Hybrid High Temperature Superconductor/GaAs 10 GHz Microwave Oscillator: Temperature and Bias Effects

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Abstract—**Hybrid $YBa_2Cu_3O_{7-x}$ superconductor/GaAs microwave oscillators have been designed, fabricated and characterized. The planar oscillators were built on a single 10 mm × 10 mm $LaAlO_3$ substrate. The active elements in the hybrid oscillators were GaAs MESFETs. A ring resonator was used to select and stabilize the frequency. A superconducting ring resonator had a loaded Q at 77 K which was 8 times larger than the loaded Q of a ring resonator fabricated out of copper. S-parameters of the GaAs FET were measured at cryogenic temperatures and used to design the oscillator, which had a reflection mode configuration. The transmission lines, rf chokes and bias lines were all fabricated from $YBa_2Cu_3O_{7-x}$ superconducting thin films. The performance of the oscillators was measured as a function of temperature. The rate of change of the frequency as a function of temperature was smaller for an oscillator patterned from a pulsed laser deposited film than for an oscillator patterned from a sputtered film. As a function of bias at 77 K, the best circuit had an output power of 11.5 dBm and a maximum efficiency of 11.7%. The power of the second harmonic was 25 dB to 35 dB below that of the fundamental, for every circuit. At 77 K, the best phase noise of the superconducting oscillators was −68 dBc/Hz at an offset frequency of 10 kHz and less than −93 dBc/Hz at an offset frequency of 100 kHz. At an offset frequency of 10 kHz, the superconducting oscillator had 12 dB less phase noise than the copper oscillator at 77 K. The superconducting oscillators at 77 K had 26 dB less phase noise than the copper oscillator operating at 300 K.**

I. Introduction

The APPLICATION of high temperature superconducting thin films to microwave circuits is advantageous since the films have a lower surface resistance than gold or copper at microwave frequencies. Some of the passive microwave structures that have shown improved performance using high temperature superconductors are ring resonators [1]–[3], multiple pole filters [4] narrowband filters [5], and antennas [6]. The advantage of using high temperature superconducting films for resonators is the larger quality factor (Q) values that superconducting resonators have compared to normal metal resonators. The larger loaded Q of a resonator has the potential for lowering the phase noise of oscillators. In the Leeson model, the phase noise of a feedback oscillator when measured in a one hertz bandwidth can be given in dBc/Hz by [7]

$$L(f_o) = 10\log\left[\frac{kTFG}{P} + \frac{\alpha}{2\pi f_o} + \frac{kTFG}{4PQ_L^2}\left(\frac{f_c}{f_o}\right)^2 + \frac{\alpha f_c^2}{8\pi Q_L^2 f_o^3}\right]. \quad (1)$$

Here k is Boltzmann's constant, T is the temperature, F is the noise figure associated with the negative resistance device, G is the gain of the amplifier after it has reached a steady-state oscillation, P is the output power, Q_L is the loaded Q of the resonator, and α is the combined flicker noise constant of the amplifier and the resonator. As can be seen from the third and fourth terms, a larger loaded Q will decrease the phase noise.

The hybrid oscillators employing high temperature superconductors that have been published include a parallel feedback oscillator [8] and a series feedback oscillator [9]. For the parallel feedback oscillator, the feedback network consisted of a superconducting linear resonator acting as a narrow band pass filter. Only the feedback network was cooled to 77 K. The amplifier was implemented in normal metals and operated at room temperature. This oscillator operated at 10 GHz and had an output power of 6.0 dBm when the resonator was cooled to 80 K. A highly integrated microwave system will require the whole oscillator to be operating at cryogenic temperatures on a single substrate. The series feedback oscillator fit on a 10 mm × 10 mm $LaAlO_3$ substrate with a coplanar resonator stabilizing the frequency at 6.5 GHz. It had an output power of 4.9 dBm when immersed in liquid nitrogen. The power of the second harmonic was only 10 dB down. In this paper, we report on the design, fabrication and testing of microstrip hybrid oscillators. Each oscillator was fabricated on a 10 mm × 10 mm $LaAlO_3$ substrate. The phase noise of the superconductor oscillators at 77 K is compared to a copper oscillator at 77 K and 300 K. It would also be advantageous if the frequency of the oscillators were not sensitive to variations in the temperature or bias conditions. The frequency and power of these circuits were measured as a function of the temperature and the bias conditions.

II. Design

Since our objective was to implement the entire oscillator on a single substrate to be operated at cryogenic temperatures, the S-parameters of the transistors at 77 K were obtained.

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TABLE I
PERCENT CHANGE OF THE S-PARAMETERS FROM 300 K TO 77 K AT 10 GHz

S_{11}		S_{21}		S_{12}		S_{22}	
magnitude	phase	magnitude	phase	magnitude	phase	magnitude	phase
3.3%	19.3%	20.4%	8.8%	8.8%	6.7%	36.5%	37.8%

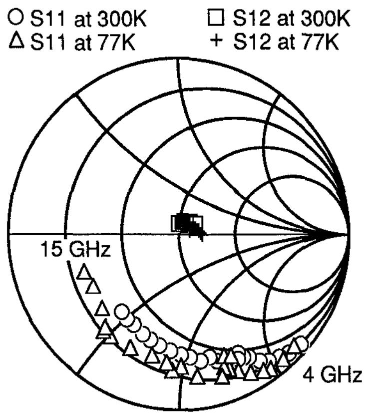

Fig. 1. S-parameters at 300 K and 77 K for S_{11} and S_{12} in the range of 4 to 15 GHz.

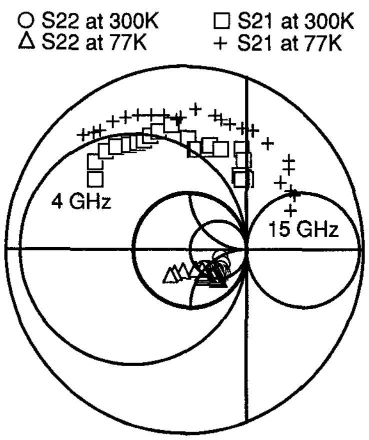

Fig. 2. S-parameters at 300 K and 77 K for S_{21} and S_{22} in the range of 4 to 15 GHz on a compressed Smith Chart.

These S-parameters were used in the design of the oscillators. The design of the oscillators was performed using simulations on commercially available software (Touchstone™) [10]. The simulations were performed using the S-parameters obtained when the bias on the transistor was maintained at $V_{ds} = 3$ V and $I_d = 10$ mA and the temperature was 77 K. The design had a ring resonator which was parallel coupled to the transmission line in the matching network off the drain.

A. Cryogenic S-Parameter Measurements

The active devices used in the oscillators were Toshiba GaAs FETs (JS8830-AS). This transistor is a low noise MESFET with a 0.25 μm gate length and a gate width of 250 μm. The S-parameters of the FET for frequencies of 4 to 15 GHz were measured over a temperature range from room temperature (300 K) to 40 K. The values for the S-parameters from 4 to 15 GHz are shown in Fig. 1 and Fig. 2 with the transistor biased at drain voltage $V_{ds} = 3$ V and drain current $Id = 10$ mA at 300 K and 77 K. To achieve this drain current, the gate bias was adjusted to $V_{gs} = -1.04$ at 300 K and to $V_{gs} = -1.19$ V at 77 K. Of the S-parameters, the largest change in magnitude as a function of temperature occurred for the S_{21} values. This was due to an increase in the electron's mobility at the reduced temperatures. The variation in phase of S_{11} and S_{22} was the only other major change. The percent change of the phase and magnitude of the S-parameters at 10 GHz due to the change in temperature from 300 K to 77 K is listed in Table I.

B. Reflection Mode Oscillator

The design of the oscillator was performed using the small signal S-parameters of the FET that were measured at 77 K. The input reflection coefficient looking into the drain of the FET was made very large by varying the length of open circuited transmission lines on the source and the gate. The selected lengths of the transmission lines from the source and the gate were 1.57 mm and 2.79 mm, respectively. The output of the oscillator was taken off the drain. The layout of the oscillator is shown in Fig. 3. This configuration is a reflection mode oscillator.

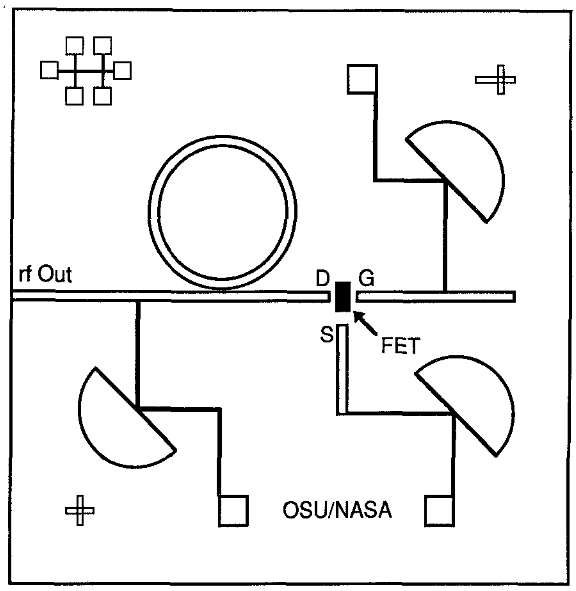

Fig. 3. The physical layout of the reflection mode oscillator on a 1 cm^2 $LaAlO_3$ substrate.

The matching network, which included the ring resonator, was designed such that the magnitude of the real part of the impedance of the matching network was less than the magnitude of the real part of the impedance looking into the drain of the FET. The magnitude of the imaginary part was equal to zero at the resonant frequency. To achieve the impedance match, the ring resonator, with a fundamental resonant frequency of 10 GHz, was placed $\lambda/4$ from the drain of the transistor. It was parallel coupled to the output transmission line with a coupling gap that was 40 μm wide. With the impedance criteria met, the oscillator will start upon proper biasing of the FET. The rf chokes have a half-moon structure that is a large shunting capacitor to ground for the rf signal on the bias lines. They are a quarter wavelength removed from the transmission lines by a high impedance line.

III. Experimental Details

The $YBa_2Cu_3O_{7-x}$ superconducting thin films were deposited by pulsed laser deposition (PLD). The substrate temperature during deposition was 805 °C while the oxygen pressure was maintained at 170 mTorr. A KrF excimer laser with a wavelength of 248 nm was used. The energy density of the laser beam at the target was 0.8 J/cm^2. The pulse rate was two per second. This deposition procedure has produced films with a critical temperature of 90.5 K and a critical current density of greater than 2×10^6 A/cm^2 at 77 K. The effective surface resistance of a superconducting thin film patterned into a ring resonator was 1.36 mΩ at 77 K and 10 GHz [11]. The superconducting films were patterned into the oscillators using standard positive photolithographic techniques. The etchant used was a 100:1 solution of deionized water:H_3PO_4.

Three reflection mode oscillators were fabricated and tested. The transmission lines, rf chokes, and bias lines were fabricated out of 2.4 μm thick copper for one circuit while the other two circuits were fabricated out of $YBa_2Cu_3O_{7-x}$ high temperature superconducting thin films. One of the superconducting thin films was made by the pulsed laser deposition procedures described previously while the other film was a sputtered film purchased commercially. The sputtered film was guaranteed to have a critical temperature of greater than 88 K and a surface resistance of less than 0.8 mΩ at 77 K. Contacts to the superconductor for the output and wire bonding pads were made with silver with a gold overlayer, patterned by lift-off photolithography. Wire bonding pads were located at the bias pads as well as the ends of the transmission lines near the FET. The ground plane for the three oscillators was 2.4 μm of copper with a 300 Å titanium layer to promote adhesion. The GaAs FET was epoxied onto the $LaAlO_3$ substrate. Connections between the FET and transmission lines were made with 18 μm diameter gold wire by thermosonic wirebonding.

Measurements of the power and frequency as a function of the temperature and bias conditions on the oscillator were made with the oscillator mounted on a brass fixture inside a closed cycle cryostat. The phase noise could not be measured with the sample mounted inside the cryostat since the vibration of the closed cycle refrigerator induced more than 1 MHz of jitter in the signal. Phase noise measurements were performed with the oscillators mounted inside a sealed brass test fixture and submerged in liquid nitrogen. The single sided phase noise was measured on a HP 8592A spectrum analyzer with a resolution bandwidth of 300 Hz. The measured data was converted to a bandwidth of 1 Hz through the following equation [12]:

$$\text{Phase Noise (dBc/Hz)} = \text{Measured Value} - 10\log(1.2 \times 300) + 2.5 \qquad (2)$$

In this equation, the measured value is the difference in dB between the peak power and the side-band power at a specific offset frequency. The resolution bandwidth of 300 Hz is multiplied by 1.2 to account for filtering in the spectrum analyzer. The additive term of 2.5 is a correction for the logarithmic amplification within the spectrum analyzer. When phase noise measurements are performed in this manner, the measured phase noise may be limited by the phase noise of the internal oscillator of the spectrum analyzer. The phase noise of a synthesized source was measured to check this. At offset frequencies greater than 10 kHz, the data presented for the two superconducting oscillators approach the limit of this technique. The data presented for these two circuits at larger offset frequencies is an upper limit on the phase noise. A dc block was located between the test fixture and the spectrum analyzer for all measurements.

IV. Results and Discussion

A superconducting ring resonator patterned from a PLD film had a loaded Q value of 940 and an unloaded Q value of 2100. A copper ring resonator had loaded and unloaded Q values of 120 and 250, respectively, when measured at 77 K and 10 GHz. The effective surface resistance of the $YBa_2Cu_3O_{7-x}$ was 1.36 mΩ at 77 K which was 19 times smaller than the copper value of 25.8 mΩ at 77 K. The rate of change of the resonant frequency as a function of temperature for the superconducting resonator was -1.25 MHz/K at 77 K.

All three oscillators exhibited a 10 GHz signal and a much weaker 20 GHz signal. The oscillators' power and frequency were measured as a function of temperature at fixed bias. The temperature was raised from near 20 K until the oscillations disappeared. A 77 K, the frequency and power were measured as a function of the gate and drain voltages. The single-sided phase noise of the oscillator made from the sputtered film was measured as a function of the drain bias at 77 K and the phase noise of all three oscillators was compared at a bias of $V_{ds} = 2.5$ V and $V_{gs} = 0$ V.

Figs. 4 and 5 show the oscillation frequency and power as a function of temperature, respectively, for all three circuits. The copper circuit was biased at $V_{ds} = 2.0$ V, $V_{gs} = -1.0$ V, and $I_d = 29$ mA. The oscillations could be maintained up to room temperature by increasing V_{gs} to raise the drain current to nearly 40 mA. The frequency of this oscillator changed very little. Its sensitivity to temperature was -70 kHz/K over the temperature range of 25 K to 100 K. The power decreased from 4.8 dBm at 25 K to 2.8 dBm at 100 K. At 77 K, the signal power was 3.8 dBm at 10.074 GHz and the second harmonic was reduced by 21 dB. The efficiency of the circuit at these bias conditions at 77 K was 4.1%.

The PLD film used for the reflection mode oscillator had a critical temperature of 88.5 K. For the data presented in Figs. 4 and 5, this oscillator was biased with $V_{ds} = 3$ V and $V_{gs} =$

TABLE II
SUMMARY OF RESULTS AT 77 K FROM TEMPERATURE EXPERIMENTS

Circuit	T_c (K)	Frequency (GHz)	$\Delta f/\Delta T$ (kHz/K)	V_d (Volts)	V_g (Volts)	I_d (mA)	Power (dBm)
Cu		10.074	−70	2	−1	29	3.8
PLD	88.5	9.967	−1,500	3	0	22	5.4
Sputtered	88.6	10.058	−10,000	2	−0.5	20	6.4

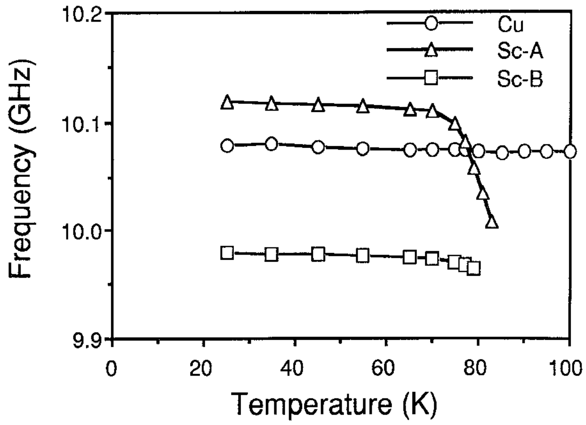

Fig. 4. Frequency as a function of temperature for all three oscillators. The Cu oscillator's FET was biased at V_{ds} = 3.0 V and V_{gs} = 1.0 V. Sc-A is the sputtered film and Sc-B is the PLD film. The FETs were biased at V_{ds} = 2.0 V and V_{gs} = −0.5 V and at V_{ds} = 3.0 V and V_{gs} = 0.0 V, respectively.

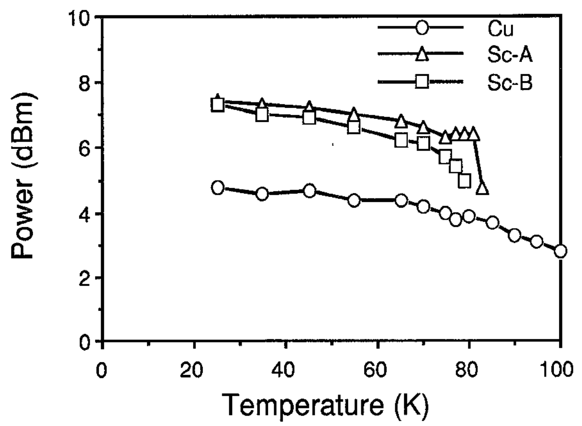

Fig. 5. Power as a function of temperature for all three oscillators. The Cu oscillator's FET was biased at V_{ds} = 3.0 V and V_{gs} = −1.0 V. Sc-A is the oscillator from sputtered film biased at V_{ds} = 2.0 V and V_{gs} = −0.5 V and Sc-B is the oscillator from the PLD film, biased at V_{ds} = 3.0 V and V_{gs} = 0.0 V.

0 V, which resulted in I_d = 22 mA at 77 K. The temperature was increased from 25 K until the oscillation disappeared. The frequency decreased from 9.979 GHz to 9.964 GHz over this range. 9 MHz of this 15 MHz drop occurred between 75 K and 79 K. The dependence of the frequency on temperature is typical of a change in the phase velocity of a superconductor resulting from a variation in the penetration depth as a function of temperature [1], [2], [13]. The sensitivity of the frequency of the oscillation to temperature was −1.50 MHz/K at 77 K. This is nearly identical to the rate of change of the frequency as a function of temperature of the ring resonator patterned from the PLD film and of a series feedback oscillator, also patterned from a PLD film [11]. The output power was 5.4 dBm at 77 K with the power of the second harmonic reduced by 29.2 dB. The power decreased from 7.3 dBm to 5.0 dBm over the range of 25 K to 79 K. The efficiency of the circuit at these bias conditions and 77 K was 5.4%.

For the measurements as a function of temperature, the oscillator patterned from the commercially purchased sputtered film, which had a critical temperature of 88.6 K, was biased at V_{ds} = 2 V and V_{gs} = −0.5 V which gave a current of I_d = 20 mA at 77 K. The frequency of the signal was 10.082 GHz with a power of 6.4 dBm at 77 K. The efficiency was 10.4%. The power of the 20 GHz signal was 35.5 dB less than the 10 GHz signal at 77 K. The power of the 10 GHz signal varied from 7.4 dBm at 25 K to 6.4 dBm at 81 K and then dropped sharply to 4.8 dBm at 83 K, beyond which the oscillation ceased. The frequency varied from 10.119 GHz to 10.008 GHz. The temperature at with the frequency started to decrease rapidly was 75 K. The sensitivity of the frequency to temperature for this circuit was −10 MHz/K at 77 K, which is much larger than from any of the other circuits. Another oscillator patterned for a sputtered film had a comparable rate of change for the frequency as a function of the temperature, −9.75 MHz/K at 77 K.

Table II shows a summary of the measurements at 77 K from the temperature variation experiments for all three oscillators. The rate of change of the frequency as a function of temperature was determined by the film used for the microstrip transmission lines. The rate of change of the frequency with temperature was the least for the oscillator made from copper. The frequency of the oscillator patterned from the PLD films was less sensitive to temperature than the sputtered oscillators by nearly a factor of eight. To decrease the sensitivity to the temperature, the temperature of operation could be decreased. For example, at 70 K, the rate of change for the frequency for the PLD oscillator was −0.4 MHz/K and it was −1.4 MHz/K for the sputtered oscillator. At 25 K, the rate of change of the frequency for both superconductor oscillators was nearly identical to the copper oscillator.

Figure 6 shows the single sided phase noise of the three oscillators at 77 K and also for the copper oscillator at 300 K. For these measurements, all three oscillators were biased with V_{ds} = 2.5 V and V_{gs} = 0 V. The phase noise of the superconducting oscillators was nearly identical at all offset frequencies. They have phase noise values of −61 dBc/Hz at an offset of 10 kHz and −88 dBc/Hz at an offset of 100 kHz. At an offset frequency of 10 kHz, the phase noise of the copper oscillator when measured at 77 K and 300 K was 13 dB and 32 dB higher, respectively. At an offset frequency of 100 kHz, the difference was 6 dB and 22 dB, respectively.

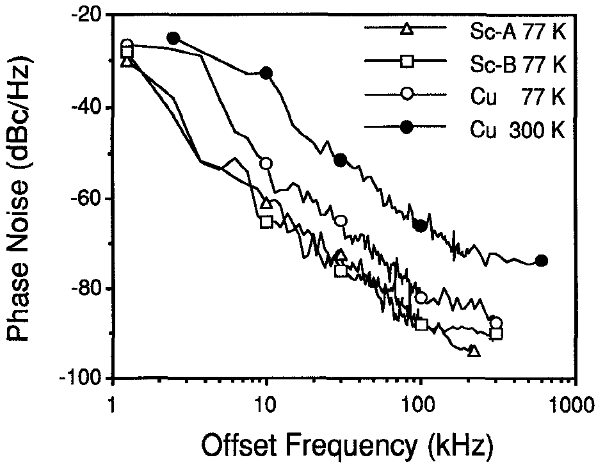

Fig. 6. Single sided phase noise for the three oscillators. All three oscillators were biased at $V_{ds} = 2.5$ V and $V_{gs} = 0$ V. Sc-A is the sputtered film and Sc-B is the PLD film. The siperconducting oscillators were held at 77 K and the Cu oscillator was measured at 77 K and 300 K.

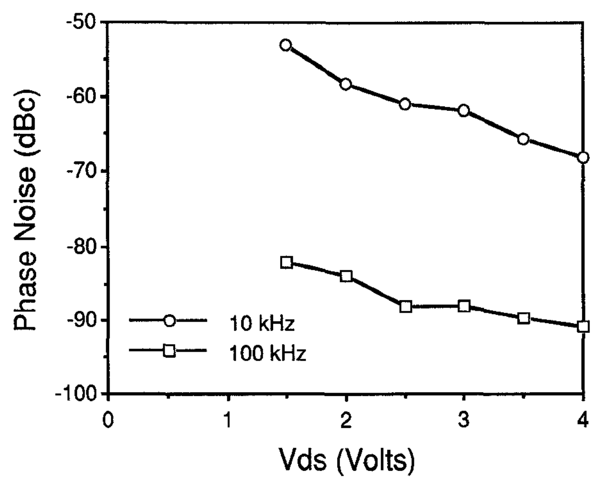

Fig. 7. Single sided phase noise of the sputtered oscillator at offset frequencies of 10 kHz and 100 kHz as a function of the drain voltage.

Fig. 7 shows the phase noise at offsets of 10 kHz and 100 kHz as a function of the drain voltage of the sputtered oscillator. For these measurements, $V_{gs} = 0$. As the drain bias was increased from 2.5 V to 4.0 V, the power increased by 8 dB. At an offset frequency of 10 kHz, the phase noise decreased by 15 dB while at an offset of 100 kHz, the phase noise decreased 9 dB. The decrease in the phase noise at an offset frequency of 10 kHz was faster than at 100 kHz because the influence of power on the phase noise at an offset of 100 kHz was primarily through the floor noise, the first term of (1), while the phase noise at an offset of 10 kHz was affected by the power through both the floor noise and the third term in (1). At large offset frequencies, the phase noise would decrease by the same amount that the output power increased. In our measurement, the power increased by 8 dB while the phase noise decreased by 9 dB at an offset frequency of 100 kHz.

The frequency and power of the oscillators were also measured as a function of drain voltage at a temperature of 77 K. For these measurements, the gates were biased at the same voltages used for the measurements as a function of the temperature. The drain voltage for each circuit was decreased from 4 V until the signal disappeared. Figure 8 shows the frequency of oscillation as a function of the drain voltage. The solid symbols mark the drain voltages used during the measurements as a function of temperature. The copper oscillator and the oscillator patterned from the sputtered film had frequencies very near each other since the temperature was maintained at 77 K. This is near the crossover point for the two circuits in Fig. 4. For these two oscillators, the frequency decreased 87 MHz for drain voltages of less than 1.5 V. Above 1.5 V, the frequencies were less sensitive to drain voltage. The frequency of the oscillator patterned from the PLD film decreased 2 MHz as the drain voltage was decreased. The frequency was less sensitive to drain voltage at higher voltages for this circuit as well.

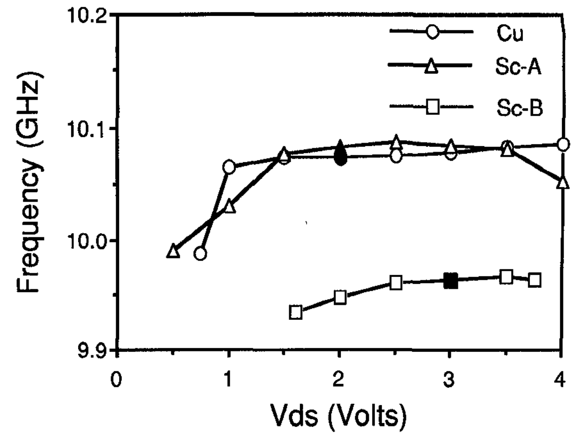

Fig. 8. Frequency as a function of drain voltage for all three oscillators at 77 K. The Cu oscillator was biased at $V_{gs} = -1.0$ V while the FETs in Sc-A (the sputtered film) and Sc-B (the PLD film) were biased at $V_{gs} = -0.5$ V and at $V_{gs} = 0.0$ V, respectively. The solid symbols mark the bias points during the measurements as a function of temperature.

The power at 10 GHz as a function of drain voltage is shown in Fig. 9 for all three circuits, with the solid symbols indicating the drain voltages used during the measurements as a function of temperature. For all three circuits, the power decreased as the drain voltage decreased, with the rate of decrease becoming large at smaller voltages. The drain currents are quite different for the three curves shown in this figure. For example, at $V_{ds} = 3$ V the copper circuit had $I_d = 36$ mA with $V_{gs} = -1.0$ V, the sputtered deposited circuit had $I_d = 29$ mA with $V_{gs} = -0.5$ V and the PLD circuit had $I_d = 22$mA with $V_{gs} = 0$ V. The specified ranges for the pinch-off voltage and saturated drain current for these transistors are -0.5 V to -5 V and 20 mA to 70 mA, respectively, at $V_{ds} = 3$ V. The transistors used here had pinch-off voltages of -1.55 V, -2.15 V, and -3.2 V for the $YBa_2Cu_3O_{7-x}$ PLD circuit, the circuit fabricated from the sputtered film and the copper circuit, respectively.

Figs. 10 and 11 show the frequency and power as a function of gate bias at 77 K for all three circuits. For each circuit, the drain voltage was held at the same value used during measurements as a function of temperature. The data points at the gate biases used in those measurements are marked with solid symbols. The copper circuit oscillated for gate

TABLE III
SUMMARY OF RESULTS AT 77 K FOR $V_{ds} = 2.0$ V

Circuit	V_g (Volts)	I_d (mA)	Power (dBm)	Frequency (GHz)	Efficiency (%)
Cu	−1.4	22	0.6	10.095	2.6
PLD	0	18	0.9	9.949	3.3
Sputtered	−0.6	18	5.2	10.092	9.3

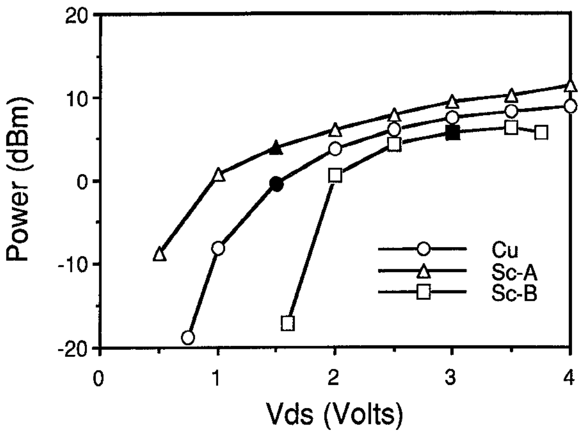

Fig. 9. Power as a function of drain voltage for all three oscillators at 77 K. The Cu oscillator was biased at $V_{gs} = -1.0$ V while the FETs in Sc-A (the sputtered film) and Sc-B (the PLD film) were biased at $V_{gs} = -0.5$ V and at $V_{gs} = 0.0$ V, respectively. The solid symbols mark the bias points during the measurements as a function of temperature.

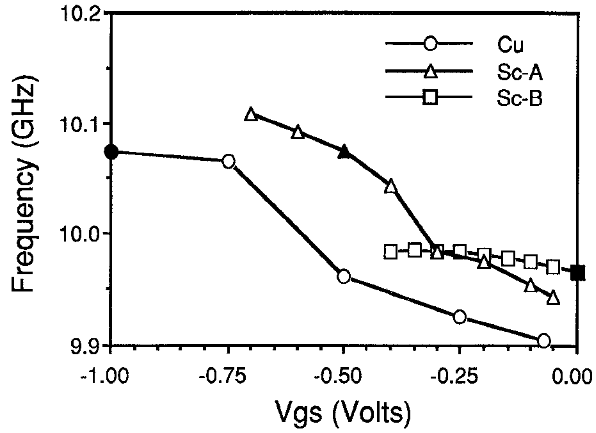

Fig. 10. Frequency as a function of gate voltage for all three oscillators at 77 K. The Cu oscillator was biased at $V_{ds} = 2.0$ V while the FETs in Sc-A (the sputtered film) and Sc-B (the PLD film) were biased at $V_{ds} = 2.0$ V and at $V_{gs} = 3.0$ V, respectively. The solid symbols mark the bias points during the measurements as a function of temperature.

voltages from 0 V to −1.4 V. The full ranges for the other circuits are shown. The frequency increased 200 MHz as V_{gs} was decreased for the copper oscillator. The oscillator patterned from the PLD film showed little variation, but the sputtered sample's frequency increased 170 MHz as the gate bias decreased to −0.7 V. The frequency was more sensitive to variations in the gate bias than to the drain bias. For all three circuits, the power decreased as the gate bias decreased. The power for the copper circuit decreased 6.7 dB as V_{gs} was varied from 0 V to −1.4 V. Its drain current varied from 62 mA to 22 mA over that range. The power of the oscillator patterned from the PLD film decreased sharply as the gate voltage neared −0.4 V. Its drain current ranged from 22 mA to 12 mA. Finally, the power of the oscillator patterned from the sputtered film decreased from 8.9 dBm to 5.2 dBm, while its current ranged from 38 mA to 15 mA. The large differences in currents are a result of the different pinch-off voltages of the transistors, as discussed in the previous paragraph. The largest power output of any circuit was for the sputtered oscillator. It delivered 11.5 dBm with a bias of $V_{ds} = 4.0$ V and $V_{gs} = -0.5$ V.

Table III shows a summary of the results with $V_{ds} =$ 2.0 V and the gate voltage adjusted to give comparable drain currents at 77 K. The different gate biases were a result of the transistors having different pinch-off voltages. The largest power and the most efficient oscillator was the oscillator fabricated from the sputtered film.

V. CONCLUSION

Hybrid superconductor/GaAs oscillators were successfully implemented on 10 mm × 10 mm $LaAlO_3$ substrates. The entire circuit operated at cryogenic temperatures. The S-parameters of the GaAs MESFET used in the design of the oscillators were measured at 77 K. The design was a reflection mode oscillator and used a ring resonator to stabilize the frequency. The ring resonator was coupled to the output line off the drain of the FET. A $YBa_2Cu_3O_{7-x}$ ring resonator, which was tested separately, had a loaded Q that was eight times larger than that of a copper ring resonator. Three oscillators were fabricated and tested, one from copper and two from high temperature superconductors. All three exhibited both 10 GHz and 20 GHz oscillations. The power

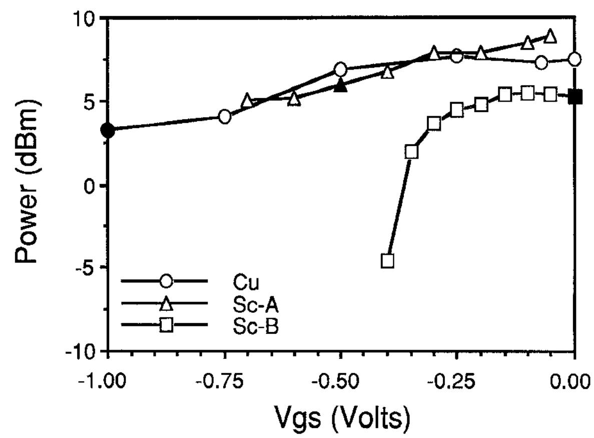

Fig. 11. Power as a function of gate voltage for all three oscillators at 77 K. The Cu oscillator was biased at V_{ds} =2.0 V while the FETs in Sc-A (the sputtered film) and Sc-B (the PLD film) were biased at $V_{ds} = 2.0$ V and at $V_{gs} = 3.0$ V, respectively. The solid symbols mark the bias points during the measurements as a function of temperature.

of the 20 GHz oscillation was 20 dB to 35 dB lower than the power of the 10 GHz oscillation for these three circuits. The lowest phase noise at 77 K of −68 dBc/Hz and −93 dBc/Hz at offset frequencies of 10 kHz and 100 kHz, respectively, was obtained for the sputtered oscillator with $V_{ds} = 4.0$ V. Compared to the copper circuit, the superconducting oscillators had 12 dB less phase noise at an offset of 10 kHz and 26 dB less noise at an offset at 100 kHz. The sensitivity of the frequency to temperature at 77 K was −10 MHz/K for the sputtered oscillator, while that of the PLD circuit was −1.5 MHz/K. The stability, power, and efficiency improved as the temperature was decreased. The output power and frequency were dependent upon the bias conditions. The frequency of the oscillators were less sensitive to the drain voltage than to the gate voltage. The oscillator patterned from a sputtered film had the largest output power and the highest efficiency.

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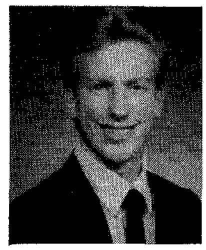

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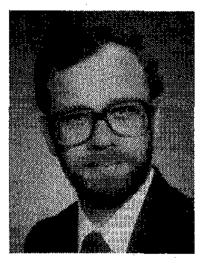

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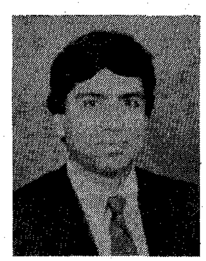

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