Phase Noise in Cryogenic Microwave HEMT and MESFET Oscillators

Olivier Llopis, Robert Plana, Hicham Amine, Laurent Escotte and Jacques Graffeuil

Abstract— **This paper addresses the influence of cooling on the phase noise of HEMT and MESFET oscillators. The initial measurements of the device dc characteristics and low frequency noise (0.1 kHz–100 kHz) under cooling give indications on the suitability of a given device for use in low phase noise cooled oscillators. Cooled pseudomorphic AlGaAs/GaInAs/GaAs HEMT's (PHEMT's) turn out to be particularly well-suited as they are free of collapse and they are free of g-r noise in the frequency range of interest. We report on 4 GHz oscillators operated at 110 K and featuring a phase noise below -100 dBc/Hz at 10 kHz from the carrier in spite of a very modest loaded Q (160). It is suggested that high temperature superconductor resonators could greatly enhance the spectral purity of PHEMT's oscillators.**

I. Introduction

With the advent of high quality thin films of high Tc superconductors (HTCS), the interest in the microwave cryogenic oscillator has sprung up. In particular, recent results have shown that the performance of microstrip resonators made of HTCS and operated at liquid nitrogen temperature compare favorably with those of ambient temperature dielectric resonators [1]. Particular configurations of cryogenic HTCS resonators have been proposed in order to reach quality factors in excess of 10^5 or 10^6 in the microwave range which are needed to achieve high stability and the low phase noise in microwave oscillators. For example, the problem of HTCS deposition on curved surfaces can be overcome by using the dielectric-superconductor configuration [2], [3]. Also, it has been shown that these quality factors could be obtained by means of a sapphire-superconductor resonator [2]–[4].

However, the effect of cooling on active solid state oscillating devices has not been fully assessed yet and as a high spectral purity oscillator will require complete cooling to match miniaturization requirements and uncontrolled phase shifts due to thermal gradients, the behavior of active components at low temperature becomes a major issue.

In this paper, the electrical characterizations of HEMT and MESFET devices at low temperatures (approx. 110 K) is reported. The electrical parameters considered in these measurements are those of prime importance for the development of a high spectral purity oscillator. Then the phase noise of cooled microwave oscillators obtained from devices characterized before is reviewed and finally the high potential of certain devices is considered in relation to cooled low phase noise microwave oscillators. Also as the heterojunction bipolar transistor [5] is a good candidate for low phase noise cooled oscillators, measurements have been done on these structures but have not been reported here because their low frequency noise has not been fully evaluated and HBT are not yet commercially available, thus preventing any extensive investigations. In addition, conventional microwave silicon bipolar transistors are of limited interest at low temperature because of carrier freeze out.

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II. Low Temperature Electrical Characterization

A. Cryogenic Experimental Apparatus

The devices under test are placed in a coaxial test jig with a high thermal capacity located inside a vacuum chamber. The test jig is maintained on a cold plate in contact with a liquid nitrogen reservoir. Two coaxial cables provide an access for measurements in the microwave and the low frequency ranges.

B. DC and Low Frequency Measurements

These measurements allow assessment of those devices which are potentially best-suited for low temperature oscillators. Two types of measurements have been carried out against temperature:

$I_{ds} = f(V_{ds})$ characteristics, and transconductance G_m versus V_{gs}.

Low Frequency (LF) noise spectra (100 Hz–100 kHz).

LF noise characterizations are particularly useful for high spectral purity oscillators because this LF noise is converted into microwave phase noise by the active device nonlinearities. The current-voltage characteristics are also investigated at low temperature to check whether i) transconductance is large enough to provide sufficient gain and ii) the drain current is large enough to provide sufficient output power.

Two MESFET's and nine different HEMT's, most of which are commercially available, have been characterized with respect to $I_{ds} = f(V_{ds})$. MESFET's behave satisfactorily at low temperature. For example the MGF1402 device features a slight increase (~10%) in drain current and transconductance (Fig. 1). The HEMT behavior is much more complex on account of the so-called collapse phenomenon [6], [7] due to the carriers being captured by deep levels. By way of an example, Fig. 2 shows a sharp decrease in HEMT drain current at low temperature and low V_{ds}. Nevertheless, at V_{ds} beyond 2 V and V_{gs} near 0 V, transconductance G_m is still similar to that observed at ambient temperature. However, the $G_m(V_{gs})$ curve

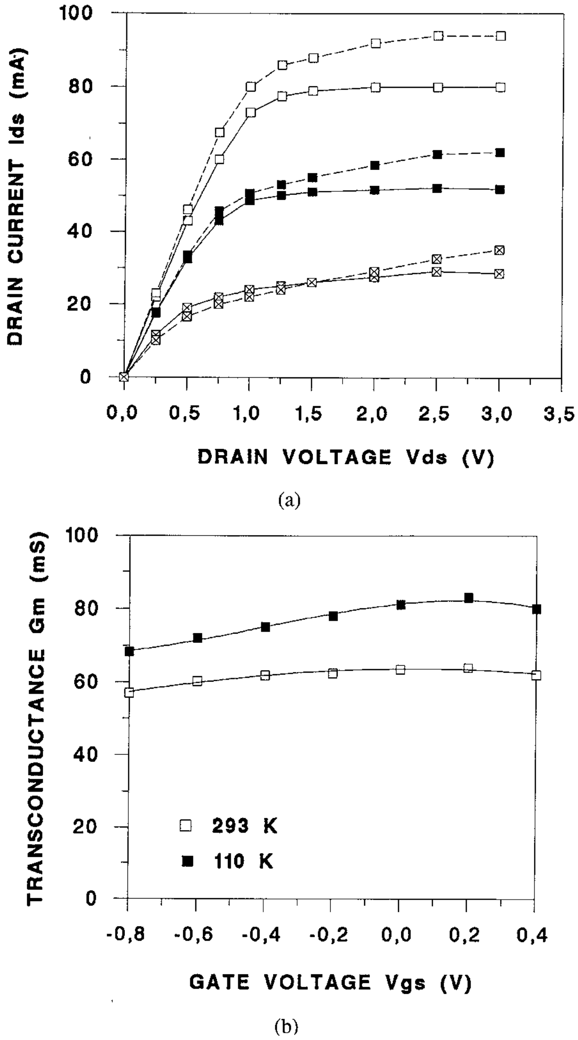

Fig. 1. MESFET MGF1402 current-voltage characteristics (a) at ambient temperature (solid line) and 110 K (dashed line). —□— $V_{gs} = 0$ V, —■— $V_{gs} = -0.4$ V, —⊠— $V_{gs} = -0.8$ V. Transconductance (b) at the same temperatures and $V_{ds} = 3$ V.

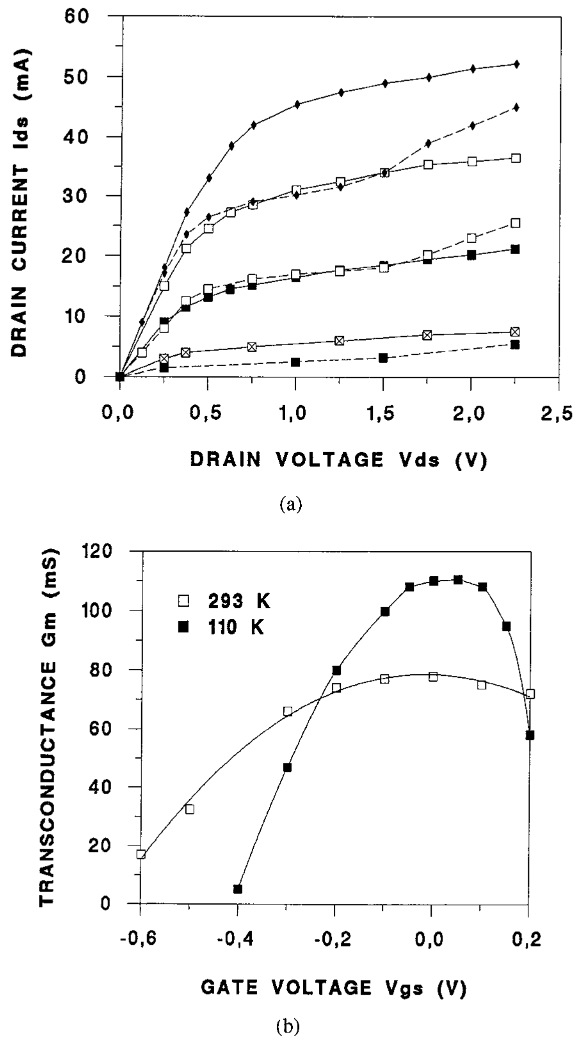

Fig. 3. SLHEMT current-voltage characteristics (a) at ambient temperature (solid line) and 110 K (dashed line). —▲— $V_{gs} = 0.2$ V, —□— $V_{gs} = 0$ V, —■— $V_{gs} = -0.2$ V, —⊠— $V_{gs} = -0.4$ V. Transconductance (b) at the same temperatures and $V_{ds} = 2$ V.

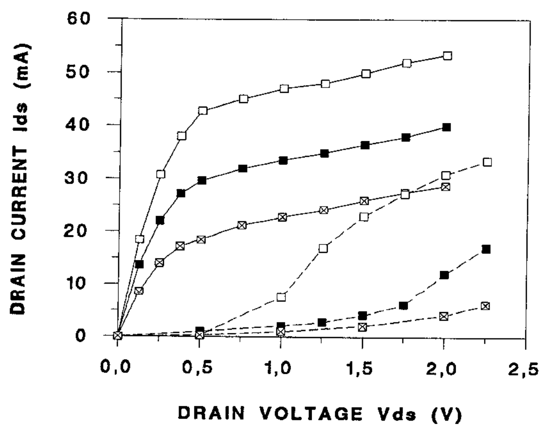

Fig. 2. HEMT FHX06 current-voltage characteristics at ambient temperature (solid line) and 110 K (dashed line) which reveals a strong collapse phenomena.

peaks very sharply and, together with the low drain current at low V_{ds}, is responsible for a low power out under oscillation.

Certain techniques have been proposed to overcome this drawback. For example, to limit the influence of the DX center, which is one of the most often observed traps in these structures (located in the doped GaAlAs layer) and usually responsible for the collapse, it is possible to substitute this layer by a superlattice of n-GaAs and AlAs layers [8]–[10]. The dc characteristics of one of these devices (which is not a commercially available component) are shown in Fig. 3. As expected a slight improvement in the transconductance value can be noticed at low temperature. In this paper, this transistor will be referred to as "SLHEMT."

DX centers also depend on the aluminum concentration in the nGaAlAs layer. In some special structures, the 2D electron gas concentration can be kept high enough in spite of a lower aluminum concentration. An example is given by the pseudomorphic structure: AlGaAs/GaInAs/GaAs used in the commercially available pseudomorphic HEMT (PHEMT). Fig. 4 shows the $I_{ds}(V_{ds})$ characteristics obtained from a MGF 4313 PHEMT. Unlike the results of other authors [11], no increase in I_{ds} and G_m is observed during cooling. However, the decrease in I_{ds} (50%) and G_m (15%) observed at 110 K does not severely limit the use of this device at low temperature.

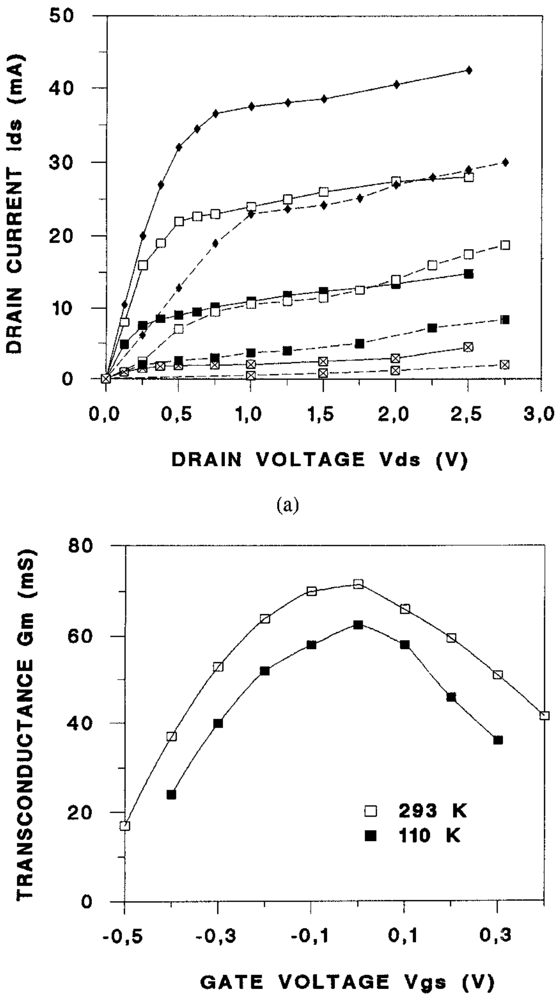

Fig. 4. PHEMT MGF4313 current-voltage characteristics (a) at ambient temperature (solid line) and 110 K (dashed line). —▲— $V_{gs} = 0.2$ V, —□— $V_{gs} = 0$ V, —■— $V_{gs} = -0.2$ V, —⊠— $V_{gs} = -0.4$ V. Transconductance (b) at the same temperatures and $V_{ds} = 2$ V.

Therefore, the MESFET MGF1402, SLHEMT and PHEMT MGF 4313 devices have been selected for further investigations. The spectral density $S_v(f)$ of the equivalent input gate LF noise voltage generator has been measured for each device against temperature and plotted in Fig. 5. Gate bias has been maintained at 0 V since in these devices it corresponds to maximum transconductance. It clearly appears in Fig. 5 that there is a moderate change in MESFET LF noise due to cooling (−6 dB max.). On the other hand, the SLHEMT and PHEMT LF input noise is greatly reduced in the upper frequency range (above 1 kHz, −11, and −14 dB at 100 kHz) and increased below 300 Hz. It is worth recalling at this stage that in most GaAs FET's the LF noise is due to the composite of traps related generation-recombination (g-r) noise and background $1/f$ flicker noise. The plot of the product $f \cdot S_v(f)$ versus f features several bulges at every frequency f_b equal to $1/2\pi\tau_b$ where τ_b is the time constant of one of the traps involved in the noise generation. Therefore the number of bulges is indicative of the number of traps which contribute to the overall g-r noise over the frequency range of interest (100 Hz to 100 kHz). When cooling the

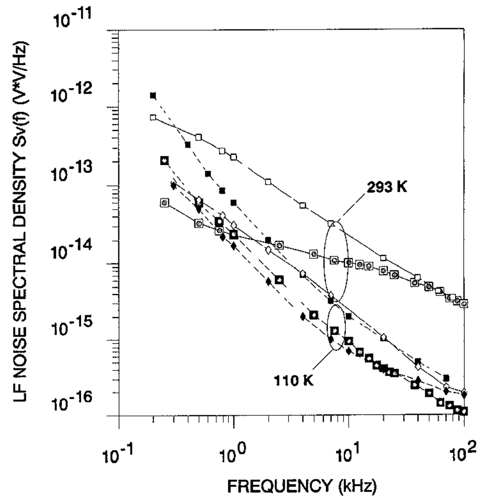

Fig. 5. Input LF noise spectral density at ambient temperature (solid line) and 110 K (dashed line). □ ■ PHEMT (V_{ds} = 2 V), □ ■ SLHEMT ($V_{ds} = 2$ V), ◇ ◆ MESFET ($V_{ds} = 3$ V).

device, the trap time constants greatly increase and produce a bulge shift toward the low frequency range (below 100 Hz). Therefore the g-r noise contribution on phase noise at baseband frequencies above 100 Hz will decrease at low temperatures. From the Arrhenius plot of τ_b versus $1/T$ it has been found for example in the considered frequency range that two different traps ($E_{g1} = 0.08$ eV; $E_{g2} = 0.22$ eV) contribute to the LF noise in the PHEMT and only one in the SLHEMT ($E_g = 0.36$ eV). None of these traps correspond to the DX center. This is consistent with other published results [10]–[12].

The advantage of MESFET over HEMT for a high spectral purity oscillator has already been shown [13] at normal temperature. Our LF noise measurements suggest that this could no longer be the case in a cryogenic environment. However, a direct comparison of the absolute level of LF noise for these three components is not sufficient to reach a definite conclusion on the potential performance of these devices embedded in an oscillator circuit. A comparison of the LF noise magnitude normalized with respect to the gate area of each component would be more interesting. The MESFET gate area is the largest (width: 400 μm, length: 0.75 μm) followed by SLHEMT (width: 200 μm, length: 0.8 μm) and PHEMT (width: 200 μm, length: 0.35 μm). With respect to the smallest gate area, the cooled PHEMT features a very low LF noise compared to the two other devices [14] but it is still insufficient to state a definite conclusion and the LF noise conversion process into phase noise must be evaluated.

III. Phase Noise in Cooled Microwave Oscillators

A. Experimental Conditions

The process of LF noise conversion into phase noise strongly depends on the oscillator circuit. Thus to compare the phase noise of different oscillating devices, a sufficiently representative oscillator topology must be selected, with a capability for adjustment so as to optimize the oscillation condition of each transistor. The parallel feedback topology (Fig. 6) is probably

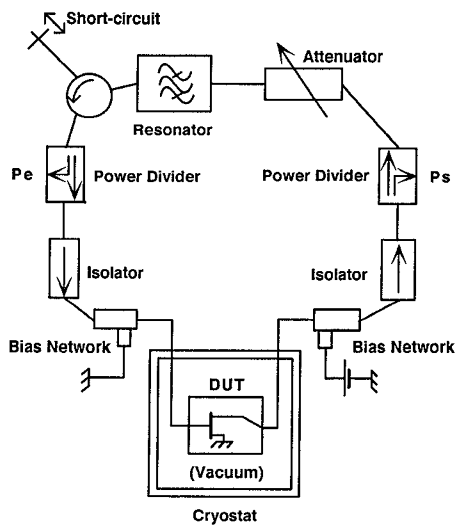

Fig. 6. Schematic diagram of the 4 GHz oscillator used in the phase noise measurements.

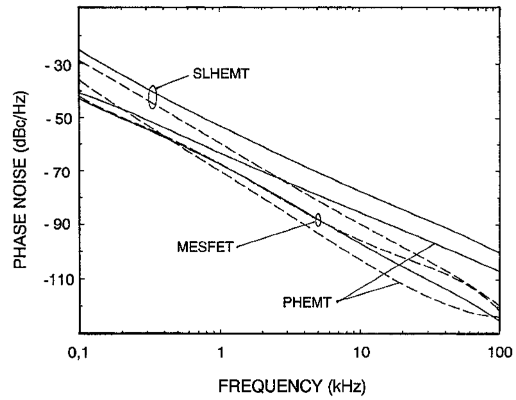

Fig. 7. Comparison between phase noise spectra of the three oscillators at ambient temperature (solid line) and low temperature (dashed line).

best-suited for our investigations. Firstly, the transistor is in a stable configuration and the instability (the oscillation) can only arise from the high Q feedback loop thereby preventing any parasitic oscillations. Secondly, resonator coupling inside the feedback loop may be small enough as to provide an optimized loaded quality factor. Oscillation is maintained as long as the transistor gain is large enough to preserve a loop gain higher than unity in the neighborhood of the resonant frequency. Thirdly, this topology easily allows oscillation optimization by controlling two basic parameters: loop gain (and power out) with a variable attenuator in the loop, and loop phase shift with a variable length line.

In the set up used, the resonator is maintained at ambient temperature and has a constant quality factor: $Q_L = 160$ at 4 GHz. This is a fairly bad quality factor (compared to a dielectric resonator) but the corresponding phase noise is higher and therefore easier to measure. Other measurements (not shown here) have been carried out with a higher quality factor cavity ($Q_L \sim 1000$) and have confirmed the general trends that will be reported. The active device input and output are loaded onto 50 Ω and therefore, the power gain of the active device itself is not maximum. However, loop gain has been optimized with the help of both variable attenuator and variable length line to maximize $P_{\rm osc} = P_s - P_e$ where P_e and P_s are the power in and power out of the active component. Maximizing $P_{\rm osc}$ in an oscillator circuit also reduces phase noise: based on Kurokawa's theory [15], [16], the frequency fluctuation δf is inversely proportional to the product of the resonator's quality factor and the square root of the power out.

This frequency fluctuation δf at a given baseband frequency f off the carrier also depends on LF noise in the active device. It is sometimes useful to introduce a conversion factor k_c (in Hz/V) to evaluate this phenomenon [13]: $\delta f = k_c\sqrt{S_v(f)}$ where $S_v(f)$ is the spectral density of the input voltage noise at frequency f.

It can be shown experimentally that, in most cases, k_c remains practically constant from a few tens of Hz to 100 kHz from the carrier. The frequency noise spectrum will therefore have a similar shape to the LF voltage noise spectrum measured at bias conditions which corresponds to the quiescent point of the oscillating device. The difference in phase noise between two devices with a similar LF noise value will result from the differences in the magnitude of k_c. As already pointed out, k_c depends on the quality factor Q_L and on $P_{\rm osc}$. Another important feature is LF loading [17], [18]. In our case, the devices gate was always dc short circuited. The gate voltage noise source is then preeminent thereby facilating comparison between different devices and avoiding externally induced perturbations on the gate.

Also, it has been shown that the gate-to-source capacitance of the field effect transistor is the nonlinear element responsible for the conversion of low frequency noise into phase noise, whereas amplitude noise is determined by nonlinear transconductance [19]. This partition between the effect of the resistive and reactive non linear elements was also noted in the Kurokawa's theory [15], [16], but without reference to any noise conversion mechanism.

Bearing this in mind, the 4 GHz phase noise measurements given in Fig. 7 can be interpreted, at least qualitatively. These measurements were carried out with an active phase noise test-set [20] which transposes the microwave spectra around 10 MHz, thanks to a quiet reference source. Different techniques are available for the analysis of the IF signal. Because of the relatively bad value of the resonator's quality factor, a frequency discriminator together with a low frequency FFT spectrum analyser were used in lieu of a phase lock loop which necessitates phase locking of the oscillator under test itself. The observed frequency drift was only due to temperature fluctuations and was small enough to permit measurements close to the carrier (a few tens of Hz).

B. Phase Noise at Ambient Temperature

Firstly, note that all the reported results on phase noise have been obtained at maximum $P_{\rm osc}$, or near the maximum in the case where too many losses in the loop prevented it from being reached (SLHEMT). This is important because at lower P_e the phase noise usually decreases (probably because of a reduction of the C_{gs} nonlinear behavior). The observed phase noise reduction between $\max(P_{\rm osc})$ and the minimum power needed for sustaining the oscillation (loop gain close to unity) is about 6 dB for HEMT's and only 4 dB for MESFET. However max(P_{osc}) is the ideal working point providing a large enough oscillating frequency band and stable operation.

At 293 K and 10 kHz off the carrier, the lowest phase noise (−97 dBc/Hz) has been observed in the MESFET oscillator, the intermediate one (−86 dBc/Hz) in the PHEMT oscillator and the largest one (−77 dBc/Hz) in the SLHEMT oscillator (Fig. 7). This is in good agreement with the classification that can be done with the LF noise magnitude at 10 kHz. However, the differences observed on the phase noise of the different oscillators cannot be entirely accounted by differences in the LF noise spectra such as the very low phase noise of the MESFET oscillator compared to the other oscillators. These differences may also partly result from the different values of P_{osc}: the higher values are successively obtained from MESFET (16 dBm), PHEMT (13.5 dBm), and SLHEMT (10.5 dBm).

C. Phase Noise at Cryogenic Temperatures

The three previously investigated ambient temperature oscillators were cooled to 110 K and their measured phase noise is reported in Fig. 7. The MESFET oscillator shows an enhanced power out ($P_{osc} = 18$ dBm) while a decrease is observed in HEMT's (SLHEMT and PHEMT: $P_{osc} = 8$ dBm). With respect to the phase noise, the slight increase observed on the cooled MESFET oscillator is not too significant. On the other hand, note that a phase noise reduction of about 10 dB is observed on the cooled SLHEMT oscillator and that a reduction in excess of 15 dB is also observed on the cooled PHEMT oscillator (at 10 kHz off the 4 GHz carrier).

In the latter case, the phase noise reduction which could have been predicted from the LF noise reduction under cooling is not as large as observed. We therefore suspect that the C_{gs} nonlinearity that governs the conversion factor is less important at cryogenic temperatures. That could be due to some free carriers captured in deep levels (even if there is no pronounced collapse phenomenon [7]) which could result in a reduction of C_{gs}. Also note that the inverse phenomena has already been reported in MESFET's where a C_{gs} enhancement at low temperature has been observed [21]. This behavior, along with the fact that the variation of V_{gs} (and therefore C_{gs}) becomes larger because of an enhanced P_e at low temperature, could explain why the phase noise in the MESFET oscillator is not reduced (the C_{gs} behavior at low temperature will be developed in a separate paper).

IV. Conclusion

We have observed that the low frequency generation-recombination noise component in HEMT's devices is responsible for the bad phase noise performance of HEMT's oscillators at ambient temperature. However, under cooling at 110 K the g-r traps time constants are so large that the g-r noise component is not preeminent over the $1/f$ noise beyond a few hundred Hz so that the flicker noise is responsible for most of the phase noise. It has therefore been observed that the phase noise of a cooled HEMT oscillator can be reduced by more than 10 dB for a baseband frequency above 1 kHz. The pseudomorphic HEMT shows remarkable potential for low phase noise cooled oscillators with relatively low $1/f$ noise and low conversion factor at low temperature. In addition this device features a high small signal microwave power gain which makes it able to oscillate with a very weak coupled cavity in the feedback circuit (i.e., with a high loaded quality factor) at frequencies much higher than MESFET devices. By way of example, a phase noise less than −100 dBc/Hz at 10 kHz off the center (4 GHz) has been obtained in spite of a very low loaded quality factor (160). We believe that PHEMT's have a very promising future for low phase noise cryogenic microwave oscillators, where a high quality factor resonator made of HTCS can be used as a stabilizing element. However, investigations on HBT's devices are being done in order to compare their performance for cooled oscillators applications with that of PHEMT's.

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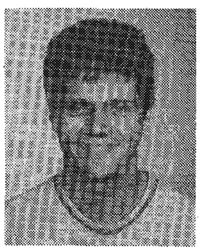

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