On the performance of different HEMT cryogenic mixers

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Abstract

Performance of different HEMT mixers -i.e. gate, drain and resistive (microstrip and waveguide) has been studied experimentally at room and cryogenic temperatures. Conversion gain (loss for the resistive mixers) at cryogenic temperatures improves approximately 1÷1.5 dB. The noise figure improves too - all the mixers show 2- 3 dB improvement in the noise figure performance.

Introduction

It is well known that HEMTs can be operated successfully as amplifiers and oscillators at room and cryogenic temperatures. There is a significant improvement in the performance of low noise amplifiers when they are operated at cryogenic temperatures. Such cryogenic amplifiers have been built at frequency up to 120 GHz. There are many successful attempts to operate the HEMT as an oscillator at room and cryogenic temperatures too. Both theory and practice of use of MESFET and HEMT as mixers in different configurations (resistive, gate, drain) at room temperature are well established now [1-13]. But there are not so many attempts to investigate the cryogenic behavier of different types of HEMT mixers and to compare their performance.

In this work HEMT device (MGF4317) was used in different mixer configurations, i.e. resistive, drain and gate mixers, in order to evaluate the accuracy of the device models, their impact on the circuit parameters both at room and cryogenic temperatures. In order to improve the accuracy of the modeling of the passive elements and to reduce the influence of the manufacturing tolerance on the mixer performance most of the mixers were build at relatively low frequency (X-band). Better accuracy of the cryogenic noise figure measurements is much easier to achieve at this low frequency too.

The Device Large Signal and Temperature Modeling

DC and S- parameters (1-18 GHz) measurements were made in a wide temperature range (15-400K) on many HEMT devices from different manufacturers in order to select the device which can be operated successfully both as a low noise and a large signal device in this temperature range. Mitsubishi packaged transistor

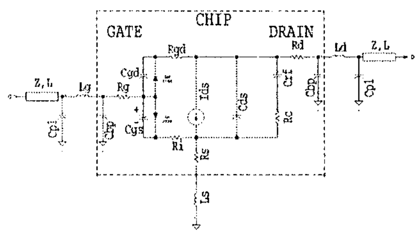

Fig. 1 Equivalent circuit of the tramsistor

MGF4317D was one of the devices fiting well for this purpose and was used in all four X-band mixers. At Q-band the InP HEMT chip manufactured at Chalmers was used in the waveguide resistive mixer. From the measured parameters the small and large signal models of the transistors were extracted. The equivalent circuit of the transistor is shown in Fig. 1. We have found that the Chalmers large signal model can be successfully used to design all the 3 mixer types. The equation for the drain current of a FET device in our model is given by [14,15]:

$$I_{ds} = I_{pk}[1+\tanh(\psi)](1+\lambda V_{ds})\tanh(\alpha V_{ds}) \quad (1)$$

$$\psi = P_1(V_{gs}-V_{pk}) + P_2(V_{gs}-V_{pk})^2 + P_3(V_{gs}-V_{pk})^3 \quad (2)$$

$$V_{pk}(V_{ds}) = V_{pk0} + (V_{pks}-V_{pk0})\tanh(\alpha_s V_{ds}) \quad (3)$$

$$\alpha = \alpha_r + \alpha_1[1+\tanh(\psi)] \quad (4)$$

$$P_1 = P_{1sat}[1+\frac{B_1}{\cosh^2(B_2 V_{ds})}] \quad (5)$$

where I_{pk} is the current and V_{pks} is the gate voltage for peak transconductance at saturated drain voltages. V_{pk0} and V_{pks} are V_{pk} measured at V_{ds} close to zero and in the saturated region, respectively.

Temperature changes in model parameters for the selected HEMT devices in the temperature range 17-400K are presented in Table 1. We found that the most critical temperature range for the transistor operation was in the vicinity of 70-100 K. Nearly all of the transistors measured showed some problems in their large signal behavior (collapse of IV characteristics, significant kink effect,etc.). Generally, in the temperature range 150-400K the

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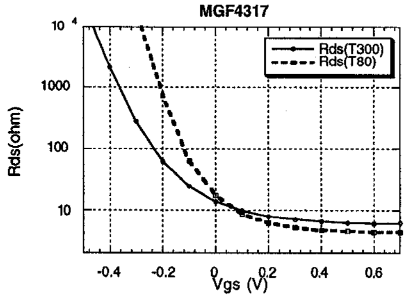

Fig. 2. R_{ds} vs. gate voltage at RT and 30 K

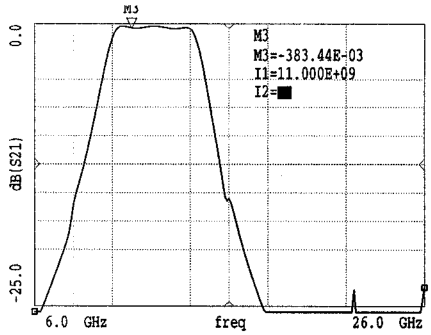

Fig. 3a Frequency response of the MS filter.

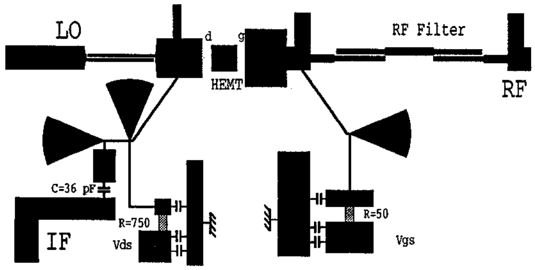

Fig. 3b- Microstrip Drain Mixer

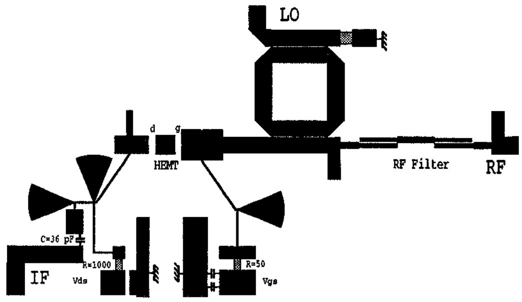

Fig. 3d- Microstrip Gate Mixer

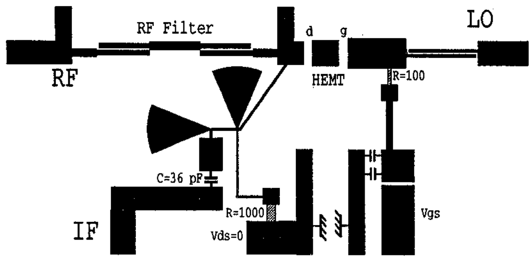

Fig. 3c- Microstrip Resistive Mixer

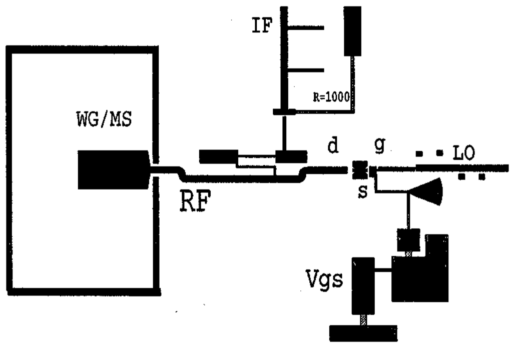

Fig. 3e- Waveguide X and Q-band Resistive Mixer

Fig. 3. Layout of the mixers

changes of the model parameters with temperature are usually smooth. The voltages at which we have maximum transconductance, V_{pk0} and V_{pks}, increase linearly at low temperatures, P_{1s} is almost independent of temperature, because of the nearly monotonous increase of both g_m and I_{pk}, at low temperatures. The changes of the transconductance are mainly due to I_{pks} increase at cryogenic temperatures. The largest change we monitored was the increase of the coefficient P_{10} at cryogenic temperatures. This observation is very important for resistive mixers. It means that it will be possible to reduce the local oscillator at cryogenic temperatures. Increases of λ and α_s for all transistors are observed at low temperatures. The total channel resistance, Fig. 2 at low drain voltages ("on" resistance) $R_{on}=r_{ch}+R_s+R_d$ is one of the most important parameters of the transistor if it is to be operated as a resistive mixer. R_{on} decreases from 6.2 ohm at room temperature (RT) to 4.4 ohm at 20 K. The changes of the capacitances C_{gs} and C_{gd} with temperature are very small, 10÷20 % in the whole temperature interval 17K- 300K.

Mixers design

In order to reduce the influence of the device parasitics and to improve the accuracy of the measurements and designs, a

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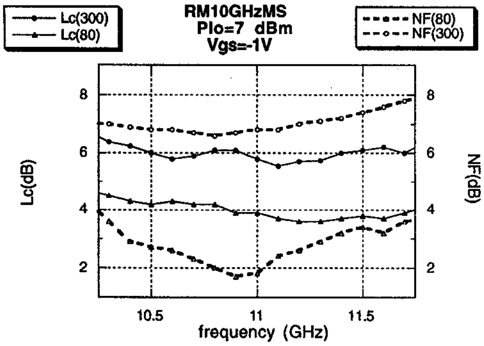

Fig. 4a LC and NF of the MS resistive mixer

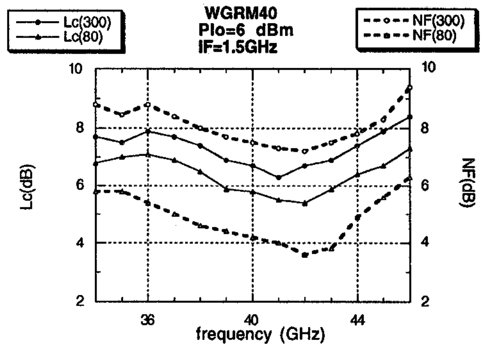

Fig. 5b LC and NF of the Q-band WG resistive mixer

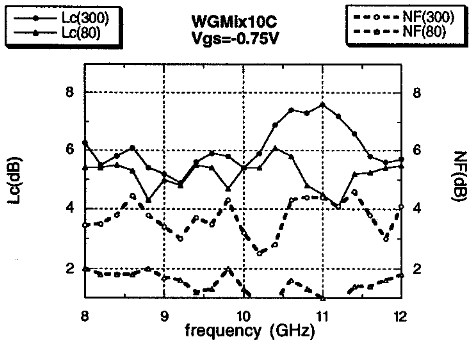

Fig. 4b LC and DSB NF of the X band WG resistive mixer

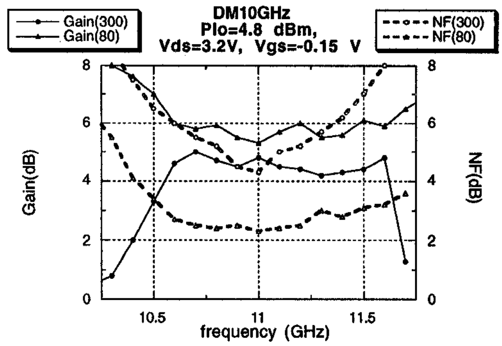

Fig. 6 Gain and NF of the drain mixer

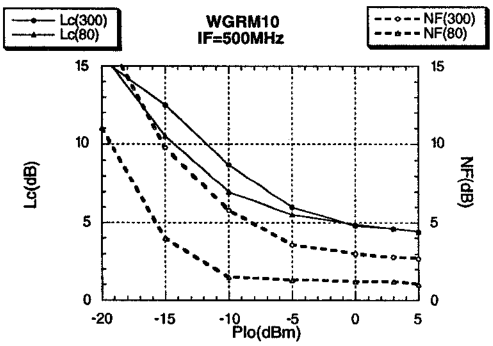

Fig. 5a LC and DSB NF of the WG resistive mixer

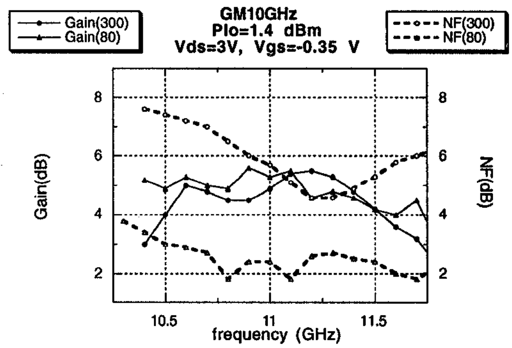

Fig. 7 Gain and NF of the gate mixer

relatively low frequency was selected for the mixers performance evaluation. The local oscillator frequency for all microstrip mixers was selected to 10 GHz and the RF bandpass filter (Fig. 3a) was the same for all the microstrip mixers (11÷13 GHz). This type of RF filters has a reduced leakage at second harmonics which can contribute to better overall performance. Five different cryogenic mixers were designed and tested, i.e. a microstrip drain mixer (MSDM)- Fig. 3 b, microstrip resistive mixer (MSRM)- Fig. 3c, gate mixer (MSGM)- Fig. 3 d, a waveguide X band (8-12 GHz) resistive mixer (WRM)- Fig. 3 e, and a Q-band waveguide (32-46 GHz) mixer with a topology identical to the X-band waveguide mixer. MDS from HP and Microwave Harmonica (Compact) were used in the design of the mixers. In comparison with the resistive and drain mixer, the gate mixer was most difficult to design because the LO and RF on the later are applied at the same terminal and it is difficult to optimize the large signal performance for both frequencies simultaneously. The local frequency selection was more critical for the gate mixer, because a ring filter (which is inherently narrow band) was used to apply the LO to the gate. A waveguide to microstrip transition for the waveguide mixer was optimized using HFSS (HP) and later tested separately in order to obtain maximum possible RF bandwidth from the waveguide mixers. Losses of the waveguide to microstrip transition in the frequency range 8-12.4 GHz were below L≤0.8 dB (typically below 0.4 dB) with fixed position of the backshort. The X-band waveguide restive mixer was used as a scaled model for the Q-band mixer. Soft substrate with dielectric constant e_r=2.94, h=15 mil was used for the X-band microstrip mixers. For the waveguide mixers a high dielectric constant material was used. The dielectric thickness was 25 mil for the X-band mixer (e_r=10.5) and 5 mil alumina was used for the Q-band mixer in order to facilitate bonding and mounting.

Measurement results

The experimentally obtained results are shown in Fig. 4-7 . HP 8757D, HP8970B and HP83650A were used for the conversion loss and noise measurement and a CTI Cryogenics refrigerator in the cryogenic measurements. Fig. 4 and 5 shows the conversion loss and noise figure of the resistive mixers at both room temperature and 80 K The conversion loss was slightly lower at 80 K and the noise figure was improved by 1.5-3 dB across the waveguide band (5.6 dB minimum). The noise figure (DSB) and conversion loss (Fig. 4b) of the waveguide resistive mixer were better, because there is no RF filter in the waveguide mixer. The noise figure and conversion loss of the waveguide Q-band RM is shown in Fig. 5b. To our knowledge this is the lowest reported conversion loss for the resistive HEMT mixer working in the Q-band.

The cooling of the mixers improves conversion gain (loss for the resistive mixers)->1÷1.5 dB. The noise performance improves a lot- there is a 2-3 dB improvement of the noise figure on all the mixers. As it was expected the conversion loss and noise figure were much better at low LO power levels at cryogenic temperature. At -10 dBm LO power the noise figure and conversion loss were nearly 3 dB lower compared to the room temperature with the same pumping power, Fig. 5 a. The performance of the Q-band waveguide resistive mixer is similar.

The best obtained SSB drain mixer noise figure (RT) was 4.4 dB, Fig. 6 and this value decreased approximately 3 dB from room temperature to liquid nitrogen temperatures. The gain can be adjusted from 3 dB to 5 dB by changing the bias conditions. The gate mixer performance is shown in Fig. 7. We found that this mixer was the most sensitive to bias and LO conditions. The best noise figure obtained was 4.2 dB at room temperature and it dropped to around 2 dB at 80K. Further improvement of the noise figure performance of the mixers is expected in the planned measurements at 20K.

Conclusions

The performance of different HEMT mixers -i.e. gate, drain and resistive has been studied experimentally at room and cryogenic temperatures. The conversion gain (loss for the resistive mixers) at cryogenic temperatures improves 1-1.5 dB. The noise figure improves significantly - all the mixers show 2- 3 dB improvement in the noise figure performance. This means that it is possible to design the complete HEMT receiver consisting of an amplifier, a mixer and an oscillator working at cryogenic temperatures. This can significantly simplify the system design and improve the reliability.

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Table 1. MGF4317D: V_{ds}=2V: 20 K and 300 K.

T K	I_{pks} mA	V_{pks} V	V_{pk0} V	P_{1s} 1/V	P_{10} 1/V	B 1/V	P_2 $1/V^2$	P_3 $1/V^3$	l 1/V	a_s 1/V	C_{gs0} fF	C_{gd0} fF	Cds fF	Rg W	Rd W	Rs W	Rin W
20	53	0.33	.048	2.5	7.5	4	-0.2	7.8	0.17	3.5	240	35	120	1.9	2.1	1.6	4
300	44	0.30	.05	2.55	6.1	4	-0.8	3.8	0.15	2.4	280	35	120	2.5	2.7	1.8	5