FET's and HEMT's at Cryogenic Temperatures—Their Properties and Use in Low-Noise Amplifiers

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Abstract—**This paper reviews the performance of a number of FET's and HEMT's at cryogenic temperatures. Typical dc characteristics and *X*-band noise parameters are presented and qualitatively correlated wherever possible with other technological or experimental data. While certain general trends can be identified, further work is needed to explain a number of observed phenomena. A design technique for cryogenically cooled amplifiers is briefly discussed, and examples of realizations of *L*-, *C*-, *X*-, and *K*-band amplifiers are described. The noise temperature of amplifiers with HEMT's in input stages is usually less than half of that for all-FET realizations, setting new records of performance for cryogenically cooled, multistage amplifiers.**

I. Introduction

THE FEASIBILITY of cooling GaAs FET amplifiers has been very well documented [1], [2]. Recently, very low noise temperatures for cryogenically cooled HEMT's have also been reported [3], [4], [34]. It has long been recognized, however, that the cryogenic performance of both HEMT's and FET's may not be inferred from room-temperature performance. In fact, for both HEMT's and FET's several different phenomena were observed which render some devices useless for cryogenic applications. Besides low-noise applications, the emerging importance of cooling of HEMT's and FET's for high-speed applications makes it important at least to list the observed phenomena, even without full explanation. While certain general trends can be identified, their explanation is not possible, even qualitatively, without detailed knowledge of the device structure and processing. For obvious reasons, this information is not always easily available. This paper is, therefore, intended to provide a comprehensive view to what is observed in HEMT's and FET's at cryogenic temperatures. The second section deals with FET's, the third with HEMT's, the fourth describes briefly a computer-aided design technique of cryogenically cooled amplifiers and gives examples of amplifiers built with cryogenically well-behaved FET's and HEMT's for *L*- through *K*-band frequency range.

Manuscript received April 24, 1987; revised September 15, 1987.
The authors are with the National Radio Astronomy Observatory, Charlottesville, VA 22903. The observatory is operated by Associated Universities, Inc. under contract with the National Science Foundation.
IEEE Log Number 8718363.

II. FET's

Sample transistors of the following types have been tested at cryogenic temperatures: MGF1412, MGF1405 (Mitsubishi), NE75083, NE04583, NE71083 (NEC), FSC10FA, FSX02FA (Fujitsu), 2SK525 (Sony). While the choice of transistors is hardly balanced, it follows the past history of good cryogenic performance [1], [2], [18]–[20].

Table I presents the comparison of noise performance of FET's that were found most useful for cryogenic application. Table II gives the room-temperature noise parameters of the same FET's. All were measured by the method described in [12] with estimated accuracy of T_{min}: ± 9 K and ± 1.5 K, R_{opt}: $\pm 1.5\ \Omega$ and $\pm 0.7\ \Omega$, X_{opt}: $\pm 4\ \Omega$, g_n: ± 1.5 mS and ± 0.7 mS, at 297 K and 12.5 K, respectively. A description of the test fixture used both for dc and noise measurement is given in [3], [4], and [13]. Although the data of Tables I and II are self-explanatory, the following comments could be useful.

There appears to be no correlation between room- and cryogenic-temperature values of minimum noise temperature T_{min}. It can be explained [1] by a large difference in the relative contribution of thermal noise in parasitic resistances to the value of T_{min} at room and cryogenic temperatures. However, as subsequently demonstrated, large differences between cryogenic dc characteristics for different FET's which are not understood should be considered another contributing factor.

The spread in minimum noise temperature between transistors of the same type but from different lots is much greater than from within the same lot. In fact, in the latter case the spread may be as low as 2 K. For repeatable cryogenic performance of amplifiers, it is always useful to use transistors from the same lot.

Relatively poor cryogenic noise performance for FET's with otherwise orderly behavior can usually be traced to the poor pinch-off characteristic at the cryogenic temperatures, not necessarily noticeable at the room temperature. As an example, a comparison of room- and cryogenic-temperature characteristics of two NE75083 FET's having very different noise performance at cryogenic temperatures (15 K and 23 K at 8.5 GHz) is shown in Fig. 1. Note the small differences in room-temperature characteristics, as

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TABLE I
NOISE PERFORMANCE COMPARISON OF BEST GaAs FET'S AT 8.5 GHz AND 12.5 K

TYPE	GATE		BIAS		NOISE PARAMETERS OF SAMPLE FET				RANGE OF T_{min} [K]		ASSOC. GAIN dB
	L µm	W µm	V_{ds} V	I_{ds} mA	T_{min} K	R_{opt} Ω	X_{opt} Ω	g_n mS	MIN	MAX	
MGF1412	.7	400	4.5	10	20	7.1	38	3.7	18	26	12
FSC10FA	.5	400	3	10	20	3.6	32	6.6	15	24	9
NE75083*	.3	300	3	10	15	4.5	32	4.3	15	23	11.1
FSX02FA		200	2	5	17	5.9	24	4.5	-	-	11.5
NE04583	.3	200	1.5	5	19	3.7	42	6.1	-	-	11.4

*NE75803 production has been discontinued.

TABLE II
ROOM TEMPERATURE NOISE PERFORMANCE OF FET'S OF TABLE I AT 8.5 GHz

Device	V_{ds} V	I_{ds} mA	T_{min} K	R_{gopt} Ω	X_{gopt} Ω	g_n mS	G_{AS} dB
MGF1412	3	10	122	13.4	40	11.5	9.0
FSC10FA	2.5	10	125	10.7	33	12.8	7.3
NE75083	3	10	89	9.4	32	8.4	9.7
FSX02FA	2.5	10	94	9.4	23	10.3	10.3
NE04583	3	10	84	8.2	42	12.1	10.3

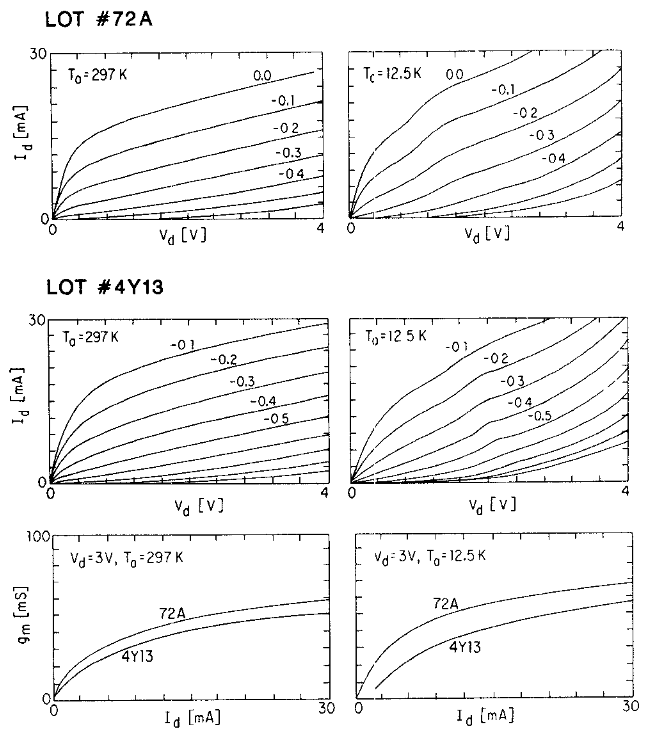

Fig. 1. The dc characteristic at room and cryogenic temperatures of two NE75083 FET's of the same type with different cryogenic noise performance at 8.5 GHz. Lot #72A FET exhibited $T_{min}=15$ K. Lot #4Y13 FET exhibited $T_{min}=23$ K.

opposed to large differences at 12.5 K between these two transistors. Worse pinch-off characteristics for the lot 4Y13 in comparison with lot 72A can be qualitatively explained by different crystal quality and/or electrical characteristics of the interface region between the semi-insulating buffer layer and the active layer. The importance of the quality of the interface for low-noise room-temperature operation has been known [22], [23]. It appears from this example that the cryogenic noise performance is much more sensitive to characteristics of the interface region than the room-temperature performance.

For most of the FET's, the dc measured transconductance g_m does not vary appreciably upon cooling. It usually goes up by about 20 percent of the room-temperature value. However, examples can be found to the contrary, as is shown in Fig. 2, where dc measured transconductance g_m is plotted as a function of ambient temperatures for the transistor samples of Tables I and II. A notable exception is the MGF1412 transistor (Fig. 2), where an increase in

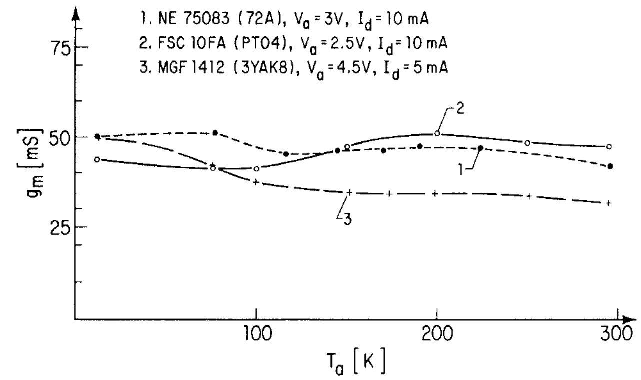

Fig. 2. The measured transconductance as a function of ambient temperature for some FET samples of Tables I and II.

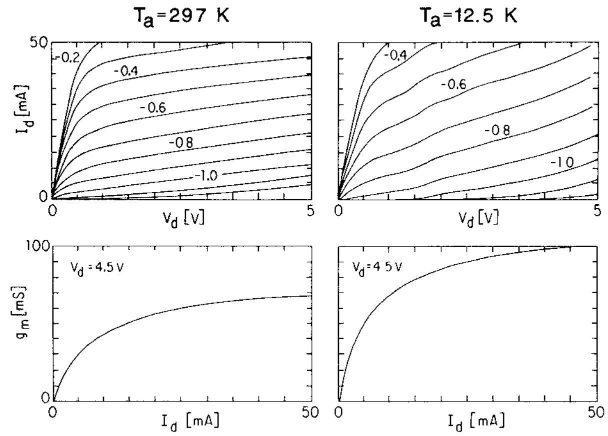

Fig. 3. Typical dc characteristics at room and cryogenic temperatures of MGF1412 FET (3YAK8) exhibiting $T_{min} = 20$ K at $f = 8.5$ GHz and $T_a = 12.5$ K.

transconductance as large as 50 percent of the room-temperature value was observed; this is about the same as for good cryogenic HEMT's (30 to 60 percent increase [3], [4]). An example of the dc characteristic of the MGF1412 FET is shown in Fig. 3. For all FET's, together with an increase in transconductance, a reduction of small-signal shunt drain resistance is observed (Figs. 1 and 3).

Theoretical studies [5]–[7] predict linear dependence of the minimum noise temperature on the gate length, even for submicron gate devices [6], [7]. In this light, comparison of the gate dimensions (published by the manufacturer) with the noise performance of the best FET's (Table I), which reveals no correlation, indicates the importance of quality and/or structure of epitaxial GaAs from the point of view of cryogenic applications. In particular, the superb quality of MGF1412 epitaxial GaAs and/or structure is quite apparent. The cryogenic dc data, notably the $g_m = f(I_{ds})$ characteristic, also support this conclusion. Bearing in mind that the existence of trapping centers, especially at the channel substrate interface, could greatly influence the properties of cryogenic FET's, it is interesting to point out that MGF1402/12 FET's have been found to exhibit the lowest $1/f$ noise spectra at room temperature [24], also attributed to the existence of traps.

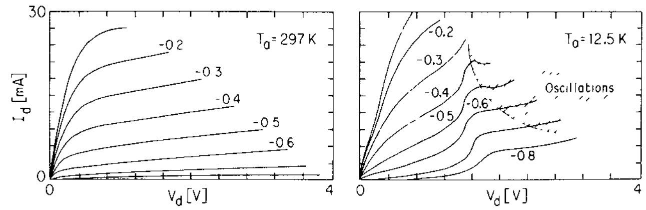

Fig. 4. Example of unusual distortion of $I-V$ characteristics at cryogenic temperatures observed for NE71083 FET's.

Not all transistors present such an orderly behavior when cooled as those in Figs. 1 and 3. Unusual distortion of the $I-V$ characteristic (example of NE71083 is shown in Fig. 4) or oscillations which are most likely caused by the Gunn type instabilities in GaAs (a number of MGF 1405 transistor samples) are sometimes present. Other relevant data can be found in [14].

III. HEMT's

The sample HEMT's of the following type have been tested: H-503-P70 (Gould-Dexel), JS8901-AS (Toshiba), 2SK676 (Sony), and FHR01FH (Fujitsu). Samples of their dc characteristics at room and cryogenic temperatures are shown in Figs. 5 and 6, and a comparison of their noise performance is given in Table III. All these HEMT's had to be illuminated with light to be time-invariant, memoryless devices at cryogenic temperatures. A red-light-emitting diode has been used for illumination. With the notable exception of FHR01FH, all failed to pinch off properly at the cryogenic temperatures, exhibiting a large portion of drain current not controlled by the gate voltage. Judging from the available manufacturer information [8]–[10], this effect seems to be linked to the very high doping ($2-3\times10^{18}$ cm^{-3}) of the AlGaAs layer. Devices with moderate doping, as reported in [3] and [34], do not exhibit this effect.

The dc characteristics at 12.5 K have been measured also for a dark Fujitsu HEMT, which was previously illuminated, and are shown in Fig. 6. In this case, it is important to specify the measuring procedure, since in the dark the device possesses memory and is not time-invariant, as indicated earlier. The $I-V$ characteristics of Fig. 6 were taken stepping the drain voltage from 0 to 2.5 V for each of the gate voltages, starting at $V_{gs} = -0.9$ V. It is shown here to demonstrate that the illumination greatly affects the measured characteristics at relatively small drain voltages, while at $V_{ds} = 2.5$ V the effect of illumination becomes insignificant. The "wiggles" of $I-V$ characteristics of an illuminated HEMT ($V_d < 0.75$ V) have been determined to be the result of an insufficient amount of light reaching the intrinsic HEMT (hence, the HEMT is not a memoryless device in this region), as they were taken for packaged HEMT. Care was taken to eliminate parasitic oscillations as a probable cause of this effect. Also, sample characteristics of an FHR01X chip, sufficiently illuminated and dark, were taken and are shown in Fig. 7.

The observed dc behavior of the Fujitsu HEMT at 12.5 K is qualitatively the same as recently reported in [25] and is linked to the existence of DX centers in doped AlGaAs.

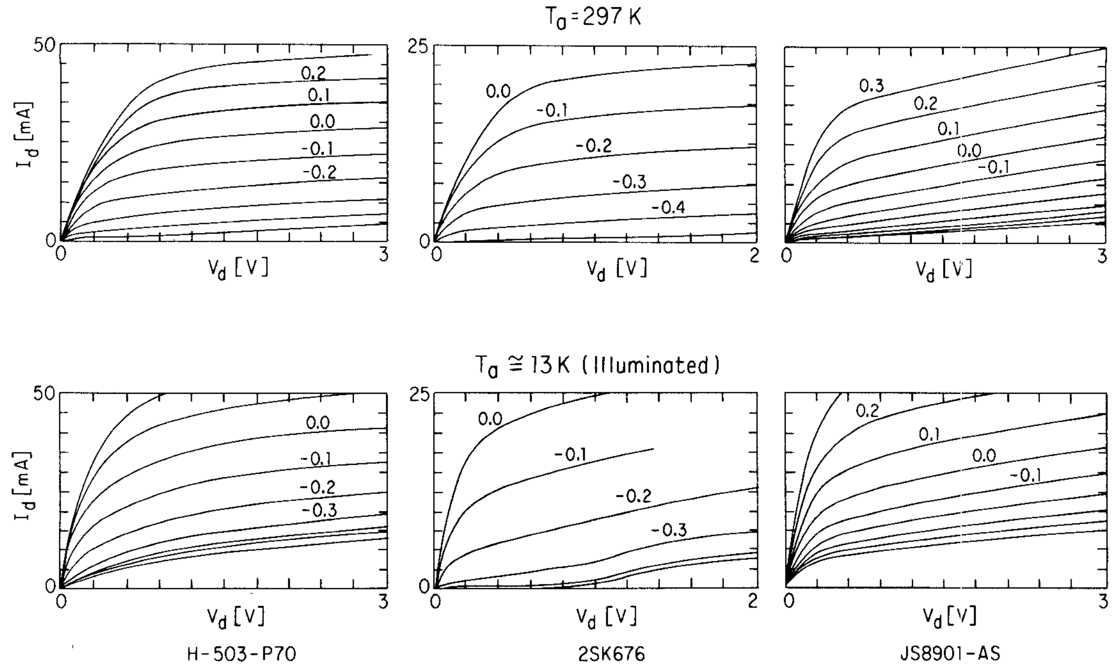

Fig. 5. Examples of room and cryogenic temperature characteristics of commercially available HEMT's. All were taken with light illumination.

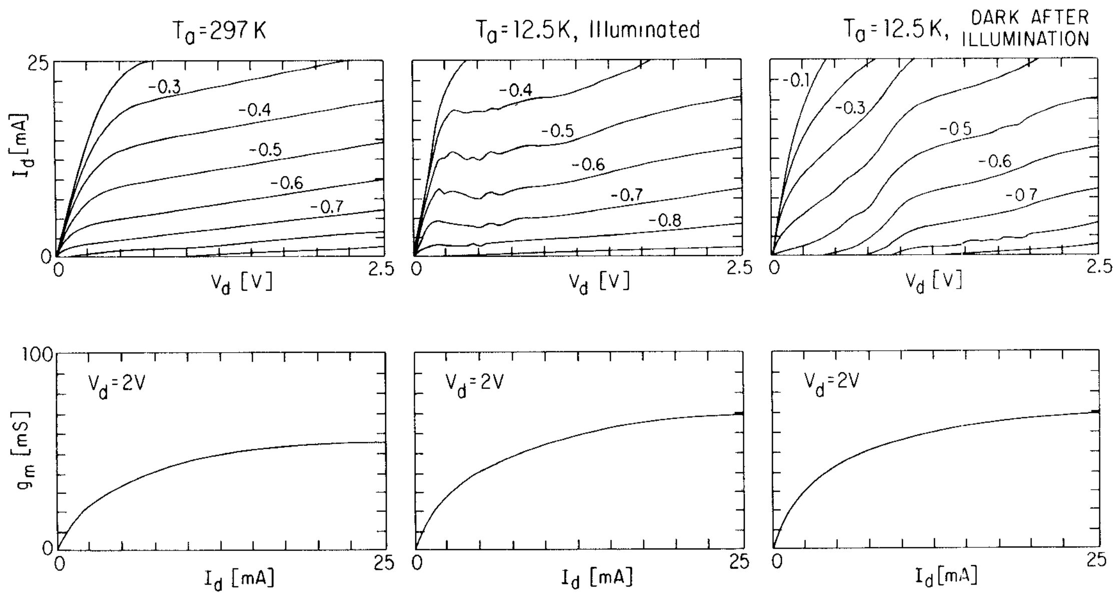

Fig. 6. The dc characteristic of FHR01FH HEMT with excellent cryogenic noise performance, demonstrating the effect of light illumination. Note large influence of light at small drain voltages. (Compare Fig. 7.)

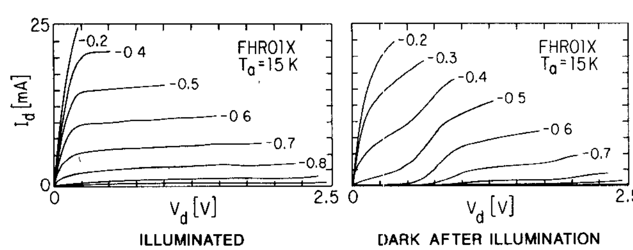

Fig. 7. The comparison of dc characteristics at 12.5 K for FHR01X chip, for which the amount of light reaching AlGaAs layer was sufficient. (Compare Fig. 6.)

TABLE III
CRYOGENIC NOISE PERFORMANCE OF SAMPLE HEMT'S AT $T_a = 12.5$ K, $f = 8.5$ GHz

DEVICE	H503-P70	JS8901-AS	2SK676	FHR01FH
T_{MIN} [K]	25	27	14	9.4

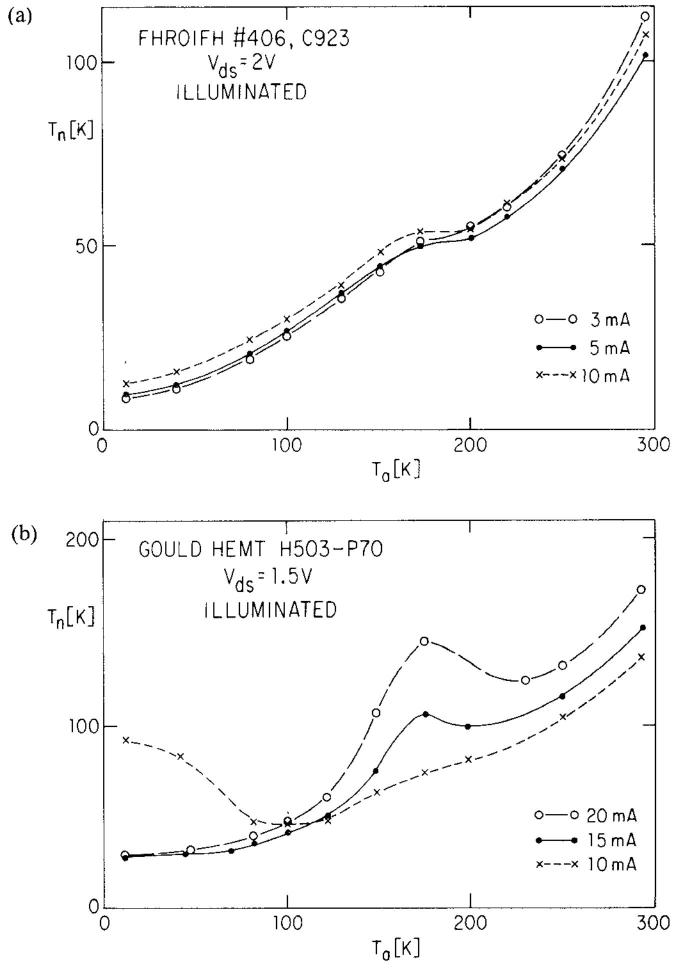

Fig. 8. The noise temperature of a single-stage (a) FHR01FH and (b) H-503-P70 amplifiers versus ambient temperature. Source impedance is optimal for cryogenic temperature.

For the illuminated HEMT's, the dc and noise data taken at a number of different temperatures between 297 K and 12.5 K reveal the same qualitative behavior and sensitivity to light as reported in [3]. This has again been linked to the existence of traps but, as yet, is not fully understood. As an example, the dependences of the noise temperature T_n of the single-stage 8.5-GHz amplifier employing the Gould and Fujitsu HEMT's measured with light illumination as a function of ambient temperature are shown in Fig. 8. Both characteristics exhibit a "hump" around $T_a \simeq 175$ K, which is very small for Fujitsu HEMT with excellent cryogenic performance, and very large for Gould HEMT with poor cryogenic performance.

The noise parameters of the FHR01FH HEMT both at room and cryogenic temperature are given in Table IV. The minimum noise temperature $T_{\min} = 9$ K at 8.5 GHz and $T_a = 12$ K is, within the measurement error, equal to the values reported previously for GE HEMT's [3], [34]. However, recent measurements on experimental GE HEMT's of similar structure indicates $T_{\min} = 5.5$ K at 8.5 GHz and $T_{\min} = 1.4$ K at 1.4 GHz [35]. The noise temperature of FHR01FH was found to be almost independent of drain voltage between 2 V and 3 V, i.e., the region in which the dependence of dc characteristics on illumination is very small (Fig. 6). However, if cooled down in the dark, it required illumination to achieve low-noise state. A typical difference in noise temperature prior to and after illumination was 3 K.

TABLE IV
NOISE PARAMETERS OF FHR01FH HEMT AT $f = 8.5$ GHz

T_a = 12.5 K

I_{ds} mA	V_{ds} V	T_{min} K	R_{gopt} Ω	X_{gopt} Ω	g_n mS	Assoc. Gain dB
3	2	9.4	4.3	18.3	2.7	11.8
5	2	10.3	4.6	17.0	2.6	13.1
10	2	13.0	5.3	16.3	2.7	13.4
15	2	16.3	5.7	15.6	3.2	13.7

T_a = 297 K

I_{ds} mA	V_{ds} V	T_{min} K	R_{gopt} Ω	X_{gopt} Ω	g_n mS	Assoc. Gain dB
5	2	81	8.6	18.4	12.5	10.8
10	2	78	10.5	17.5	9.4	11.7
15	2	81	11.0	16.7	10.1	12.5

An interesting comparison of noise parameters of the Fujitsu HEMT and FET with the same gate periphery, measured at the same bias, is shown in Table V. Although the packages of both devices are different (FH and FA styles), the noise parameters $T_{\min}$ and $4NT_0$ remain the same for a chip with a source bond wire inductance only, as they are invariant upon lossless transformation at input and output. Both these parameters for a FHR01FH HEMT are approximately half those for a FSX02FA FET. The ratio $4NT_0/T_{\min}$ is a measure of correlation between a pair of noise sources representing noise properties of a two-port [17]; it would be equal to one in the case of a perfect correlation. The ratio is usually larger for FET's than for HEMT's (compare Table V), indicating stronger correlation for the latter, which agrees with computer modeling of noise in HEMT's and FET's [6], [26].

IV. AMPLIFIER EXAMPLES

A number of amplifiers were constructed for radio astronomy applications, using both FET's and HEMT's with good cryogenic performance. It was found that in the

TABLE V
COMPARISON OF NOISE PARAMETERS OF FUJITSU HEMT AND FET

T_a = 12.5 K, f = 8.5 GHz									
	I_{ds} mA	V_{ds} V	T_{min} K	R_{gopt} Ω	X_{gopt} Ω	g_n mS	$4NT_0$ K	$\frac{4NT_0}{T_{min}}$	Assoc. Gain dB
FHR01FH	3	2	9.4	4.3	18.3	2.7	13.5	1.4	11.8
FSX02FA	3	2	17.0	4.9	24.5	5.1	29.0	1.7	10.8
$T_n = T_{min} + T_0(g_n/R_g)\|Z_g - Z_{gopt}\|^2$, $N = g_n R_{opt}$, T_0 = 290 K									

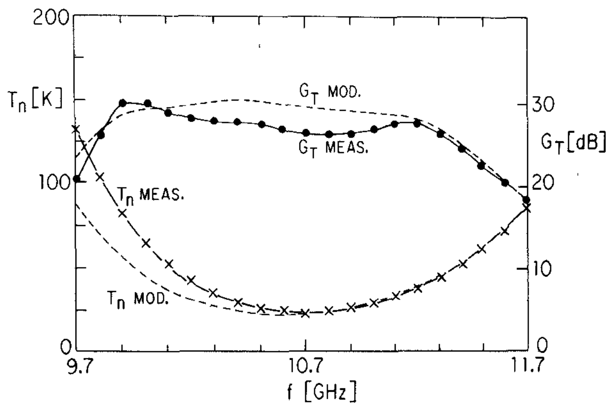

Fig. 9. Comparison of computer-predicted and measured noise temperature and gain of the 10.7 GHz, three-stage amplifier with NE75083 transistors at 12.5 K. All transistors are biased at $V_d = 3$ V, $I_d = 10$ mA. At 10.7 GHZ, $T_n = 26$ K.

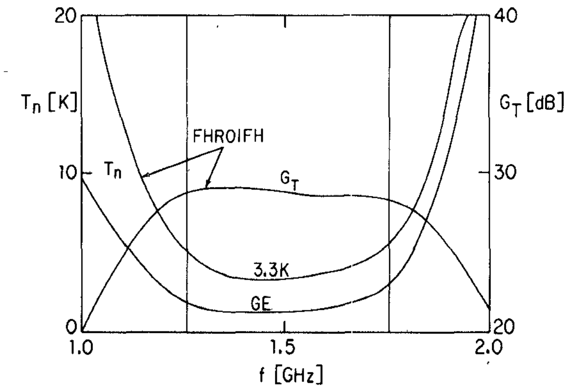

Fig. 10. Typical noise and gain characteristics of cryogenically cooled, three-stage, *L*-band amplifier with FHR01FH in input stage and MGF1412's in subsequent stages. The noise characteristic of an amplifier with an experimental GE HEMT in input stage is also shown for comparison. Design of similar all-FET amplifier has been described in [2] and [30].

process of computer-aided design of cryogenically cooled amplifiers with well-behaved FET's and/or HEMT's, the room-temperature *S*-parameter data and cryogenic noise parameter data can be used with accuracy sufficient for practical applications. The change in amplifier gain upon cooling can be accounted for by the changes in transconductance and small-signal drain resistance (compare Figs. 2 and 3).

The example of computer-predicted and measured cryogenic performance of an all-FET (NE75083), three-stage, 10.7-GHz amplifier is shown in Fig. 9 [29]. In this example, the following frequency dependence of the noise parameters of a chip was assumed:

$$T_{min} = Af \quad R_{opt} = \frac{B}{f} \quad X_{opt} = \frac{C}{f} \quad g_n = Df^2 \quad (1)$$

and the constants *A*, *B*, *C*, and *D* were determined from the measurement at 8.5 GHz (Table I) by de-embedding the elements of the package equivalent circuit using computer routines [15], [16], [29]. The frequency dependence of the minimum noise temperature below 20 GHz given by (1) is confirmed by a number of studies [5]–[7], [26]–[28], both for HEMT's and for FET's, while that of R_{opt}, X_{opt}, and g_n comes from the analysis by Pucel, *et al.* [5] for intrinsic chip (parasitic resistances excluded) under the approximation $\omega^2 C_{sg}^2 R_i^2 \ll 1$. This frequency dependence of the noise parameters is also the one preserving the fundamental inequality [17], [32]:

$$T_{min} \leqslant 4NT_0 \qquad \text{where } N = R_{opt} g_n \qquad (2)$$

at all frequencies. It should be noted that for this model the ratio $4NT_0/T_{min}$ is not only invariant through lossless reciprocal two-ports at input and output, but is also frequency independent.

In Figs. 10 through 14, the typical characteristics of cryogenically cooled *L*-, *C*-, *X*-, and *K*-band amplifiers built with FET's and those built with Fujitsu HEMT's in input stages are compared. Noise temperature of *L*-band and *X*-band amplifiers built with experimental GE HEMT's is also shown for comparison. In general the HEMT amplifiers have noise temperature lower by a factor of two or more than all FET realizations. The minimum noise temperature in the band for *C*- through *X*-band

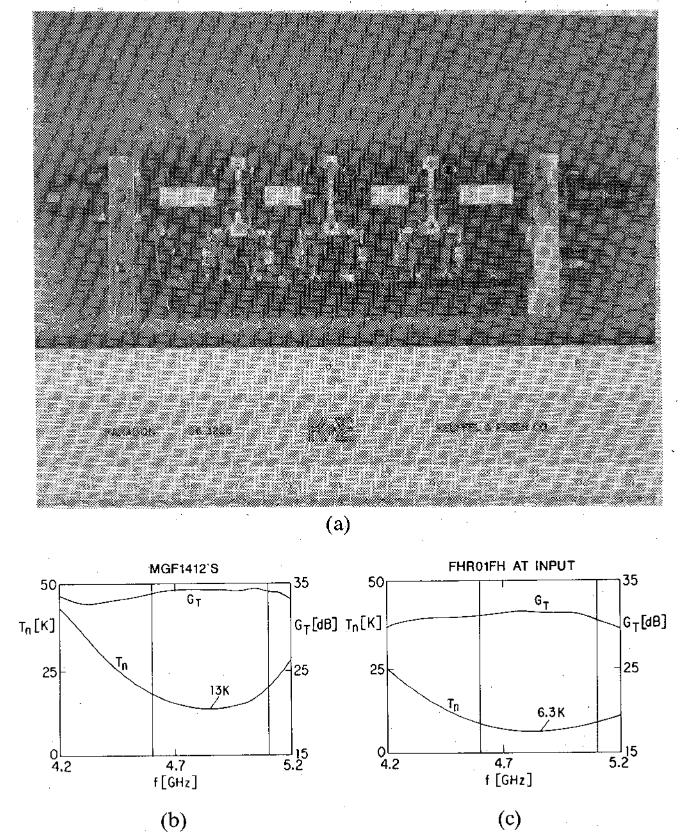

Fig. 11. Cryogenically cooled, three-stage, *C*-band amplifier. (a) Photograph. (b) Typical characteristics of all-FET realization (MGF1412's) [21]. (c) Typical characteristic for FHR01FH in input stage and MGF1412's in the following stages.

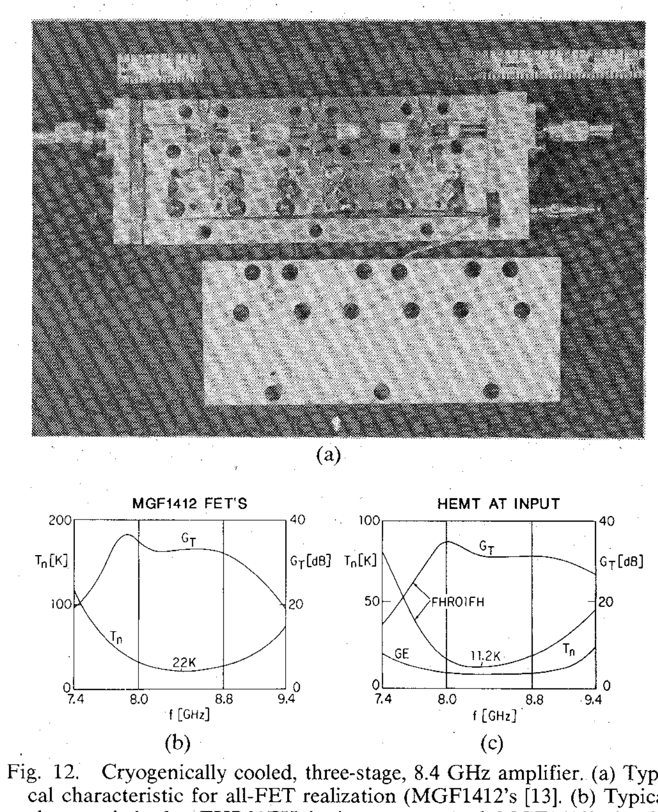

Fig. 12. Cryogenically cooled, three-stage, 8.4 GHz amplifier. (a) Typical characteristic for all-FET realization (MGF1412's [13]. (b) Typical characteristic for FHR01FH in input stage and MGF1412's in the following stages. The noise characteristics of an amplifier with an experimental GE HEMT is also shown for comparison.

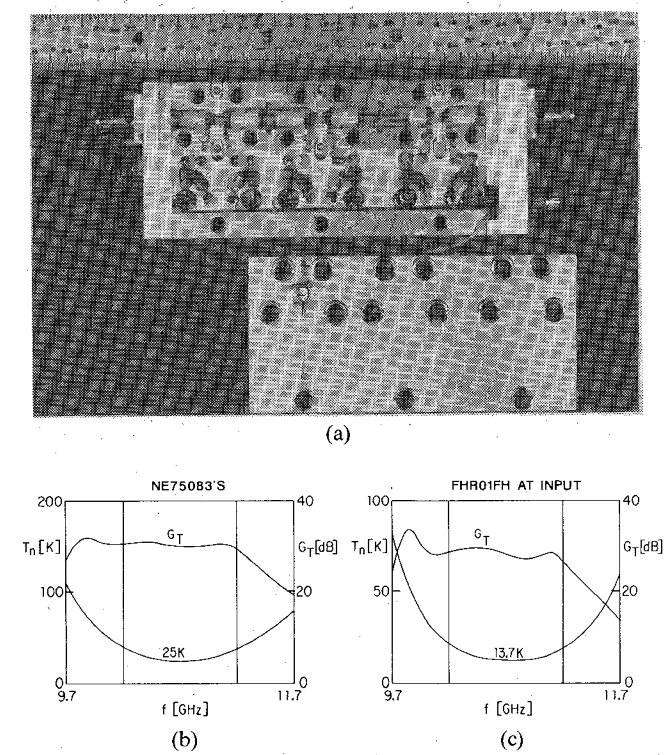

Fig. 13. Cryogenically-cooled, three-stage, 10.7 GHz amplifier. (a) Photograph. (b) Typical characteristic for all-FET realization (NE75083's). (c) Typical characteristics for FHR01FH in input stage with NE75083 in the following stages.

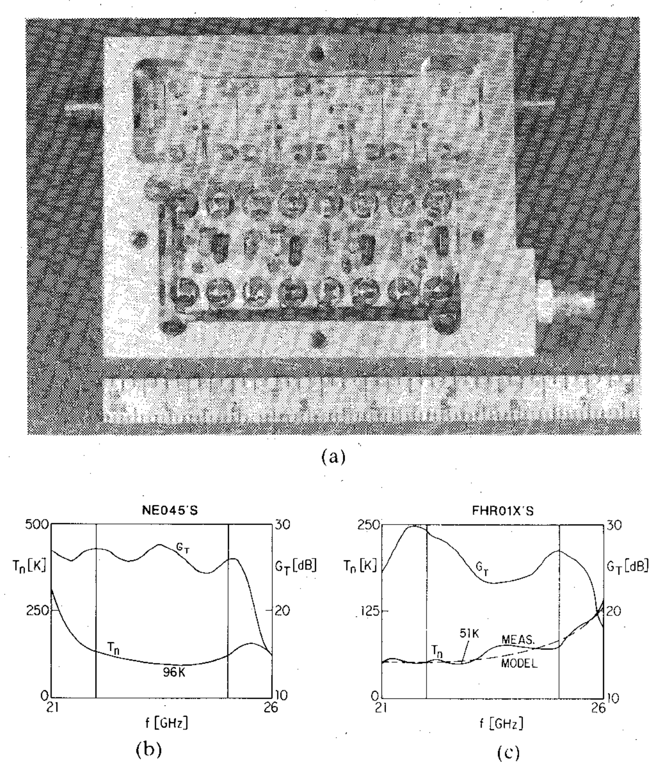

Fig. 14. Cryogenically cooled, four-stage, 23 GHz amplifier: (a) Photograph. (b) Typical characteristics for all-FET realization (NE045 chips). (c) Typical characteristics for FHR01X chips in first two stages and NE045 chips in the following stages. The noise and gain data are for the amplifier with cold isolators both at the input and output. The noise predicted by the computer model for two-stage FHR01X amplifier with cold isolator at the input is also shown for comparison.

realizations is approximately proportional to frequency with proportionality factor 1.3 K/GHz and 2.6 K/GHz for Fujitsu HEMT and FET realizations, respectively. This translates into 1.1 K/GHz and 2.2 K/GHz factors for the minimum noise temperature of FHR01FH HEMT and best FET, respectively, directly confirming the validity of expression (1) for T_{min}. The results at *L*-band slightly deviate from the proportional dependence, most likely due to the influence of $1/f$ noise. On the other hand, *K*-band results still closely follow it. For example, the noise temperature of a cold, single-stage, FHR01X microstrip amplifier at 22.5 GHz predicted using the noise and signal model based on room-temperature *S*-parameter measurement, *X*-band noise measurement, and relations (1) was 33 K, precisely as measured; for the chip with bond wire inductance only, the model predicts $T_{min} = 26$ K at this frequency. Furthermore, computer-predicted noise temperature for the two-stage, *K*-band FHR01X amplifier with isolator at the input is compared in Fig. 14 with the measured noise temperature of a four-stage experimental amplifier, demonstrating a good agreement.

More detailed information concerning the design, construction, and performance of some of the amplifier examples presented briefly in this paper can be found in a number of NRAO reports[1] and related papers [2], [13]–[16], [21], [29], [30].

IV. Conclusions

The properties of commercially available FET's and HEMT's at cryogenic temperatures have been described. Several phenomena were observed which await full explanation. In this light, testing of the devices at cryogenic temperatures could provide additional insight into the device physics. This would be of great importance not only for low-noise, but also for high-speed applications.

Noise testing of best FET's and an HEMT showed that the minimum noise temperature of Fujitsu HEMT at 12.5 K is approximately half of the best FET at any given frequency and for the *C*- to *K*-band frequency range is given by the approximate relation $T_{min} = 1.1 * f(\text{GHz})$ kelvins. There is, however, room for improvement—recent results with GE HEMT's [35] with structure similar to that published in [3] and [34] exhibited $T_{min} = 5.5$ K at $f = 8.5$ GHz and $T_a = 12.5$ K.

The examples of cryogenically cooled, multistage amplifiers built for radio astronomy applications from *L*- through *K*-band represent the current state of the art and at frequencies below *X*-band their performance is comparable to 4 K masers, with enormous reduction in cost, not only of the microwave parts but also of the cryogenic systems [33].

Acknowledgment

Part of this work was done under cooperative agreement between the National Radio Astronomy Observatory and the Jet Propulsion Laboratory to allow the use of the Very Large Array for the purpose of signal reception from Voyager during the Neptune flyby.

The excellent technical assistance of B. Lakatosh, K. Crady, and R. Simon of NRAO is gratefully acknowledged.

[1] National Radio Astronomy Observatory Electronics Division Internal Reports are distributed to interested persons upon request.

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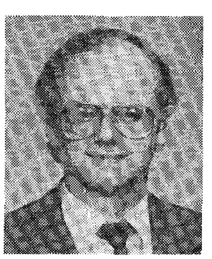

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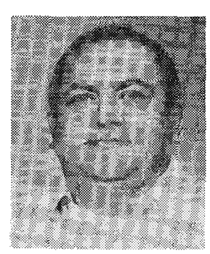

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