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DESIGN AND PERFORMANCE OF CRYOGENICALLY-COOLED, 10.7 GHz AMPLIFIERS

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M. W. Pospieszalski

I. Introduction

This report covers the design and performance of cryogenically-cooled, 10.2-11.2 GHz amplifiers. The design approach follows that described in a previous report [1] for the 8.0-8.8 GHz amplifiers. The typical parameters measured at the cold input of the amplifier were: minimum noise temperature of midband T_{nmin} = 25K, average noise temperature over 1 GHz bandwidth T_{nAV} = 31K and gain G_{AV} = 29.5 ± 1.5 over the same bandwidth. The noise temperature values are about 5K better than those reported for the previous design [2]. This can be attributed to the better transistor used (NE75083) and the use of computer-aided design. Good agreement between the measured results and those predicted from computer optimized design suggest that the amplifier performance is close to that presently attainable for commercial GaAs FET's. Improvements in noise performance by about a factor of two may be expected with the use of state-of-the-art HEMT's [3].

In section II of this report, the signal and noise parameters of the NE75083 transistor are discussed. The design, construction and performance, both measured and computer predicted, of the three-stage amplifier are described in section III.

The NE75083 transistor is no longer commercially available and, therefore, the design described in this report may not be easily repeated. Nevertheless, the complete description of the design process and the comparison between the computer predicted and experimental results allow one to judge the effectiveness of the design approach. The resulting conclusions are summarized in section IV.

II. Noise and Signal Properties of NE75083 Transistor

The measured S-parameter data of the NE75083 transistor (lot 72A) for the optimum noise bias V_{ds} = 3V, I_{ds} = 10 mA were provided by R. Lane of California Eastern Laboratories. Using the FARANT program [4], [5], the procedure was developed to find the elements of the equivalent circuit to fit the measured S-parameters with minimum error. The topology of the equivalent circuit employed and the resulting values of the circuit elements are given in Figure 1. The measured values of the S-parameters and those computed from the equivalent circuit for frequency range 2-18 GHz are given in Figure 2 and Table I.

The noise parameters of the NE75083 (72A) FET were measured at the frequency f = 8.4 GHz and reported in [3]. The noise parameters of a chip were obtained by deembedding the external source inductance and the package parasitics (compare Figure 1). The results of this operation for the external source inductance of L_s = .03 nH and the transistor biased at V_{ds} = 3V, I_{ds} = 10 mA are shown in Table II.

TABLE II. Noise Parameters of NE75083 at V_{ds} = 3V, I_{ds} = 10 mA, f = 8.4 GHz:

T_a [K]	12.5		297	
	Pack.	Chip	Pack.	Chip
T_{min} [K]	15.2	15.3	89	89.5
R_{opt} [Ω]	4.5	11.2	9.4	22.8
X_{opt} [Ω]	32.5	84	32	81
g_n [mS]	4.3	1.7	8.4	3.5

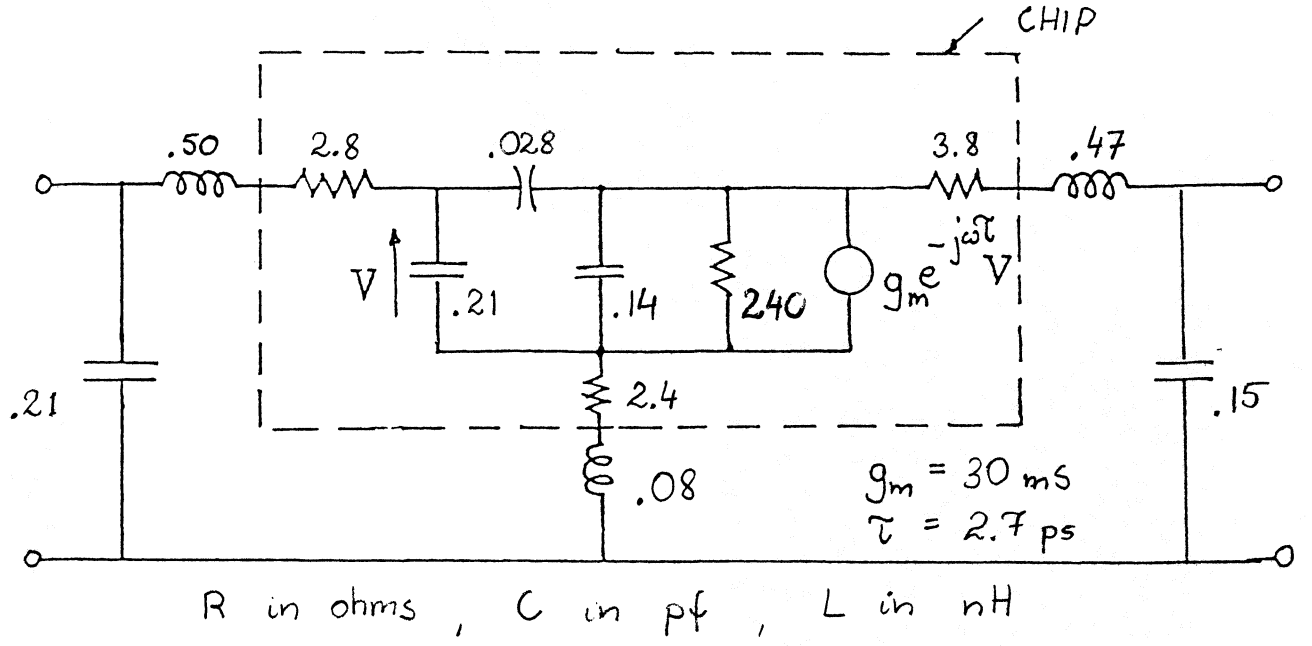


Fig. 1. The equivalent circuit of NE75083 (72A) FET at V_{ds} = 3V, I_{ds} = 10 mA, T_a = 297K.

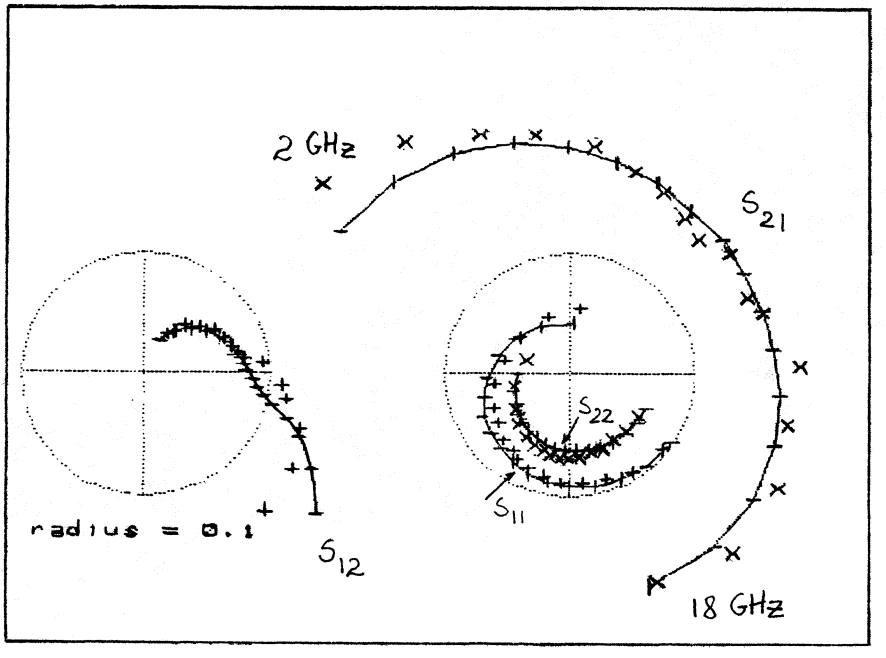


Fig. 2. Comparison between measured S-parameters and those computed from the model of Fig. 1.

TABLE I. S-Parameters as a Function of Frequency for NE75083 FET at V_{ds} = 3V, I_{ds} = 10 mA, T_a = 297K.

[S] PARAMETERS IN MAGNITUDE AND PHASE

MEASUREMENT:

	11		12		21		22		K
FREQ	MAG	ANG	MAG	ANG	MAG	ANG	MAG	ANG	FACT
2.000	.9730	-39.0	.0370	59.0	2.5230	142.0	.6540	-31.0	.20
3.000	.9430	-57.0	.0510	50.0	2.3150	125.0	.6470	-45.0	.26
4.000	.9010	-70.0	.0580	39.0	2.0910	110.0	.6390	-56.0	.47
5.000	.8930	-83.0	.0670	32.0	1.9840	98.0	.6530	-65.0	.42
6.000	.8820	-94.0	.0710	23.0	1.8600	84.0	.6640	-74.0	.49
7.000	.8520	-104.0	.0740	17.0	1.7410	72.0	.6710	-83.0	.59
8.000	.8300	-112.0	.0750	14.0	1.6670	63.0	.6770	-89.0	.66
9.000	.7970	-120.0	.0750	11.0	1.5770	54.0	.6760	-95.0	.80
10.000	.7550	-125.0	.0780	11.0	1.5220	47.0	.6540	-99.0	.99
11.000	.7560	-134.0	.0820	9.0	1.6160	38.0	.6660	-103.0	.84
12.000	.6900	-145.0	.0820	2.0	1.5650	24.0	.6470	-109.0	1.17
13.000	.6580	-155.0	.0970	5.0	1.6390	18.0	.6450	-115.0	.96
14.000	.6090	-172.0	.1100	-5.0	1.8630	2.0	.6130	-124.0	.91
15.000	.5170	167.0	.1150	-10.0	1.8050	-13.0	.5540	-134.0	1.17
16.000	.4900	143.0	.1310	-20.0	1.9220	-29.0	.4940	-146.0	1.10
17.000	.5090	109.0	.1420	-33.0	1.9750	-48.0	.4440	-167.0	.99
18.000	.5440	79.0	.1500	-49.0	1.8440	-67.0	.3640	161.0	1.04

MODEL:

	11		12		21		22		K
FREQ	MAG	ANG	MAG	ANG	MAG	ANG	MAG	ANG	FACT
2.000	.9856	-33.3	.0294	65.8	2.2027	147.6	.6730	-24.1	.14
3.000	.9698	-48.9	.0419	54.5	2.1251	132.2	.6661	-35.6	.22
4.000	.9508	-63.5	.0524	44.1	2.0348	117.5	.6581	-46.6	.29
5.000	.9303	-77.0	.0608	34.6	1.9425	103.6	.6498	-56.9	.37
6.000	.9090	-89.4	.0674	26.1	1.8561	90.4	.6416	-66.7	.44
7.000	.8873	-101.0	.0726	18.5	1.7810	77.9	.6334	-75.9	.53
8.000	.8647	-111.8	.0767	11.9	1.7200	65.8	.6248	-84.7	.61
9.000	.8406	-122.2	.0802	6.0	1.6747	54.1	.6155	-93.1	.70
10.000	.8140	-132.4	.0834	1.0	1.6460	42.6	.6050	-101.2	.79
11.000	.7835	-142.7	.0870	-3.3	1.6341	31.1	.5929	-109.1	.87
12.000	.7477	-153.5	.0913	-6.9	1.6389	19.3	.5786	-117.0	.96
13.000	.7048	-165.1	.0973	-10.2	1.6599	7.2	.5620	-124.9	1.03
14.000	.6530	-178.4	.1057	-13.5	1.6955	-5.6	.5427	-133.2	1.08
15.000	.5915	165.8	.1175	-17.4	1.7421	-19.3	.5203	-142.1	1.11
16.000	.5227	145.7	.1336	-22.6	1.7922	-34.3	.4941	-152.3	1.10
17.000	.4581	119.0	.1539	-30.0	1.8324	-50.9	.4623	-164.6	1.07
18.000	.4260	84.1	.1771	-39.9	1.8419	-69.1	.4227	179.5	1.02

For the noise parameters of a chip, the following frequency dependence may be assumed [4], which should predict reasonably well the changes in noise parameters around the frequency of measurement:

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

A, B, C, and D are constants, determined from the noise parameters measurement at the frequency 8.4 GHz and assume the following values:

T_a	A [K/GHz]	B [Ω/GHz]	C Ω/GHz]	D [mS/GHz^2]
12.5	1.8	94	706	.024
297	10.6	192	680	.050

The frequency dependence of noise parameters of the packaged transistor can be then predicted using relations (1) for noise parameters of the chip and embedding it at any given frequency into the package parasitic elements (Fig. 1). The results of this operation for the frequency range of interest are shown in Table III.

The agreement between measured and model predicted S-parameters is considered to be very good. The d.c. measured transconductance for a lot #72A transistor was g_{mo} = 41 mS, but on other samples from other lots it was as low as 33 mS. (The equivalent circuit determined from microwave measurements of another #72A lot FET gave g_m = 30 mS.) The drain to source small signal resistance R_{dso} determined from I-V measurement was in the range 350-440 Ω, while modelling based on microwave measurement gave the value R_{ds} = 240 Ω. This is about the same relative difference as observed for other FET's [6], between d.c. and RF measurement of small signal drain resistance.

TABLE III. The Frequency Dependence of Noise Parameters of NE75083 Transistor at V_{ds} = 3V, I_{ds} = 10 mA.

T_a K	Freq. GHz	T_{min} K	R_{opt} Ω	X_{opt} Ω	g_n mS	Gass dB
	6.0	10.75	5.11	55.11	2.63	14.50
	7.0	12.52	4.71	45.00	3.33	13.56
	8.0	14.30	4.50	36.94	3.97	12.75
12.5	9.0	16.09	4.44	30.15	4.53	12.04
	10.0	17.89	4.51	24.12	4.95	11.43
	11.0	19.71	4.73	18.49	5.19	10.89
	12.0	21.56	5.14	12.94	5.22	10.42
	6.0	63.19	10.69	54.82	5.35	14.10
	7.0	73.57	9.87	44.76	6.75	13.16
297	8.0	83.92	9.43	36.73	8.06	12.34
	9.0	94.23	9.31	29.96	9.17	11.62
	10.0	104.53	9.47	23.96	9.99	10.98
	11.0	114.83	9.95	18.37	10.45	10.40
	12.0	125.16	10.82	12.88	10.48	9.88

The validity of the noise parameters given in Table III has been tested by the 10.7 GHz amplifier design and measurement described in the next section. Apparently there exists a discrepancy between the associated gains determined from the signal and noise model (Table III) and those measured for sample transistor at the frequency f = 8.4 GHz. The associated gain predicted from the model for the FET biased at V_{ds} = 3V, I_{ds} = 10 mA was greater than actually measured by about 2 dB and 1 dB at room and cryogenic temperatures, respectively. However, the error in determining X_{opt} at 8.4 GHz of less than 4 Ω, which is about the estimated accuracy of X_{opt} measurement, could alone account for this discrepancy.

III. Three-Stage, 10.2-11.2 GHz Amplifier

The design approach followed that described for the 8.0-8.8 GHz amplifier [1]. In particular, the topology of the input/output matching networks and interstage coupling networks was the same, as was the realization of d.c. separation circuit (re-entrant lines) and bias circuits.

The input and first interstage coupling networks were computer optimized to yield minimum average noise in the 10.2-11.2 GHz band at 12.5K ambient temperature, while the second interstage coupling network and output network were optimized for gain flatness in the same band. The signal and noise data described in section II of this report were used.

The photograph of the completed amplifier is shown in Figure 3. The enlarged view of the first stage is shown in Figure 4. The details of the amplifier construction are the same as for the 8.4 GHz amplifier and were extensively described in [1].

The comparison between computer predicted and measured performance of the three-stage amplifier at room temperature and cryogenic temperature is shown in Figures 5 and 6, respectively. For the data of Figures 5 and 6, the FET bias was kept constant at V_{ds} = 3V, I_{ds} = 10 mA. For the computer model the positions of the low-impedance sections exactly as shown in Figures 3 and 4 were used.

In the first amplifier to be built, the length of the transistor leads which form series connected stubs were experimentally adjusted (in the same manner for all three stages) to center the noise and gain performance around 8.4 GHz. The need for these adjustments could be explained by uncertainties in determining the parasitics of the transistor mounting structure and/or the FET model inaccuracies. The fact that the transistors used for amplifier realization were from a different lot (#A-22-8) than those for which the signal and noise model was developed (#72A) could also play an important role.

The same factor could explain the differences between the computer predictions and observed performance. In particular, the minimum noise temperature at 8.4 GHz for transistors from batch #A-22-8 was $T_{min} \simeq$ 18K (for the #72A lot, $T_{min} \simeq$ 15K), which itself could account for the observed discrepancy between measured and predicted minimum value of noise temperature within the band of interest.

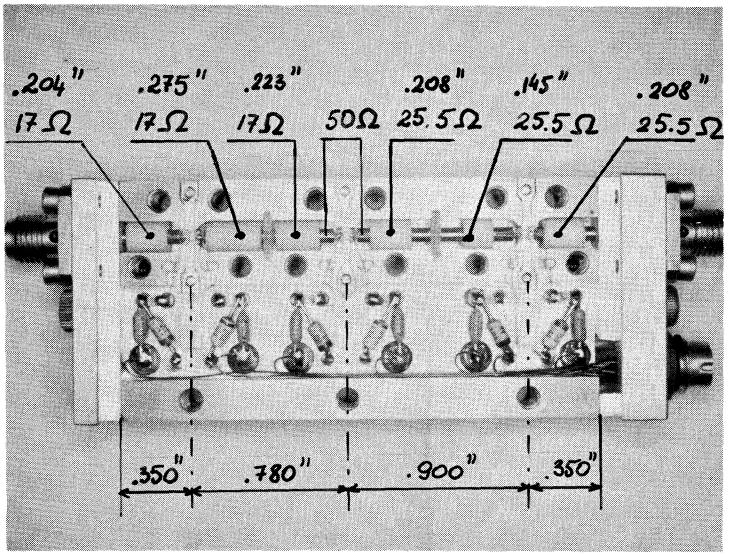


Fig. 3. Three-stage amplifier with cover removed. Input is at left and output and DC bias connector are at right.

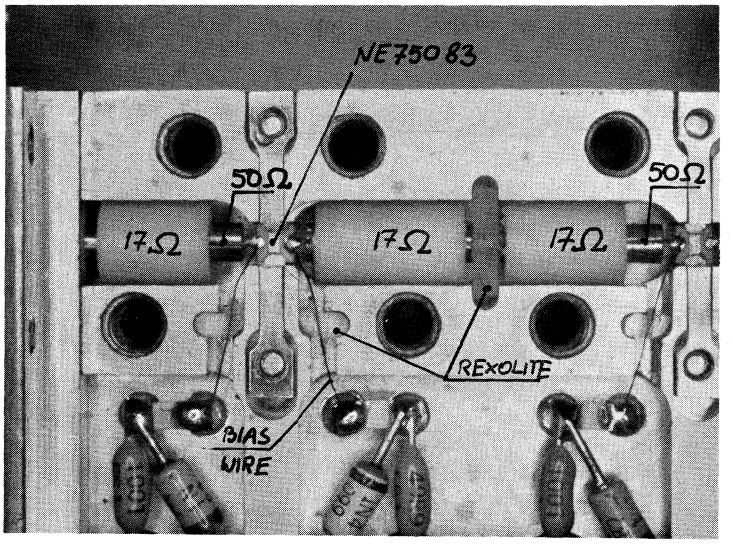


Fig. 4. The enlarged view of the first-stage section of the three-stage amplifier.

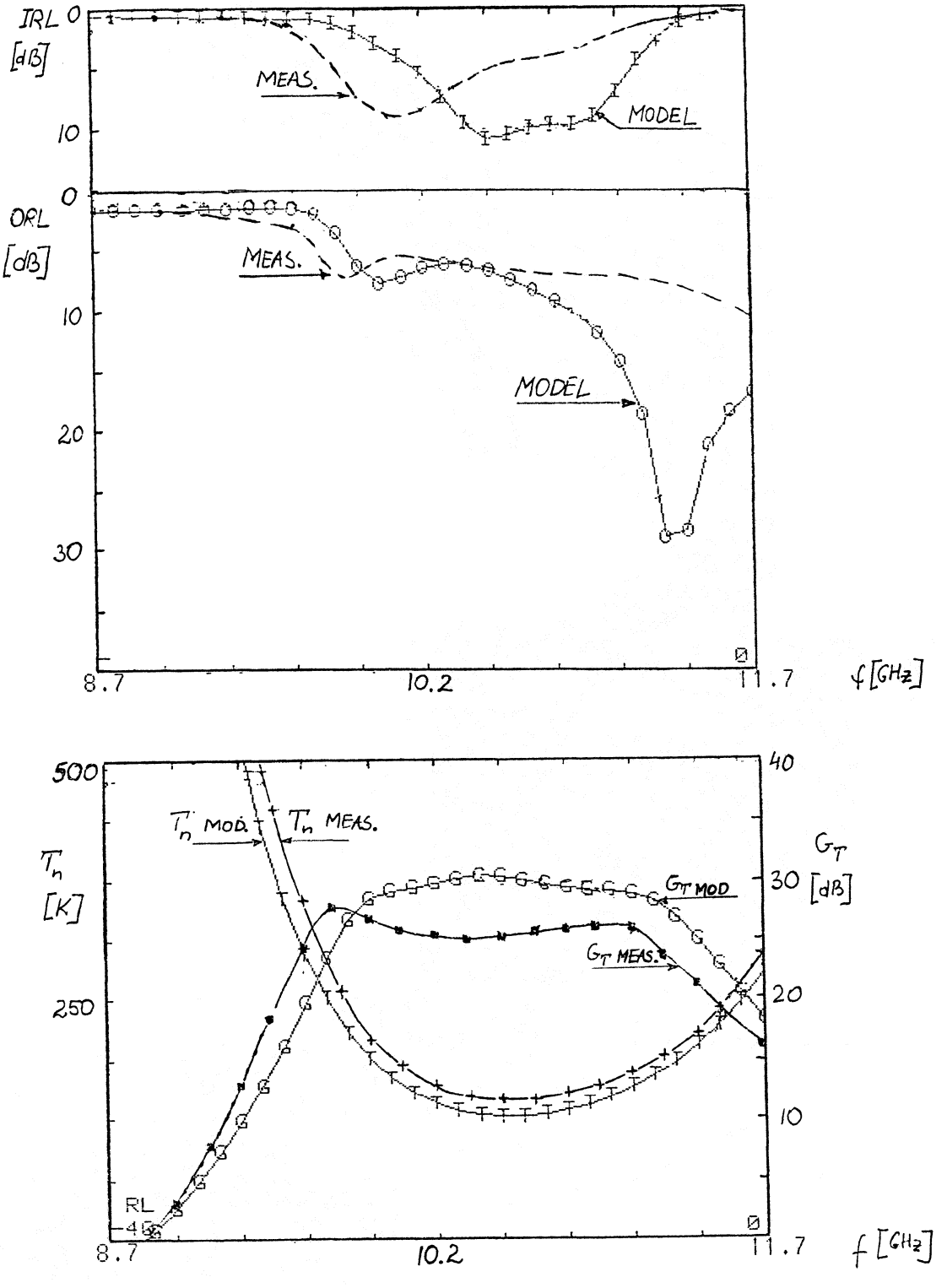


Fig. 5. The measured and model-predicted performance of the three-stage amplifier of Fig. 3 at room temperature. All transistors are biased at V_{ds} = 3V, I_{ds} = 10 mA.

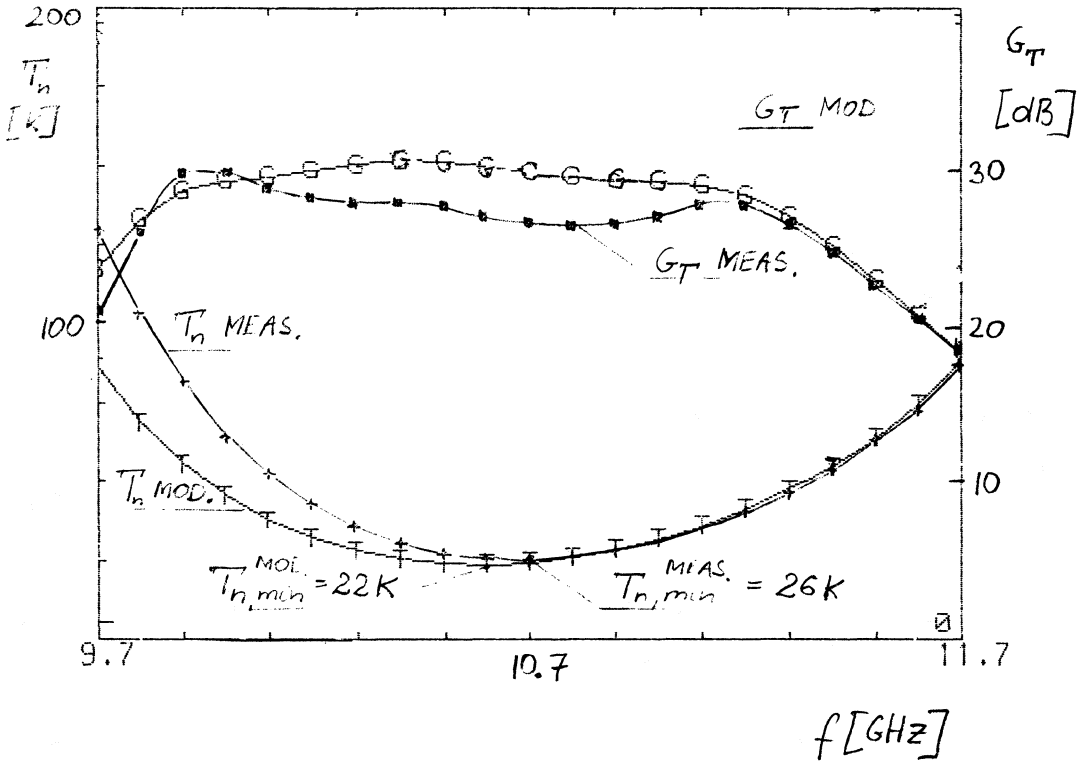


Fig. 6. Noise temperature and gain of the three-stage amplifier of Fig. 3 at cryogenic temperature (T_a = 12.5K) computed from the model and measured. All transistors are biased at V_{ds} = 3V, I_{ds} = 10 mA.

The measured increase in gain upon cooling for the transistors biased at V_{ds} = 3V, I_{ds} = 10 mA is about 2 dB. In the computer model this could be explained by, for instance, a 20% increase in g_m (g_m = 36 mS) and a 20% decrease in R_{ds} (R_{ds} = 195 Ω). An increase in g_m alone would account for more than 3 dB of gain increase. As it experimentally demonstrated in [2], the amount of change upon cooling in g_m and R_{ds} could vary significantly from lot to lot. Therefore, for consistent cryogenic performance, it is advisable to use transistors from the same lot.

The performance of the amplifier of Figure 2 in which the bias of transistors were adjusted for minimum noise and gain flatness over 10.2 to 11.2 GHz band at T_a = 12.5K is shown in Figure 6.

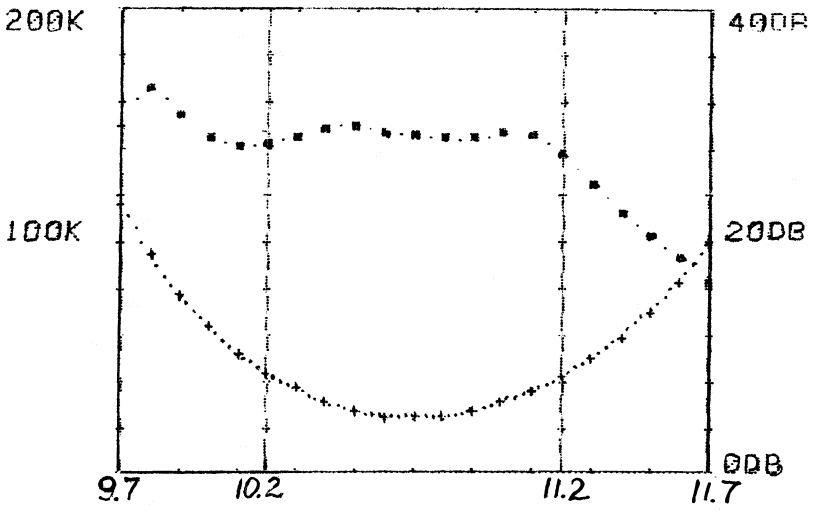
The performance of four amplifiers of this design built with off-the-shelf NE75083 transistors (lots #'s A-22-8 and A-24-8) is summarized in Table IV. The repeatability of noise and gain performance is considered to be very good.

TABLE IV. The Summary of Cryogenic Performance of the 10.2-11.2 GHz Amplifiers

	Noise Temp. [K]		Gain [dB]	
Amplifier	Minimum	Average	Minimum	Maximum
#1	26.1	31.8	29.1	32.1
#2	24.8	29.9	30.0	31.7
#3	24.0	30.8	28.2	29.7
#4	25.6	31.6	29.4	32.4

IV. Conclusions

The computer-aided design of 10.2-11.2 GHz, cryogenically-cooled amplifiers was described and verified by the experiment. The feasibility of using room temperature S-parameters for cryogenic design has been demonstrated. The estimation



F,GHZ	NOISE	GAIN,DB	F,GHZ	NOISE	GAIN,DB
10.2	43.5	28.3	10.3	36.5	29
10.4	31	29.7	10.5	27.1	29.8
10.6	24.7	29.4	10.7	24	29
10.8	24.5	28.8	10.9	26.6	28.8
11	30.1	29.3	11.1	35.1	29
11.2	41.3	27.3	11.3	49.1	24.8

Fig. 7. Noise temperature and gain for the three-stage amplifier of Fig. 3 at optimal bias conditions: first stage, V_{ds} = 2.5V, I_{ds} = 7.5 mA; second stage, V_{ds} = 2V, I_{ds} = 20 mA; third stage, V_{ds} = 2.5V, I_{ds} = 15 mA. These results are not corrected for approximately .9 dB of loss at the output (isolator and connecting lines).

of noise parameters from single frequency measurement has been shown to be accurate enough for practical design over frequency range as large as 8-12 GHz. This approach should be valid over wider frequency range determined by validity of noise model of a chip (eqn. (1)), providing the small signal equivalent circuit of the transistor is sufficiently well known over this frequency range.

The cryogenic noise performance of the amplifiers described in this report is believed to be the best yet reported for FET amplifiers at the frequency 10.7 GHz. The improvement in noise performance by about a factor of two may be expected in the use of the state-of-the-art HEMT's.

V. Acknowledgements

The author gratefully acknowledges many stimulating discussions with Dr. S. Weinreb. Kirk Crady and Bill Lakatosh are thanked for their excellent experimental and technical assistance.

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