Te of the nondegenerate paramp (less the circulator loss) is shown as follows: [6]:

$$Te = \left[\frac{\dfrac{fs}{fi} + \dfrac{fsfi}{M^2}}{1 - \dfrac{fsfi}{M^2}} \right] T_D$$

where

- fs signal frequency;
- Fi idler frequency $= fp - fs$;
- M varactor figure-of-merit $= afc$;
- a varactor nonlinearity ratio;
- fc varactor cutoff frequency;
- T_D varactor junction temperature.

The varactor cutoff frequency is defined by the following expression:

$$fc = 1/2\pi RsCo$$

where

- Rs varactor equivalent series resistance
- Co effective operating junction capacitance.

GaAs Schottky varactors with high self-resonant frequencies (>30 GHz) had operating cutoff frequencies in excess of 500 GHz. Varactors generally used GaAs as the intrinisic semiconductor material. The varactors had excellent performance at both room and cryogenic temperatures and a variety of paramps were available for the system design engineer. These LNAs were designed to operate at 20 K, 77 K, thermoelectrically cooled to -40 °C, as well as room temperature. However, similar to the MASER, paramps were relatively complex designs. The paramp generally required a very high-frequency pump source that operated at a millimeter-wave frequency. The pump source had to be temperature stabilized since changes of 0.1 dB in pump power resulted in 1.0-dB changes in gain. In addition, the circulator and paramp mount were generally integrated to control the impedance match between them to achieve unconditional stability. The circulator and paramp also had to be temperature stabilized. In addition, depending on the type of paramp used, they could be relatively large, heavy, and consumed a lot of power. A photograph of a two-stage cryogenically cooled paramp (without the compressor) that operated at 20 K is shown in Fig. 6. Over the operating frequency range of 3.7–4.2 GHz that was used for a satellite communication ground terminal, this LNA had a gain of 30 dB and noise temperature around 15 K. As varactor cutoff frequencies and circulator insertion loss improved, noise temperatures that could be obtained at room temperature were lowered. At the same time, transmitter power in the satellites was increasing. With the exception of the radio astronomers, the trend was to develop smaller, lighter weight, more economical paramps that could still meet the G/T_{op} system requirements. Thermoelectric coolers were also becoming more efficient and reliable. As a result, many new paramp designs were being developed using thermoelectric coolers where the paramp mount and circulator were cooled to about –40 °C. A thermoelectrically cooled paramp (Fig. 7) that was cooled to -38 °C had a noise temperature of 30 K over the 3.7–4.2-GHz frequency band. Comparing these two LNAs (Fig. 6 versus Fig. 7), it is quite obvious that the size and weight for the TE cooled paramp was much less than for the cryogenically cooled paramp. Since the TE cooled paramp met the ground-station requirements, they were used in the new systems and were replacements for the cyrogenically cooled units. Paramps operated successfully to about 20 GHz and a little beyond. Paramps were developed that

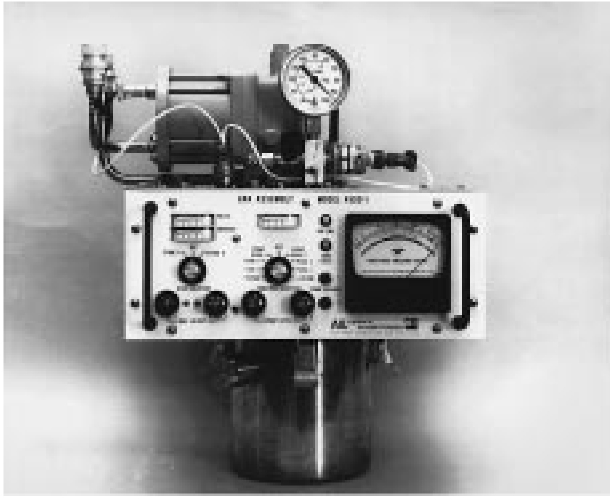

Fig. 6. Cryogenically cooled paramp (courtesy of the EDO Corporation).

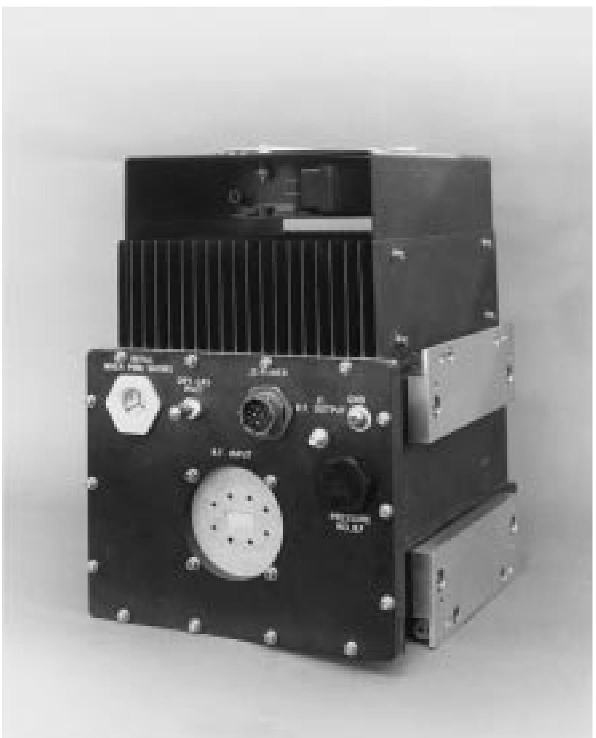

Fig. 7. Thermoelectrically cooled paramp (courtesy of the EDO Corporation).

operated at 60 GHz [7] and as high as 94 GHz [8], but these were the exception, and not the rule. However, the coming of age of the FETs, HEMTs, etc., was to change all of this. It was not long before the room-temperature and TE-cooled HEMT became the workhorse for many old applications, and enabled the LNAs of choise for new ones, thereby replacing the paramp.

Since a paramp requires a nonlinear capacitance for its mode of operation, it is basically a relatively narrow-band device. However, the paramp was capable of providing much greater bandwidths than the MASER. To achieve the broadest possible instantaneous bandwidth, the balanced amplifier was developed that used the self-resonant frequency of the varactor for the idler circuit. This paramp had a bandwidth of approximately 10%–15%.

One application that tested the performance and reliability of the paramp was the S-band communication link for the space shuttle. The space shuttle was required to communicate with the tracking ground terminals during liftoff and in orbit either directly or through the TDRSS satellite. The S-band communication antennas are located at the front-end of the shuttle. The S-band preamplifier assembly (LRU) is located on a shelf away from the antennas and, therefore, has a relatively long interconnecting line between them. The LRU had a transmit/receive diplexer, a redundant paramp followed by a bipolar amplifier. Size prevented the paramp from being integrated more closely with the antenna, and a lower noise LNA was required to meet the performance objectives. The paramp was the only LNA at the time that could meet these noise-figure requirements. The paramp was pumped at 50 GHz with a thermally stabilized Gunn oscillator. The Gunn oscillator was isolated from the paramp mount by a small section of gold flashed plastic waveguide. The four-port circulator used fiberglass ground planes that were gold plated. This innovative design served the dual purpose of both reducing the power consumption to achieve fast warmup, as well as meeting the low insertion loss to meet the noise-figure requirements. The redundant paramp performed extremely well over these many years. However, due to obsolescence of many of the component parts required for the paramp, a replacement for the paramp was required. After over 20 years of successful operation, the redundant paramp is finally starting to be replaced by a high reliability redundant HEMT amplifier that meets the 1.3-dB noise figure at the highest operating temperature. However, until the retrofit is complete, the majority of shuttles today still operate with a paramp in the S-band communication link. A photograph of a single paramp and its HEMT replacement that will be eventually installed in the space shuttle LRU is shown in Fig. 8. The noise figure for the HEMT amplifier is about the same as the paramp, but the size, weight, and power have been significantly reduced. This figure clearly demonstrates that not only has the RF performance been at least equaled, but that the LNA size and weight has been greatly reduced. Power dissipation has also been significantly reduced. The reliability of the system is also increased due to the significant reduction in the number of components and junction operating temperature. With further improvements in MMIC technology to improve overall RF performance, a further reduction in size, and providing more functions on a single chip, the LNA could eventually be integrated with the antenna to achieve optimum performance. The new technology introduced by the FETs, HEMTs, and MMIC components were rapidly changing LNA performance. These new technologies were to open the way for many new applications that were not even considered or possible during the brief age of paramps.

IV. FETs and HEMTs

The new technological developments in LNAs that started before the 1980s has rapidly progressed to the present day. This continuous improvement in three-terminal devices (i.e., FETs, HEMTs, etc.) has led to better performance in noise temperature, gain, bandwidth, frequency of operation, power

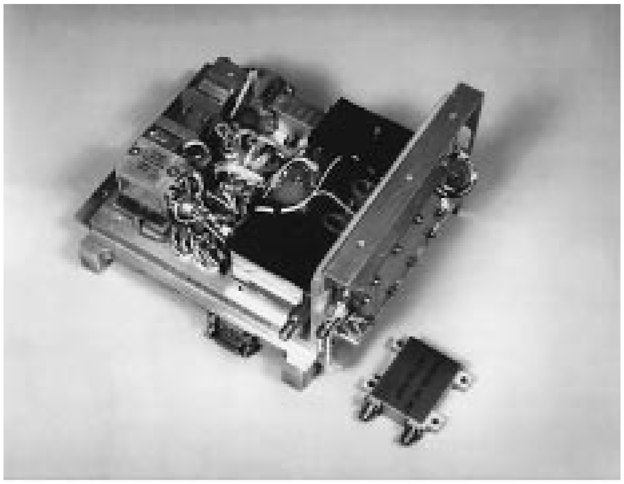

Fig. 8. Space shuttle paramp and its HEMT replacement (courtesy of the EDO Corporation).

dissipation, size, and reliability, as a minimum. With these developments, we have greatly expanded the capabilities of both our present and new systems. The performance of FETs in the early 1980s has been shown in Fig. 1. Prior to that time, GaAs FETs were developed for low-noise performance, clearly having better performance than the bipolar transistor. MESFETs and HEMTs were also under development. For example, in 1972 [9], it was reported that FETs had achieved a $F\max$ in excess of 30 GHz. A typical device at 4 GHz with a $G\max$ of 11 dB had a noise figure of 3 dB. At 8 GHz, a transistor achieved a $G\max$ of 7 dB with a noise figure of 4 dB. From these early developments, rapid improvements in semiconductor materials and processes led to greatly improved performance. If we consider the equation for minimum noise figure for FETs, we can readily determined where improvements in device parameters are required.

For FETs, the minimum noise figure is described by [10]

$$F\min = 1 + k_1 f Cgs\big[(Rg + Rs)/gm\big]1/2$$

where

$F\min$	minimum noise figure;
k_1	fitting factor;
f	frequency of operation;
Cgs	gate/source capacitance;
gm	transconductance;
Rg	gate resistance;
Rs	source resistance.

As we can see, a reduction in Cgs as well as increasing the transconductance is beneficial to reducing the minimum noise figure. In fact, transconductance has been dramatically increased over the years. This increase has been achieved as we went from FETs, to HEMTs, to p-HEMTs, and then to InP HEMTs. By 1974, MESFETs (GaAs FETs with Schottky–barrier gates) were reported that combined low noise with high gain and high dynamic range [11]. A broad-band amplifier with a gain of 20 dB over the entire 8.0–12.0-GHz frequency band with a noise figure of 5.5 dB was developed. We were then introduced to the HEMTs. HEMTs have higher cutoff frequencies than FETs due to their higher electron mobility and, therefore, has a lower noise figure. We were then acquainted with the p-HEMTs, and now the InP HEMTs. As the devices improved, the achievable noise figure in the microwave region was continuously lowered, while, at the same time, the frequency of operation was moving higher due to the increase in transconductance and the reduction in gatelength. In addition, the devices could be cryogenically cooled and, therefore, extremely low-noise temperatures were achieved. The high transconductance (≈1700 mS/mm) for the InP HEMTs has increased the operating frequency range, gain bandwidth, and provided the low-noise performance for LNAs. InP HEMTs have a gm of about 1000 mS/mm, which is almost twice the value of p-HEMTs. Recently, the performance of a MMIC LNA that operates at 183 GHz with a gain of 20 dB over a 30-GHz bandwidth has been reported [12]. The noise figure of the LNA was less than 5.5 dB. A photograph of the three-stage MMIC LNA is shown in Fig. 9. The amplifier used 0.08-μm gate InP MMIC technology. The device has a transconductance that is greater than 1000 mS/mm, a cutoff frequency above 200 GHz, and an oscillation frequency above 400 GHz. Similar performance is also being reported by other researchers [13]. Remarkable progress has been made in LNAs over these years and we expect to have even more breakthroughs in the near future.

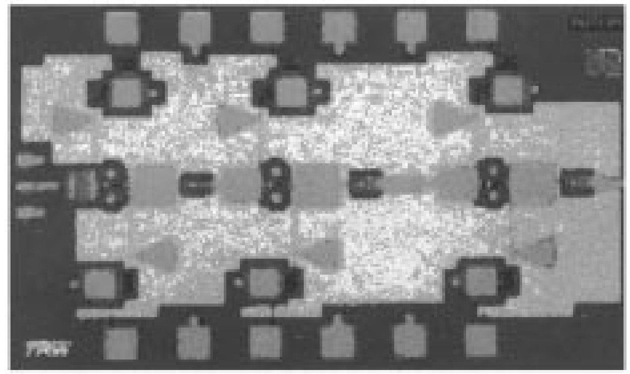

Fig. 9. Three-stage MMIC LNA at 183 GHz [12].

It is virtually impossible to enumerate all the advances that have been made in this paper. For this reason, we will highlight some of the achievements that have been reported. In Table I, [13], [14], we have tabulated the performance of both discrete/MMIC LNAs that have been reported. This is not a complete list, but does show what has been accomplished in a relatively short time.

The HEMTs, p-HEMTs, and InP HEMTs devices have been continuously improved to significantly lower the noise performance of LNAs. By cooling these LNAs in TE coolers or cryogenic systems, low-noise performance has been dramatically improved. As stated previously, cryogenically cooled HEMTs are now being used in the JPL DSN and are coming close to competing with the MASER. At X-band, an InP HEMT cooled to an operating temperature of 6 K had a noise temperature of 4.5 K at the aperture of the feedhorn [5]. At 32 GHz, a cryogenically cooled HEMT had a noise temperature of 16 K when cooled to the same 6 K. A MMIC LNA at 90 GHz had a noise temperature of 62 K when cooled to 27 K [27]. A broad-band

TABLE I

SUMMARY OF DISCRETE/MMIC LNAS

FREQ GHZ	NOISE FIGURE-dB	GAIN-dB	YEAR	CRYO	REF.
2.3-2.5	0.4	35	1993	No	15
7.0-11.0	1	21	1993	No	16
19.0-22.0	1.1	38	1995	No	17
20-25	0.4	35	2000	YES	18
43.0-46.0	1.9	22	1995	No	19
50	2.8	9	1994	No	20
60	2.2	22.8	2000	No	21
56.0-60.0	3.2	15	1992	No	22
56.6-64.0	2.7	25	1993	No	23
60-80	2.3	25	2001	No	24
73-77	0.4	25	2001	YES	24
75.0-110.0	6	23	1993	No	25
92.0-96.0	3.3	20	1995	No	26
82-106	1.6	35	2000	YES	18
183	5.5	24	2001	No	12

InP MMIC LNA that covered the 65–110 GHz had a noise temperature of 45 K across the operating bandwidth. This amplifier had a noise temperature of 30 K at a frequency of 102 GHz [28]. We can only speculate where further improvements in transistor technology will eventually lead us. However, if we review what has been recently accomplished, we can only look to the future with a great deal of anticipation.

V. Conclusion

We have seen dramatic improvements over these few years, not only in lowering noise-figure performance, but also in extending the frequency to which LNAs now operate, the broad bandwidths, as well as reductions in size, weight, and power. We can only speculate on what the future will bring. Further reductions in noise figure coupled with lower power dissipation is one of the thrusts today. However, advances in other disciplines will also drive the performance of the low-noise LNA if the technological developments come to pass. For example, if HTSC could eventually operate at room temperature, not only would we see dramatic improvements in LNAs, but also in the system architectures. However, this is but one of many future development to which we can look forward.

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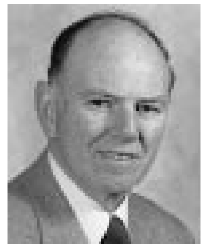

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