Low Noise Cooled Microwave Amplifiers—Simulation and Design

Iltcho M. Angelov, I. K. Stoev, Zdravko G. Ivanov, Bogdan N. Todorov, A. Y. Spasov, Erik L. Kollberg, *Fellow, IEEE,* C. O. Lindström, and B. L. Wendemo

***Abstract*—The results of a study of cooled low noise field effect transistors and transistor amplifiers are presented. The investigations were made over a broad range of temperature and frequency. The temperature dependence of equivalent circuit elements in the transistor model is reported. This makes it possible to extrapolate with sufficient accuracy the *S*-parameters up to frequencies where direct measurements are difficult. Suspended microstrip lines have been used in the amplifier designs in order to minimize the losses and to improve the mechanical stability. The results of the theoretical studies are illustrated with a presentation of cooled amplifiers for the ranges 0.5–4 GHz, 3.7–4.1 GHz, 4.8–5.2 GHz, 19–23 GHz and 26–28 GHz, which are designed on the basis of the theoretically obtained parameters.**

I. Introduction

RECENT technological developments in the area of microwave FET's have led to their successful application up to 100 GHz. These applications raised the problem of measuring *S*- and noise parameters of the transistors in a broad frequency range with a view to obtain the optimum matching impedances. The later require transistor fixtures and network analyzers and measurements at frequencies above 26 GHz which is a complicated problem [1]. In amplifier design at higher frequencies, a widely used method is based on establishing a circuit model related to the physics of the transistor at low frequencies and extrapolation of the *S*- and noise parameters of this model to higher frequencies [2].

It is well known that cooling FET transistor amplifiers to cryogenic temperatures (77 K and below) improves the noise factor and the available gain. Since the transistor parameters are not known over such a broad temperature range the following design approaches for cooled microwave amplifiers with FET's have been used [3]–[6]:

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I. M. Angelov, I. K. Stoev, B. N. Todorov, and A. Y. Spasov are with the Institute of Electronics, Bulgarian Academy of Sciences, 1784 Sofia, Bulgaria.

Z. G. Ivanov was with the Institute of Electronics, Bulgarian Academy of Sciences, 1784 Sofia, Bulgaria. He is currently with the Department of Physics, Chalmers, University of Technology, S-412 96, Gothenburg, Sweden.

E. L. Kollberg, C. O. Lindstrom, and B. L. Wendemo are with the Department of Applied Electron Physics, Chalmers University of Technology, S-412 96, Gothenburg, Sweden.

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The amplifier is designed on the basis of the *S*- and noise parameters of the transistors measured at room temperatures. Adjusting the dc bias and using adjustable tuning elements the amplifier performance is optimized at low temperatures. This method works, but it is rather difficult and time consuming to obtain optimum amplifier characteristics at a given temperature.

The transistor is included in an amplifier structure (most often a coaxial type of structure). Its characteristics are measured for various coupling circuits and the optimum parameters of the device are calculated on this basis. This approach, however is time consuming.

The main aim of this work was to develop a method for designing different types of low noise microwave amplifiers over a broad frequency range (0.3–30 GHz) and working at cryogenic temperatures. By measuring the *S*- and calculating the noise parameters of the transistor at frequencies 1–18 GHz and temperature range 100–300 K a physical circuit model for the field effect transistor was established. This allows prediction of transistor properties at higher frequencies and over a broad temperature range. The detailed scheme of the amplifier design procedure is shown in Fig. 1.

II. Measurements of the *S*-Parameters

The FETs MGF1303, 1412, 1403, 1404, 1405, NE67383, FHR01FH (Fujitsu), H503-R70 (Gould), often used in the design of low noise amplifiers, were characterized over a frequency range 1–18 GHz for temperatures between 100 and 300 K.

The length of the coaxial cable (from the hot end of the cryostat to the fixture) was minimized in order to decrease the measurement errors, related to changes in the length of the cable caused by the temperature variation. The transistors were mounted in a low loss measurement fixture with possibilities for precise measurements up to 18 GHz. The influence of the input and output lines as well as that of the fixture on the measured *S*-parameters are accounted for by a correcting computer program. Calibration is carried out by means of the three impedance standards—matched load, short and open line—connected directly to the fixture. It was also performed at two temperatures: 300 and 100 K. A system calibrated in this manner has a measurement error below 0.05 dB and 2 degrees at 18 GHz.

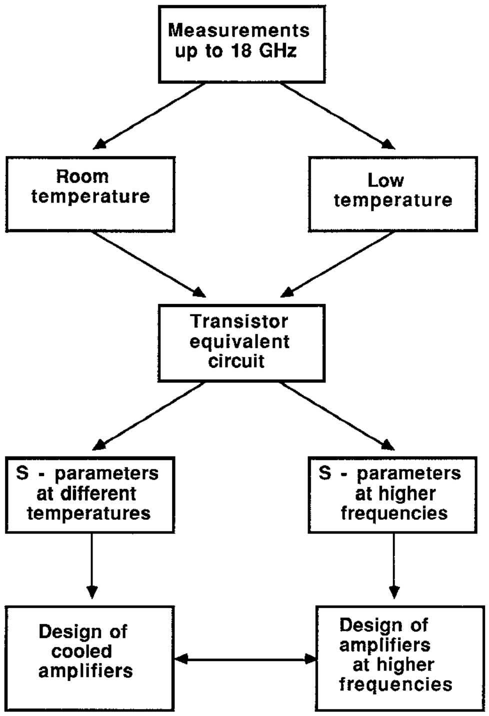


Fig. 1. Block diagram of the measurement and modeling process.

TABLE I

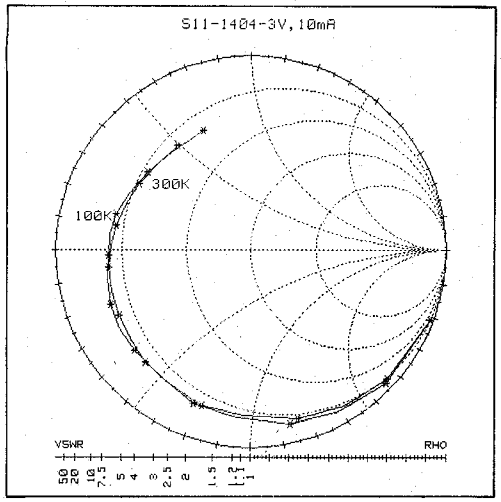
	Transistor	Manufacturer	Type	NF from Data Sheet 4 GHz [dB]	NF from Data Sheet 12 GHz [dB]	Number of Cooled Test Samples	Performance When Cooled	Result Presented in Fig.
1	MGF 1303	Mitsubishi	FET	1	2	12	Good	
2	MGF 1412	Mitsubishi	FET	0.8	1.9	4	Good	2(b)
3	MGF 1403	Mitsubishi	FET	0.8	2	8	Good	
4	MGF 1404	Mitsubishi	FET	0.6	1.55	6	Good	2(a)
5	MGF 1405	Mitsubishi	FET	0.55	1.4	3	Differs between different samples	
6	NE67383	NEC	FET	0.5	1.4–2	3	Differs between different samples	
7	H503-R70	Gould	FET	0.5	1.2	1	Good	
8	FHR01FH	Fujitsu	HEMT	0.5	1.1	4	Good, may need illumination	2(c)

A summary of estimated cooled performance is given in Table I. Notice that several of the transistors with good characteristics at room temperatures, cannot, in practice be used at low temperatures. These are usually transistors with a low breakdown voltage Ugsp for which at temperatures below 150 K there is almost no gate control of the transistor. Hysteretic phenomena are also observed, probably due to vacancies in the GaAs. This hysteresis was avoided by switching off and on the bias voltage. Such features are observed for the transistors MGF1405 and NE67383. This means that transistors of these types have to be checked before they are used in cooled amplifiers. Almost all transistors of the type MGF1303, 1403, 1412, and 1404 exhibit good properties after cooling and it is sufficient to measure only a few devices of a given batch. The HEMT transistors made by Fujitsu also yield very stable and repeatable results. The *S*-parameters for the MESFET's MGF1404, 1412, and HEMT FHR01 FH which have showed stable behavior at 300 K and 100 K are shown in Fig. 2. All the experimental amplifiers were designed using these transistors.

III. Choice of a Physical Equivalent Circuit

The equivalent circuit of the transistor and the package chosen for the simulation process are shown in Fig. 3. The equivalent circuit of the package is more complicated for better representation of the device (MESFET and HEMT) parameters at frequencies exceeding 15 GHz. The values given in parentheses are for the HEMT transistor.

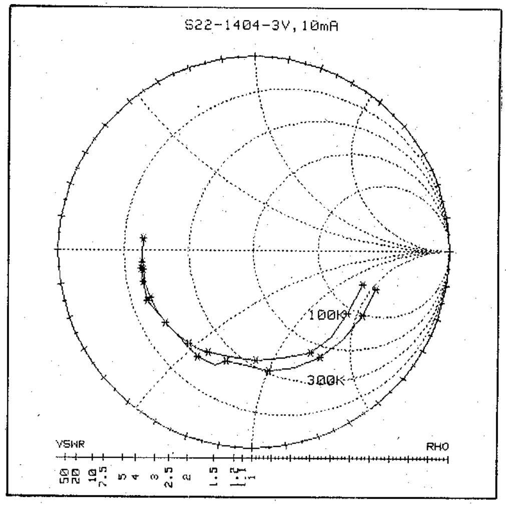
The circuit elements with the strongest influence on the properties of the transistor are Gm, Rg, Rs, Ri, Rds, Cds, and Cgs. Three types of programs—SINOPT (IE-BAS), Touchstone (EESOF), and S-Compact (Compact Software)—were initially used to find the values of the individual elements. The program S-Compact gave the best convergence and the best match with the measured *S*-parameters and with the parameters determined by means of



MGF 1404 (300 K)

S-MATRIX IN MAGNITUDE AND PHASE

	11		12		21		22	
FREQ	MAG	ANG	MAG	ANG	MAG	ANG	MAG	ANG
1.000	.984	-21.0	.025	60.0	3.500	161.0	.654	-17.0
2.000	.956	-43.0	.033	46.0	3.200	143.0	.647	-30.0
4.000	.886	-74.0	.040	37.0	2.860	110.0	.640	-57.0
8.000	.786	-134.0	.049	-5.0	2.280	54.0	.576	-104.0
10.00	.754	-154.0	.053	-21.0	2.140	28.0	.606	-118.0
14.00	.706	169.5	.063	-33.9	1.689	-23.6	.588	-164.4
18.00	.660	125.0	.100	-72.0	1.560	-68.0	.576	-174.0

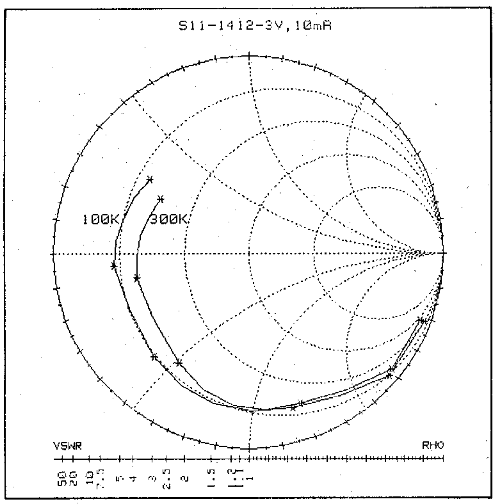


MGF 1404 (100 K)

S-MATRIX IN MAGNITUDE AND PHASE

	11		12		21		22	
FREQ	MAG	ANG	MAG	ANG	MAG	ANG	MAG	ANG
1.000	.987	-21.0	.023	60.0	4.050	162.0	.586	-17.0
2.000	.967	-44.0	.032	45.0	3.770	141.0	.579	-33.0
4.000	.902	-77.0	.040	38.0	3.400	109.0	.592	-60.0
8.000	.786	-140.0	.048	-9.0	2.710	48.0	.563	-114.0
10.00	.774	-159.0	.051	-26.0	2.570	23.0	.574	-125.0
14.00	.718	165.0	.064	-50.4	2.243	-25.3	.581	-155.8
18.00	.665	112.0	.076	-72.0	2.050	-76.0	.570	174.0

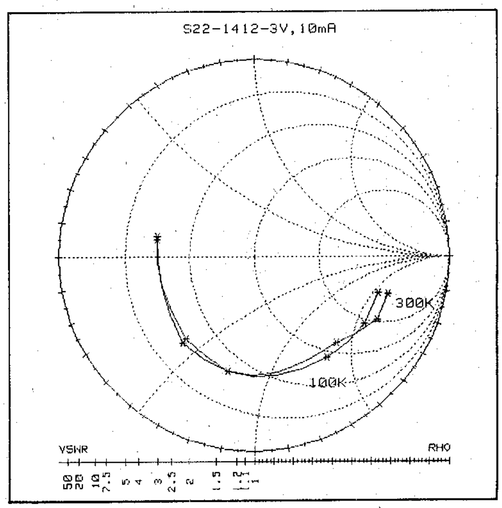
(a)



MGF 1412 (300 K)

S-MATRIX IN MAGNITUDE AND PHASE

	11		12		21		22	
FREQ	MAG	ANG	MAG	ANG	MAG	ANG	MAG	ANG
1.000	.946	-21.3	.023	70.7	3.644	156.1	.714	-15.2
2.000	.945	-39.0	.035	68.0	3.390	145.0	.709	-27.0
4.000	.817	-70.7	.073	40.0	2.961	110.7	.610	-46.0
8.000	.672	-123.2	.075	5.0	2.740	42.0	.602	-103.0
10.00	.589	-168.0	.078	-15.0	2.100	16.0	.545	-130.0
14.00	.535	149.0	.083	-45.0	1.720	-45.0	.510	170.0



MGF 1412 (100 K)

S-MATRIX IN MAGNITUDE AND PHASE

	11		12		21		22	
FREQ	MAG	ANG	MAG	ANG	MAG	ANG	MAG	ANG
1.000	.966	-21.0	.023	70.0	4.340	156.0	.666	-16.0
2.000	.955	-41.0	.040	65.0	4.020	144.0	.662	-31.0
4.000	.824	-74.0	.076	37.0	3.520	107.0	.640	-54.0
8.000	.722	-133.0	.088	5.0	3.300	39.0	.602	-103.0
10.00	.699	-175.0	.092	-17.0	2.630	13.0	.575	-130.0
14.00	.635	144.0	.083	-45.0	2.130	-45.0	.510	168.0

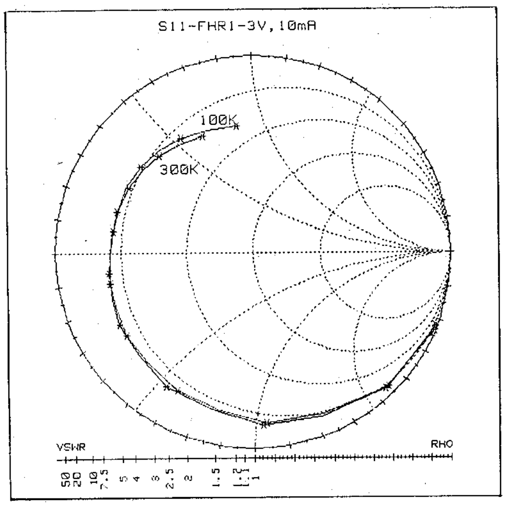
(b)

Fig. 2. *S*-parameters measured at 300 and 100 K at constant drain current. (a) MGF1404. (b) MGF1412. (c) FHR01FH.

other methods [2]–[7]. For this reason the S-Compact program (in the Random Search mode) was used. After the parameters of the physical equivalent circuit of a given transistor were specified at room temperature and the package parameters were determined, only changes in the transistor chip parameters were taken into account.

IV. Temperature Dependence of the Elements in the Equivalent Circuit

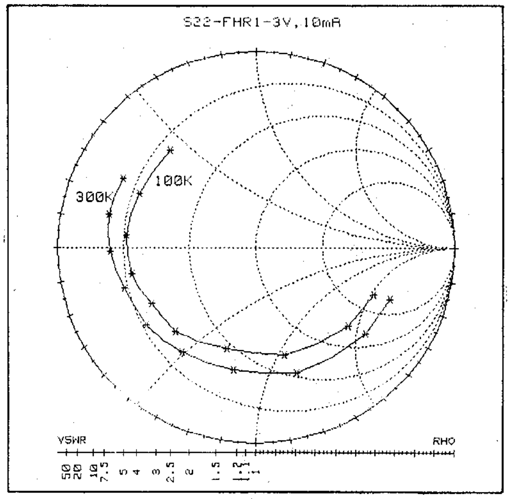
The measurement of the temperature dependence of the *S*-parameters over a broad frequency range (see Fig. 2) made it possible to determine the relation between the



FHR01 (300 K)

S-MATRIX IN MAGNITUDE AND PHASE

	11		12		21		22	
FREQ	MAG	ANG	MAG	ANG	MAG	ANG	MAG	ANG
1.000	.990	-22.0	.028	71.0	4.300	159.0	.721	-21.0
2.000	.955	-45.0	.048	56.0	4.070	139.0	.702	-38.0
4.000	.871	-86.0	.080	24.0	3.460	100.0	.663	-72.0
8.000	.760	-147.0	.089	-23.0	2.350	39.0	.639	-125.0
10.00	.735	-168.0	.091	-41.0	1.990	14.0	.673	-145.0
14.00	.702	152.0	.092	-70.8	1.539	-31.2	.734	-178.9
18.00	.639	113.0	.093	-100.0	1.390	-76.0	.753	152.0



FHR01 (100 K)

S-MATRIX IN MAGNITUDE AND PHASE

	11		12		21		22	
FREQ	MAG	ANG	MAG	ANG	MAG	ANG	MAG	ANG
1.000	.996	-23.0	.028	67.0	4.750	158.0	.638	-22.0
2.000	.955	-46.0	.047	54.0	4.520	138.0	.607	-40.0
4.000	.884	-87.0	.077	23.0	3.790	99.0	.558	-75.0
8.000	.764	-152.0	.088	-25.0	2.610	35.0	.581	-134.0
10.00	.732	-172.0	.090	-43.0	2.270	13.0	.593	-152.0
14.00	.710	142.0	.088	-76.5	1.798	-34.0	.650	174.3
18.00	.641	97.0	.088	-118.0	1.710	-82.0	.656	131.0

(c)

Fig. 2. (Continued)

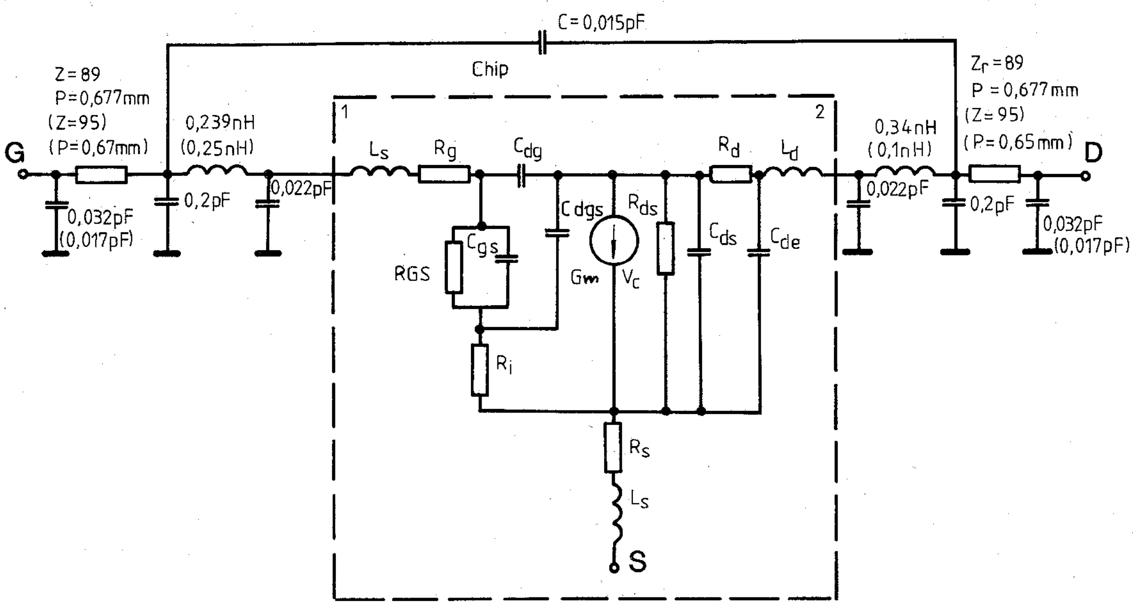


Fig. 3. FET equivalent circuit. In paranthesis the results for the Fujitsu HEMT FHR01FH are presented.

measured S-parameters and the values of the elements of the equivalent circuit (see Table II). The temperature dependences of the S-parameters of the transistors MGF1303, 1403, 1405, 1412, NE67383, and FHR01FH were studied. The values of the elements of the physical equivalent circuit for two temperatures, 300 and 100 K, were calculated according to the procedure described in the previous paragraph. The results for the transistors MGF1404, 1412, and FHR01FH were presented in the Table III.

The temperature changes of the parameters $S22$ and $S21$ were largest. The parameter $S21$ monotonically increases when the temperature is lowered. This change is mainly due to the increase in the drift velocity of the carriers upon cooling.

On the basis of the temperature dependence the elements of the physical equivalent circuit could be divided into two groups:

1) The first group includes elements characterizing the connection between the chip and the transistors package.

TABLE II

Transistor	T	Gm	Rg	Rs	Ri	Rd	Rds	Cgs	Cds	Cdg
	[K]	[mmho]	[Ω]	[Ω]	[Ω]	[Ω]	[Ω]	[pF]	[pF]	[pF]
MGF	300	43	3.57	2.36	3.07	2.4	291	0.273	0.141	0.03
1404	100	54	2.65	1.88	2.28	1.89	239	0.275	0.141	0.03
MGF	300	54	4.36	5.78	6.86	3.2	239	0.28	0.148	0.024
1412	100	71	3.4	4.52	5.43	2.34	204	0.283	0.141	0.027
Fujitsu	300	57	2.1	1.73	0.86	2.9	202	0.24	0.11	0.038
FHR01FH	100	72	1.65	1.47	0.68	2.4	201	0.26	0.11	0.040

TABLE III

Parameter	Gm	Rg	Rs	Ri	Rd	Rds	Transistor
Temperature	−1.28	1.29	1.02	1.29	1.06	0.84	MGF 1404
Coefficient	−1.57	1.1	1.09	1.04	1.34	0.73	MGF 1412
$\times 10^3$ [K^{-1}]	−1.31	1.07	0.75	1.05	0.86	1.3	FHR01FH

These are the elements which are dependent on the bonding wire and bonding method. The reactive element C and L are almost independent of temperature within the measurement error. The change in the bonding wire resistance is typical for pure gold.

2) The second group concerns the elements where the changes are due to the temperature dependence of the GaAs epitaxial layer parameters (mobility, saturation velocity etc.), the resistance of the metal layers, and the ohmic contacts. These are the elements Rds, Ri, Rg, Rd, Rs, and the capacitance Cds.

The output resistance Rds as well the resistance Ri decreased by 20–30% for all investigated transistors. This is related to the substantial change in the resistance of the epitaxial layer.

The change in the resistance Rg is about 40%. The resistance Rg can be calculated by the formula [8]:

$$Rg = \rho \cdot W/12t \cdot L \tag{1}$$

where ρ is resistivity of the gate material, W and L are gate width and length respectively, and t is the thickness of the gate metal layer.

It could be assumed that the major change in Rg is due to ρ(Au), having in mind the gate electrode structure is essentially made from pure metal. The ratio (Rg300–Rg100)/Rg300 calculated from (1) is about 40% and corresponds to experimental results, obtained after cooling from 300 to 100 K.

Rd(Rs) is the sum of the resistance of the ohmic contact Rc and the epitaxial layer resistance Re between the drain (source) and the gate. These coefficients change in Rc is mainly due to the temperature dependence $\rho(T)$ of the ohmic contact material. When the increase in the carrier mobility after cooling to 100 K is added, the total decrease in Rs and Rd is about 30%.

The coefficients, reflecting the changes in the values of the elements of the physical equivalent circuit with the largest temperature dependence, are given in Table III. These coefficients were computed on the basis of the results of the RF measurements, thus making it possible to obtain the transistor S-parameters for any frequency and temperature between 300 and 100 K.

In principle the changes in most parameters (with the exception of $S21$ (g_m) and Rd) are sufficiently small, particularly for the transistors with a gate length L below 0.5 μm, that they can be considered as linear with a rather large accuracy. If a particular transistor is used, it is possible to work with an exact relation of g_m and Rd versus temperature. However, even if the simple linear relation is used, the error is smaller than the spread in the transistor parameters and these typical coefficients may be used in estimating the temperature dependences of the S-parameters of the other microwave FET's as well.

More exact dependences could be obtained when there is more data on the transistor parameters—contact manufacturing technology, epitaxial layer parameters, etc. and the described method is augmented with the methods described in [7].

V. Experimental Study of Cooled Amplifiers

Several types of microwave amplifiers were designed on the basis of the above mentioned experimental investigation of FET's and their physical equivalent circuits (Table IV).

The following method was applied to determine the noise parameters of the transistor (resp. the amplifier) by using the physical equivalent circuit:

1) F_{min}, Γ_{opt}, Rn are calculated using the technique described by Fukui [9];

2) F_{min}, Γ_{opt}, and Rn are measured in a special test structure at a fixed frequency (4 GHz). This structure represents a low-noise amplifier in which the transformed impedance, Γ_{opt}, can be measured.

3) The values of the elements of the physical equivalent circuit are determined through the measured S-parameters and F_{min}, Γ_{opt}, and Rn are calculated using a Hewlett Packard Microwave Design Station.

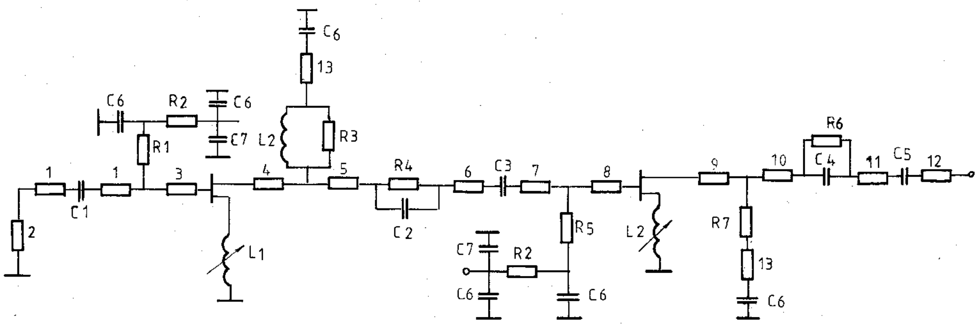
Due to spread in the transistor parameters amplifier tuning is required in all cases. Special tuning elements are included for this purpose, e.g., Pos. 4-Fig. 5(b).

Noise measurements for all amplifiers were carried out with a computer corrected noise measurement system based on an HP 8970 [10]. For quick measurements and tuning, the authors applied the calibrated noise head method with a calibrated 20 dB attenuator. For precise measurements, the method of the cold/hot load was used, where the measuring accuracy is ±1°.

TABLE IV

	Frequency Range	Transistor	Circuit	Stages	Uncooled Gain [dB]	Uncooled BW [MHz]	Uncooled Noise [K]	Cooled Gain [dB]	Cooled BW [MHz]	Cooled Noise [K]	Temp [K]	Figures Circuit	Figures Result
A	0.5–4 GHz	MGF 1404 + 1412	susp. microstrip	2	19	3500	120	21	>4000	70	77	4(a)	4(b)
B	3.7–4.1 GHz	MGF 1404	microstrip	1	13	400	45	14	400	20	15	5(b)	5(c)
C	4.8–5.2 GHz	MGF 1404	microstrip	1	14	400	65	15	800	32	15	5(b)	5(d)
D	19–23 GHz	MGF 1404	susp. microstrip	2	11	4000	330	14	5000	220	77	7(b)	7(c)
E	27–29 GHz	MGF 1404	susp. microstrip	2	10	2000	390					7(b)	7(d)
F	22–23 GHz	FHR01FH	susp. microstrip	2	11	1000	260	12	1000	70	15		8

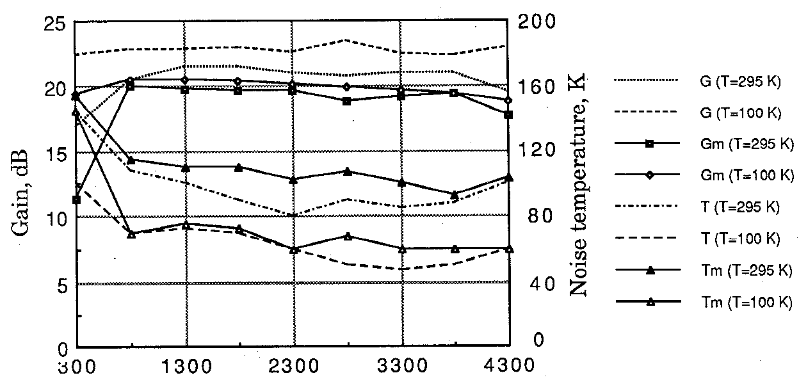
R Ω / C pf	C1	C2	C3	C4	C5	C6	C7	R1	R2	R3	R4	R5	R6	R7
Value	82	56	2,4	100	150	164	1000	3000	100	80	170	2200	58	66



ε = 10

№	1	2	3	4	5	6	7	8	9	10	11	12	13
Len mm	0,9	17	3,3	2,1	0,5	0,5	0,9	0,8	2	0,5	1,1	1	10
Z[Ω]	95	140	128	128	95	95	95	102	128	95	95	95	108

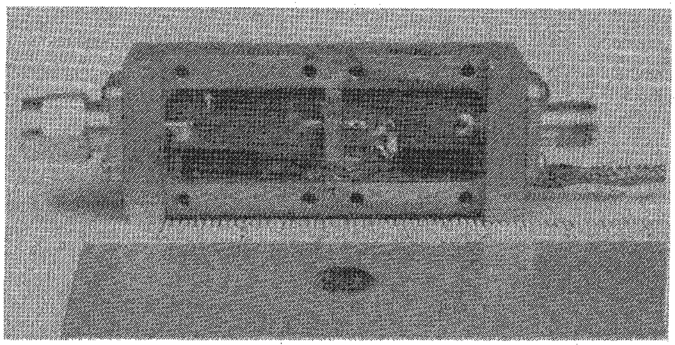
(a)



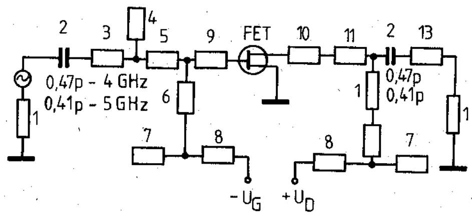
(b)

Fig. 4. Cryogenically cooled two-stage 0.5–4.0 GHz amplifier. (a) Schematic circuit and element values. (b) Theoretical (G, T) and experimental (G_m, T_m) characteristics at 300 K and 100 K.

The circuit lay-out of the amplifiers was optimized in order to obtain the best performance after cooling to the operating temperature. Suspended microstrip and coplanar lines studied previously [3] as well as other microwave structures for higher frequency ranges [11], [12] were compared theoretically. As a result of these investigations, a suspended microstrip line was chosen for the cooled amplifiers which facilitates obtaining the required



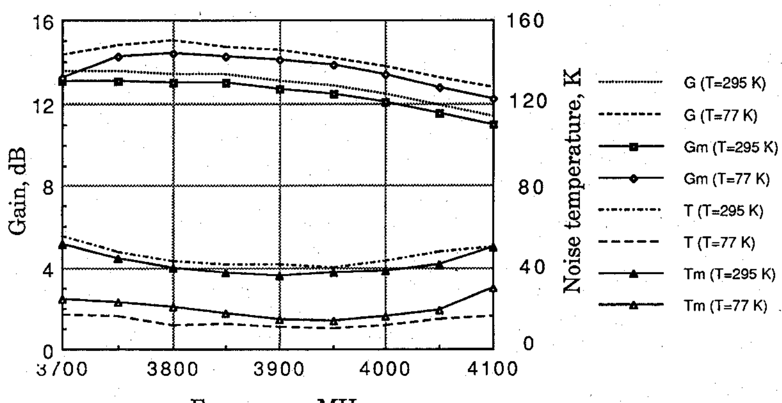
(a)



ε= 2,45

	Nº	1	3	4	5	6	7	8	9	10	11	12	13
4 GHz	Z[Ω]	50	86	45	25	80	20	90	100	100	40	80	50
	len[cm]	—	1,33	1,2	0,94	1,54	1,87	1,9	0,78	0,97	0,3	1,87	1,1
5 GHz	Z[Ω]	50	57	53	30	71	20	90	100	100	40	80	50
	len [cm]	1,17	1,17	1,17	0,2	1,35	1,5	1	0,5	0,6	0,3	1,4	1

(b)



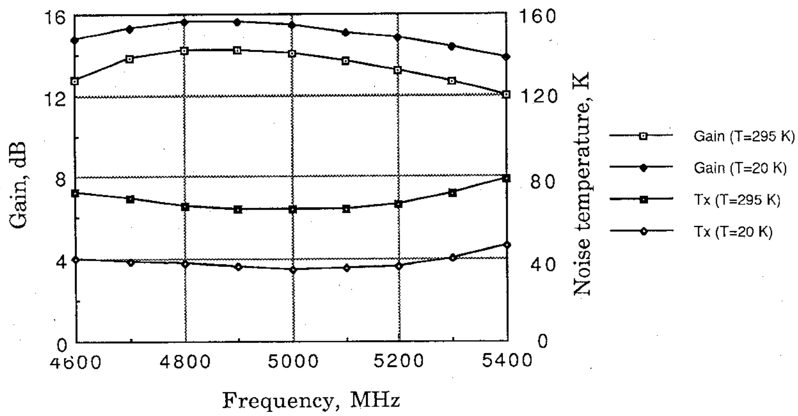
(c)

Fig. 5. Cryogenically cooled single stage 3.7-4.1 GHz and 4.8-5.2 GHz amplifiers. (a) Photograph. (b) Schematic circuit and element values. Theoretical and experimental characteristics at 300 and 100 K. (c) 3.7-4.1 GHz amplifier. (d) 4.8-5.2 GHz amplifier.

impedances with much lower losses than in the case of microstrip lines.

The amplifier circuit for the range 0.5–4 GHz is given in Fig. 4(a). A two stage amplifier circuit with several feedbacks in the sources was chosen. The transistors used are of the type FHR01FH (or MGF1404) for the first stage and MGF1412 for the second stage. By introducing additional circuit elements (*R*4, *C*2, and *C*4, *R*6 as well as the combinations *L*2, *R*3, *R*13, and *R*7, *C*13) the gain characteristic was made frequency independent (Fig. 4(b)). This amplifier can find application as the first IF amplifier in wide-band cooled radiometric system, including systems for space applications.

The single stage amplifier for operation at an environmental temperature of 20 K in the band 3.7–4.1 GHz is shown in Fig. 5(a). The transistor is of the type



(d)

Fig. 5. (Continued)

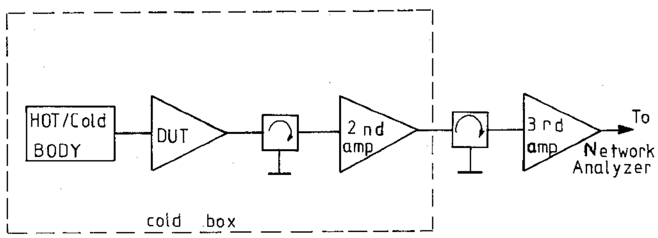


Fig. 6. Noise measurement set-up for 3.7–4.1 and 4.8–5.2 amplifiers.

MGF1404. Passive hybrid integrated circuits are used for dc stabilization. The series blocking capacitors $C2$ are printed (interdigital), thus essentially avoiding any temperature dependence. A combination of microstrip and suspended lines is used in the amplifier structure. A resistive matching circuit is used at the output in order to make the gain vs frequency characteristic flat. The input matching circuit is designed to present the optimum source impedance to the transistor thus ensuring minimum noise for the amplifier. The tuning stubs (4) essentially change the amplitude of the reflection coefficient and have almost no influence on the phase and thus not the amplifier center frequency either. The results of the experimental study are presented in Fig. 5(b) and (c). Also a 4.6–5.4 GHz amplifier was realised in a similar way as the 3.7–4.1 GHz one, with Tnoise = 35 K and a gain of 15 dB when cooled to 20 K (Fig. 5(d)). The block diagram of the test set-up for noise measurements of the amplifiers is given in Fig. 6.

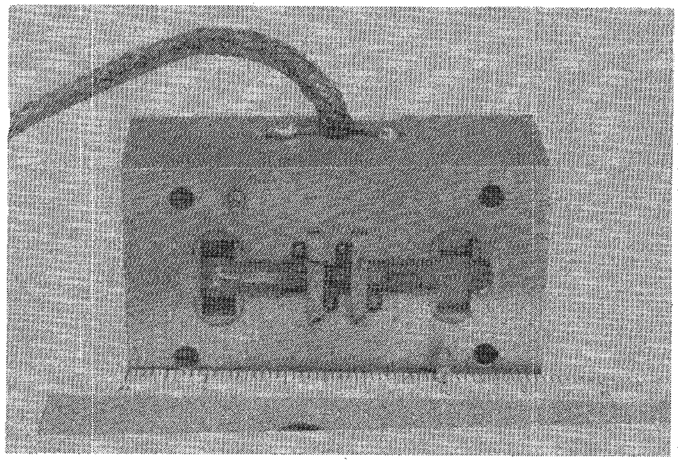
In the design of microwave amplifiers for the ranges 19–23 and 26–28 GHz HEMT transistors were used in the first stage and MGF1404 in the second stage in order to achieve the required amplification factor. The first transistor is optimized with respect to noise and the second with respect to maximum gain since at these frequencies the maximum gain does not exceed 5–7 dB. The dc parameters for the first stage are: Vds = 2 V and Ids = 10 mA and for the second stage: Vds = 3 V and Ids = 18–20 mA.

The amplifiers have waveguide inputs and outputs with probe transitions to suspended lines (Fig. 7(a) and (b)). The transmission line structures are on CuClad-3M substrates with $\epsilon = 2.45$ and thickness $h = 0.15$ mm. The results of the experimental studies of the amplifiers are given in Fig. 7(c) and (d).

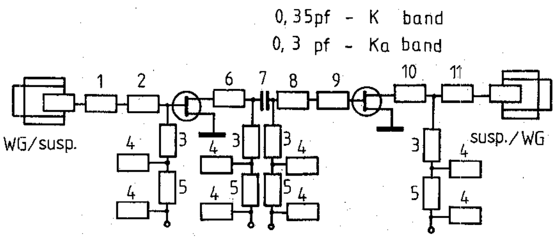
A third amplifier of the same design was optimized at 22.3 GHz for radioastronomical applications. In this case the Fujitsu HEMT FHR01FH was used in both stages. Noise temperature and gain were measured at room temperature and at cryogenic temperature (15 K). A noise temperature of 70 K and a gain of 13.8 dB were obtained at 15 K (Fig. 8).

VI. Conclusion

S-parameters were measured and noise parameters were calculated up to 18 GHz and between 100 and 300 K for several common MESFET's and for Fujitsu HEMT FHR01FH. An equivalent circuit was established for the field effect transistors and by using the SUPER COMPACT programe the values of the circuit elements were determined for the temperature range 100–300 K. The temperature dependences of the equivalent circuit elements with the strongest influence on the transistor behavior were calculated. By using these results a number of microwave amplifiers were designed for frequencies between 0.5 and 28 GHz and measured at room and cryogenic temperatures. For the amplifiers 0.5–4.0 GHz and



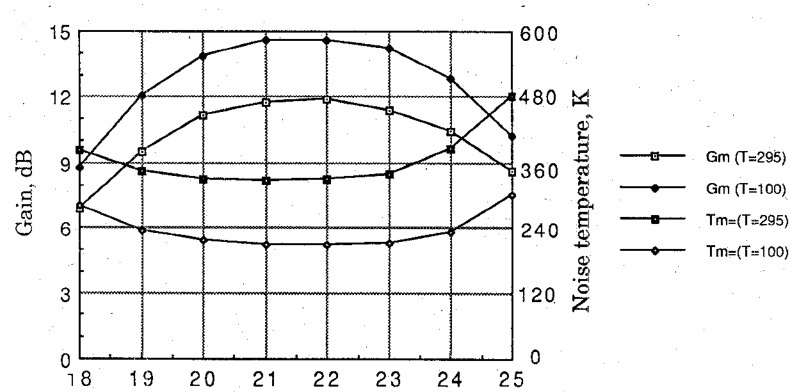
(a)



ε= 1

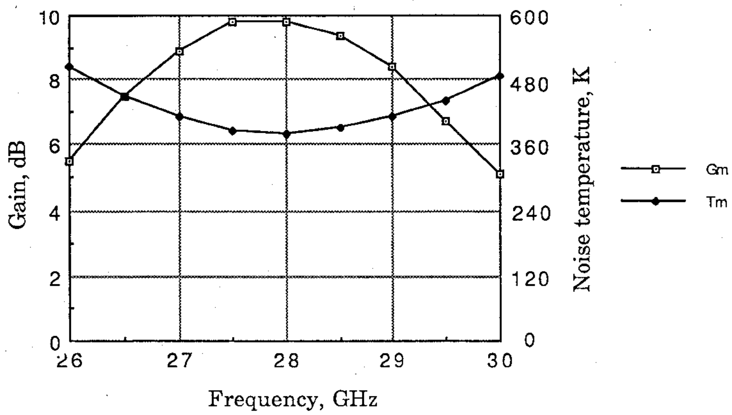
	Nº	1	2	3	4	5	6	8	9	10	11
K band	Z[Ω]	47	98	140	30	100	51	104	50	35	56
	len[cm]	0,66	0,6	0,37	0,37	0,37	0,35	0,3	0,17	0,2	0,3
Ka band	Z[Ω]	77	41	120	25	120	58	109	109	58	113
	len[cm]	0,2	0,25	0,26	0,26	0,26	0,05	0,146	0,05	0,14	0,25

(b)



(c)

Fig. 7. Cryogenically cooled two stage 19–23 GHz and 26–28 GHz amplifiers. (a) Photograph. (b) Schematic circuit and element values. Experimental characteristics at 300 and 100 K: (c) 19–23 GHz amplifier. (d) 26–28 GHz amplifier.



(d)

Fig. 7. (Continued)

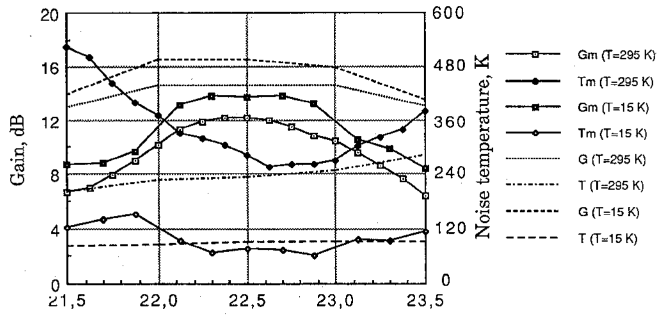


Fig. 8. Experimental and theoretical characteristics at 300 and 15 K of cryogenically cooled 22–23 GHz amplifier.

3.7–4.1 GHz good agreement between theoretically calculated gain and noise temperature and experimentally measured values was observed.

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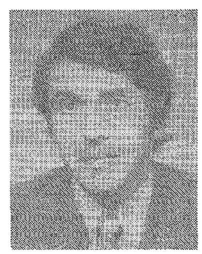
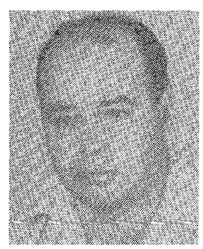


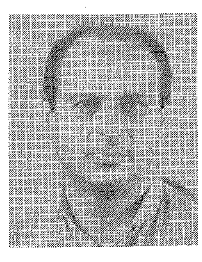
Iltcho Angelov received the degree in electronics in 1969 and joined the Institute of Electronics, Bulgarian Academy of Sciences. In 1973 he obtained the Ph.D. degree in physics and mathematics from Moscow State University, for his work in the field of distributed microwave parametric amplifiers. He also worked with IMPATT and Gunn diodes and studied nonlinear effects and synchronization phenomena in these devices.

Since 1976 he has concentrated his attention on microwave transistors. He is currently head of the Microwave Solid-State Devices Department of the Institute of Electronics, Bulgarian Academy of Sciences.



I. Stoev was born in Sofia, Bulgaria on June 30, 1957. He received the M.S. degree in microwave engineering from the Sofia Technical University, Bulgaria, in 1982.

In 1982 he joined the Institute of Electronics, Bulgarian Academy of Sciences. His research activity is in the field of modeling of microwave FET and HEMT transistors, design and investigation of microwave low noise amplifiers and receivers.



Zdravko G. Ivanov was born in Radnevo, Bulgaria, on September 23, 1949. He received the Dipl. Ing. degree in electronics from the Moscow Higher Institute of Power Engineering in 1972, and Ph.D. degree in physics from Moscow State University in 1980.

In 1980 he joined the Institute of Electronics, Bulgarian Academy of Sciences. His research has been concerned theoretical and experimental investigations of Josephson effect. In 1985–1986 he visited for one year Chalmers University of Technology, Gothenburg, Sweden, and started work on three terminal Josephson devices and superconducting transport properties of ohmic contacts. Since January 1989 he is with the group of superconducting electronics in Chalmers University of Technology, Gothenburg, Sweden, working on HTS Josephson junctions.

Bogdan N. Todorov was born in Sofia, Bulgaria, on December 31, 1947. He received the Dipl. Ing. degree in electronics from the Moscow High School of Power Engineering in 1971 and Ph.D. degree in physics from Moscow State University in 1980.

In 1980 he joined the Institute of Electronics at the Bulgarian Academy of Sciences and continued his investigations in the field of Josephson effect applications. In last years his interests are in field of low noise and low temperature electronics and applications of high temperature superconductors in microwave devices.

A. Y. Spasov was born in Bulgaria in 1934. He received the M.S. degree in radio engineering in 1962, and the Ph.D. in electronics in 1965 from Moscow Energetic Institute. He obtained the Dr. of Sciences degree in 1977.

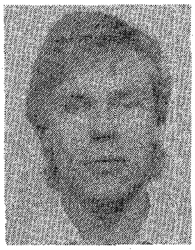
He worked on tunnel diode amplifiers, oscilators, parametric amplifiers, Impatt and Gunn diodes and studied non-linear effects in these devices. Since 1976 he began to work in the field of cryogenic electronics and Josephson devices. He is author of more than 80 papers. He is currently Director of the Institute of Electronics, Bulgarian Academy of Sciences.

Erik L. Kollberg (M'83–SM'83–F'91) received the M.Sc. degree in 1961 and the Teknologie Dr. degree in 1971 from Chalmers University of Technology, Gothenburg, Sweden.

He has been a Professor at Chalmers University of Technology since 1974. He has published more than 100 scientific papers in international journals in the field of maser amplifiers, millimeter-wave Schottky diode mixers, superconducting mixers, GaAs devices, and other subjects related to millimeter-wave techniques. The work within his group is focused on new technology concerning low noise millimeter and submillimeter wave receivers for radio astronomy.

Dr. Kollberg received the microwave prize at the European Microwave Conference in Helsinki in 1984.

C. O. Lindström was born in Gothenburg, Sweden on Jan. 1, 1937. He received the B.S. in 1961. Since that time he has been working with low noise receivers for radio astronomy as a Research Engineer at Chalmers University.



B. L. Wendemo was born in Gävle, Sweden on May 10, 1960. He received the M.S. in 1986 and the Technical Licentiate degree in 1990 from Chalmers University of Technology. At Chalmers he was mainly working with low noise amplifiers.

He is presently with Saab Marine Electronics, Linköping, Sweden.