High-Efficiency *Ku*-Band Oscillators

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***Abstract*—*Ku*-band oscillators have been experimentally found to have a high dc-to-radio-frequency (RF) efficiency. Using a packaged pseudomorphic high electron-mobility transistor (pHEMT) device, a maximum efficiency of 60% was measured at 14.5 and 15 GHz with output powers of 16 and 23 mW, respectively. Oscillator circuits also revealed efficiencies of 48% at 16 GHz and 41% at 17.1 GHz with RF output power levels of 11 and 13 mW, respectively.**

***Index Terms*—HEMT, high-efficiency transmitters, oscillators, pHEMT.**

I. Introduction

MICROWAVE oscillators are a key component in a microwave system. While much work has been done characterizing the oscillating devices in terms of stability, noise, output power, and oscillating frequency, few researchers have focused on oscillators with high dc-to-radio-frequency (RF) conversion efficiencies. The desire for highly efficient microwave oscillators is driven by wireless applications that require low operating voltages and power consumption. Two-port transistor oscillators using MESFET's and pseudomorphic high electron-mobility transistors (pHEMT's) have shown a greater dc-to-RF efficiency than one-port Gunn and IMPATT diode oscillators in the microwave frequency range. Historically, MESFET's have been used in microwave amplifier and oscillator designs. With the advent of pHEMT's in recent years, oscillator and amplifier designs based on this device have appeared.

Since an oscillator can be considered an amplifier with positive feedback, it is possible to understand the mechanics of high-efficiency oscillators by applying the classification of amplifiers to oscillators. Ideal linear Class-A amplifiers, as well as oscillators, have a theoretical maximum dc-to-RF drain efficiency of 50%, which corresponds to maximum output power [1], [2]. A maximum drain efficiency of 78.5% is theoretically possible for linear Class-B amplifiers and oscillators. Snider has shown that this efficiency operating in Class A can be increased to 63.7% if properly loaded [3]. Snider also calculated an optimum efficiency of 100% for ideal Class-B operation when the output RF voltage wave approaches a square wave, and the load impedances at even and odd harmonics are shorted and opened, respectively. Later, Kushner summarized the output powers, efficiencies, and optimum load resistance expressions for idealized Class-A and Class-B microwave power amplifiers [4], [5]. Unlike Snider's expressions for an ideal linear amplifier, Kushner includes saturation voltage and linear transconductance effects in the calculations. These enhancements provide a better estimate of the amplifier's true drain efficiency. Thus, a theoretical drain efficiency of 85% for Class-B amplifiers and 67% for Class-A amplifiers are achievable under the assumption of linear transconductance and tuned resistive loads. The oscillators reported in this paper operate most efficiently in Class AB. As the name implies, linear Class-AB operation occurs between Class-A and Class-B with efficiencies ranging between the two extremes.

Oscillator maximum output power has been the design emphasis of many researchers [6]–[11]. Maximum output power is found when the oscillator is driven into gain compression operating in Class A. However, oscillators designed for maximum output power achieve the highest efficiency by reducing the drain current to Class-AB operation, i.e., $I_{\rm ds} = 10\%–40\%\ I_{\rm dss}$. Maeda recognized these two conditions on early research with MESFET oscillators [12], and this trend is found in many published MESFET oscillator papers.

A survey of past oscillator efficiencies from C- to *Ku*-band reveals a decrease in efficiency as the operating frequency increases. Bryerton *et al.* have shown a Class-E MESFET oscillator with a 59% efficiency and output power of 300 mW at 5 GHz [13]. Wade reported on a reverse-channel MESFET oscillator operating at 7.9 GHz with an efficiency of 37% and output power of 620 mW [14]. Tserng *et al.* published the results on a number of MESFET oscillators where a 10-GHz oscillator reached a high efficiency of 45% at 50-mW output power in a common gate circuit [15]. Choo *et al.* developed a computer-aided design technique to achieve a 36% efficient oscillator at 13.54 GHz with an output power of 10 mW [16]. Rauscher presented a 17-GHz MESFET oscillator that achieved a 25% efficiency with 45-mW output power [17]. Later, Evans reported on a 0.3-μm gate-length MESFET oscillating at 16.8 GHz, 28% efficiency, and an output power of 28 mW [18]. Achieving high efficiencies as the oscillation frequency increases is hampered by the device's parasitics and maximum frequency of oscillation $f_{\max}$.

In this paper, an experimental oscillator design is presented where oscillator efficiencies are greater than 40% in the *Ku*-band. The highest dc-to-RF efficiency of 60% is achieved at 14.5 and 15.05 GHz. All of the oscillator circuits use

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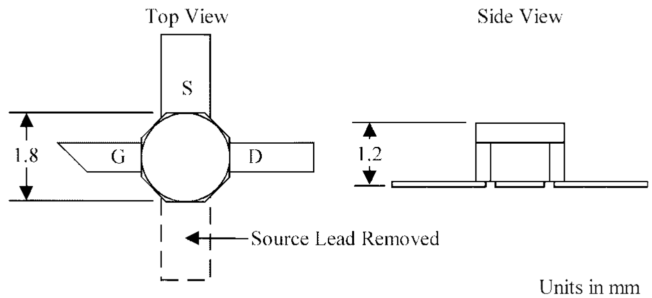

Fig. 1. Top and side views of the packaged Kukje Corporation pHEMT.

a packaged GaAs pHEMT as the oscillating device where one source lead is connected to an open-ended microstrip line and the second source lead is open. The open source lead in combination with the package parasitics results in a resonant cavity around 16 GHz in a 50-Ω system. The measurement of the small-signal S-parameters is all that is needed to estimate the operating frequency. To the authors' knowledge, the efficiencies reported are the highest obtained in the frequency range of 14–17 GHz. This low-cost low-power high-efficiency oscillator should have many applications in wireless sensors, RF identification (RFID), communications, intruder detection, local area networks, etc.

II. Small-Signal Measurements

The device used in this oscillator circuit is a low-cost Kukje Corporation GaAs pHEMT (model KH1032-C02) that is designed for X- and *Ku*-band amplifier and oscillator applications. This device comes in a hermetically sealed metal–ceramic package, as shown in Fig. 1. The saturated drain current $I_{\rm dss}$ for this device at $V_{\rm ds} = 2$ V is typically 40 mA with a maximum rating of 60 mA.

Small-signal S-parameter measurements were performed with an HP 8510B network analyzer by placing this device in an Intercontinental Microwave test fixture in a common-source configuration. Initial S-parameter measurements were taken with both source package leads grounded from 0.2 to 20 GHz at various bias conditions. Evaluation of these S-parameters revealed the device to be unconditionally stable in *Ku*-band frequencies. To provide instability to the device, one of the source leads was removed, as indicated in Fig. 1. S-parameter measurements with this source lead removed and the second source lead remaining grounded revealed the device to be highly unstable around 16.2 GHz, as shown in Fig. 2. The open-source lead was dc insulated from ground by placing a thin layer of Kapton between the pHEMT and the brass test fixture. By removing one of the source leads and leaving it open, the source contact internal to the package provides reflections to create the oscillation. A peak gain of 28 dB at 16.22 GHz was achieved at $V_{\rm ds} = 2$ V, $I_{\rm ds} = 15.6$ mA, and $V_{\rm gs} = -0.3$ V.

Since the device oscillates in the vicinity of 16 GHz at a bias that allows the drain current to flow, small-signal S-parameter measurements were performed near device pinchoff. A small amount of drain current (less than 2 mA) was allowed to flow, allowing a small amount of forward gain without the device oscillating. With the device on the verge of oscillating, several S-parameter measurements were taken around pinchoff with drain currents ranging from 0 to 2 mA. Fig. 3 shows the measured small-signal S-parameters, which are used in the oscillator circuit design with a bias of $V_{\rm gs} = -0.39$ V and power-supply level at $V_{\rm ds} = 2$ V.

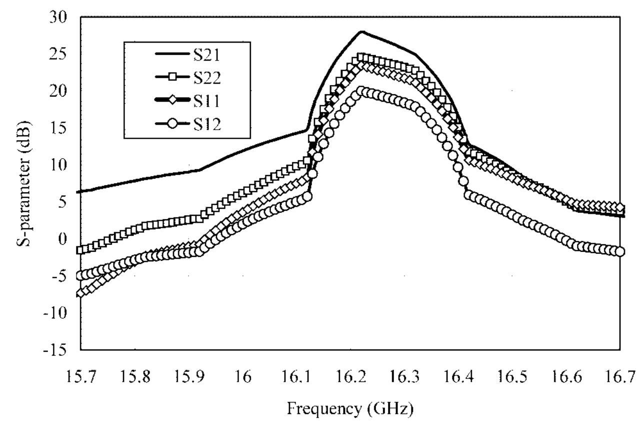

Fig. 2. Measured small-signal S-parameters of pHEMT with one source lead removed. The bias is $V_{\rm gs} = -0.3$ V, $I_{\rm ds} = 15.6$ mA, and $V_{\rm ds} = 2$ V.

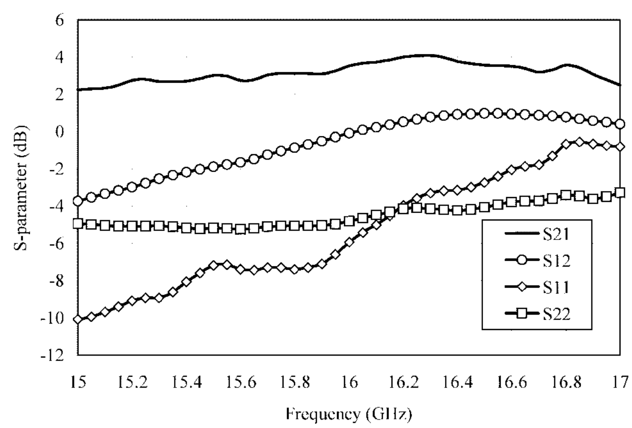

Fig. 3. Measured small-signal S-parameters of pHEMT with one source lead removed near pinchoff. The bias is $V_{\rm gs} = -0.39$ V, $I_{\rm ds} \approx 1$ mA, and $V_{\rm ds} = 2$ V.

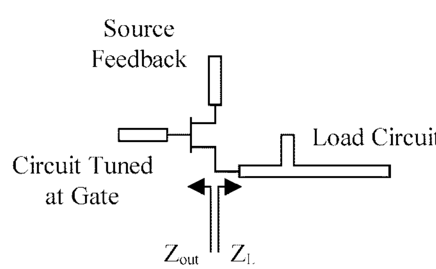

Fig. 4. Oscillator circuit configuration.

III. Oscillator Design

The negative-resistance method was used to design the oscillator circuit [19]. As seen in Fig. 4, two open-circuited microstrip lines are placed on the gate and source, and the drain is connected to the microstrip circuit load. The source open-ended microstrip line provides capacitive series feedback, and the gate open-ended microstrip line is used to control the oscillation frequency. A load circuit is used to match the oscillator to maximize the output RF power. The oscillation condition requires that

$$R_{\text{out}} + R_L = 0$$
$$X_{\text{out}} + X_L = 0 \tag{1}$$

where R_{out} and X_{out} are the impedances looking into the drain port of the oscillator and R_L and X_L are the impedances looking into the load circuit. To be more specific, R_{out} is negative when oscillating, and is usually designed to be approximately three times larger in magnitude than R_L for maximum output power [12].

The two-port small-signal S-parameters measured near pinchoff were converted into three-port S-parameters using the equations given by Khanna [20]. Touchstone was used to combine the three-port S-parameter file with the gate, source, and load S-parameter files. Similar to the approach by Rohrer *et al.*, the peak of the input reflection coefficient looking into the drain of the pHEMT was found by varying the length of the open-circuit microstrip lines on the source and gate [21]. The substrate used for the oscillator circuit is Rogers RO4350 (height $= 0.254$ mm, $\varepsilon_r = 3.48$, loss tangent $= 0.004$, and Cu conductor thickness $= 0.035\,56$ mm). Using the S-parameters of Fig. 3, the initial design predicted an oscillation frequency around 16.7 GHz. The microstrip line lengths connected to the source and gate showed a large degree of tolerance (± 0.2 mm) without greatly affecting the simulated oscillation frequency. Also, the measured S-parameters with no drain current showed the oscillation condition was not met as expected. In particular, the output resistance looking into the drain is positive. Thus, it is important to allow as much gain as possible on the small-signal measurements without oscillating the device.

The source and gate microstrip lengths were found to be 2.7 and 1.2 mm, respectively. The load circuit includes a microstrip line section and open-ended stub for providing an impedance match between the pHEMT's drain port and the 50-Ω output. 50-Ω microstrip lines where the microstrip linewidth is 0.54 mm were used in all cases, including the matching-load stub.

Fig. 5 shows the circuit layout, including the output circuit dimensions and dc-bias structure. The full-wave electromagnetic simulator program IE3D was used to simulate the entire microstrip circuit, including the bias lines.[1] A high frequency of 18 GHz and 40 cells/wavelength were used in all IE3D simulations. The S-parameters from IE3D were then used by Touchstone to simulate the overall circuit performance. The Touchstone file incorporated the simulated S-parameters of the circuit and measured small-signal S-parameters of the pHEMT. Fig. 6 shows the simulated impedance values looking into the drain port of the pHEMT and into the load circuit. Resonance occurs at 16.7 GHz, and the resistances at the drain port and load are -40 and 24 Ω, respectively.

[1] IE3D, version 4.0, Zeland Software, Inc., Fremont, CA.

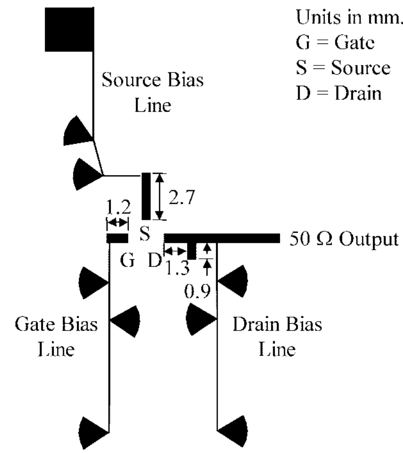

Fig. 5. 16.7-GHz circuit layout.

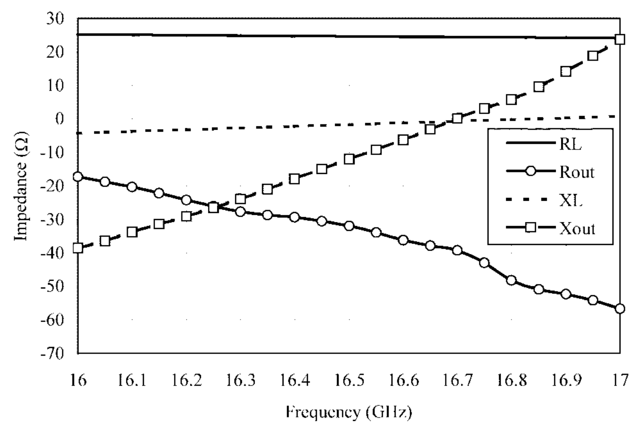

Fig. 6. Touchstone and IE3D simulation results showing resonance occurring at 16.7 GHz.

TABLE I
IMPEDANCES AND RESONANT FREQUENCIES WITH INCREASING DRAIN CURRENT

V_{gs} (v)	Resonant Frequency (GHz)	$R_{out}(\Omega)$	R_L (Ω)
-0.39	16.7	-40	24
-0.38	16.73	-50	24
-0.372	16.82	-73	24

Reviewing the small-signal S-parameters measured near pinchoff reveals how the resonant frequency and output impedances behave as the drain current is increased. Table I reveals the trend of increasing resonant frequency with decreasing output resistance. If the large-signal S-parameters could be measured, the oscillation frequency would be higher due to the increasing drain current.

IV. OSCILLATOR MEASUREMENTS

Fig. 7 shows the measured oscillation performance as a function of gate-to-source voltage where V_{ds} is a constant 2 V. The highest efficiency of 41% occurs at 17.1 GHz, where the output power is 13.4 mW. The dc-to-RF efficiency (also called

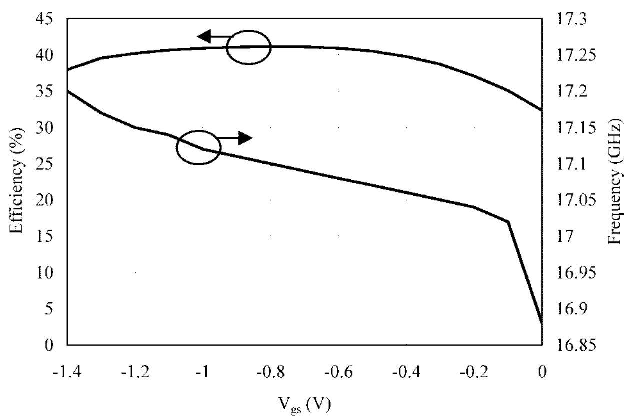

Fig. 7. Measured dc-to-RF efficiency and oscillation frequency versus $V_{\rm gs}$ with $V_{\rm ds} = 2$ V.

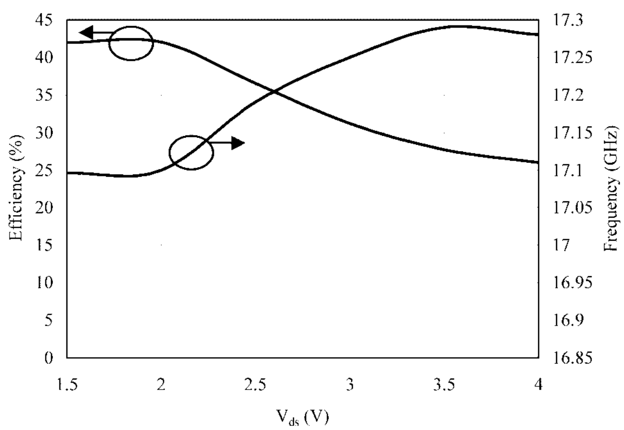

Fig. 8. Measured dc-to-RF efficiency and oscillation frequency versus $V_{\rm ds}$ with $V_{\rm gs} = -0.8$ V.

drain efficiency) is defined as

$$\eta = \frac{P_{\rm out}}{I_{\rm ds} V_{\rm ds}} \tag{2}$$

where $P_{\rm out}$ is the RF output power, $I_{\rm ds}$ is the drain-to-source dc current, and $V_{\rm ds}$ is the drain-to-source dc voltage.

Fig. 8 shows the efficiency and oscillation frequency as a function of drain-to-source voltage where $V_{\rm gs}$ remains fixed at -0.8 V. Fig. 9 shows the change in efficiency as the output power increases. These measurements were made by use of a power meter and spectrum analyzer, as depicted in Fig. 10. The spectrum analyzer monitors the oscillation frequency by detecting the radiated power. The HP 8481A power sensor has a ±4.8% uncertainty and ±2.6% probable uncertainty (RSS) at 14 GHz, and the sensor has a ±5.2% uncertainty and ±2.9% probable uncertainty at 17 GHz. Calibration of the power sensor occurred before each measurement, and the loss from the circuit to sensor is negated from the measurement.

The higher measured oscillation frequency was anticipated from the small-signal measurements. Due to the lack of a large-signal pHEMT model and knowledge of the parasitic reactance effects of the package, the output power and efficiency are difficult to predict. In a 50-Ω measurement system,

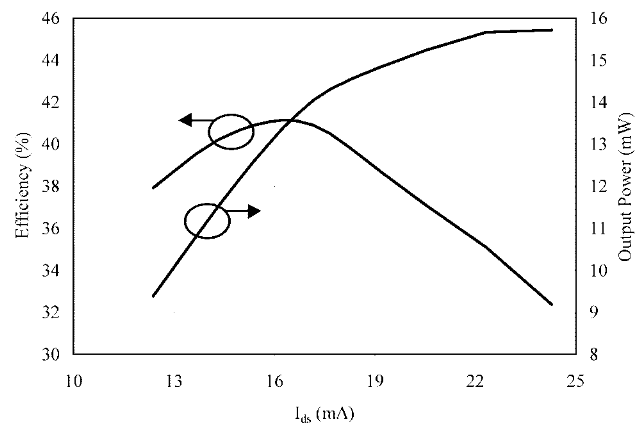

Fig. 9. Measured efficiency and output power of 17-GHz oscillator with $V_{\rm ds} = 2$ V.

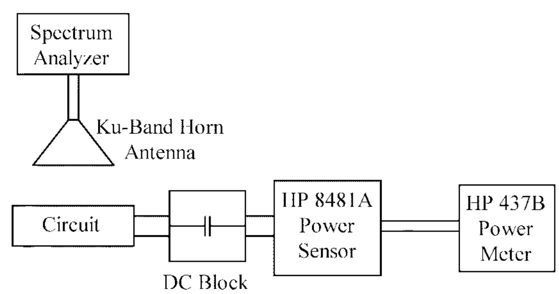

Fig. 10. Oscillator measurement setup.

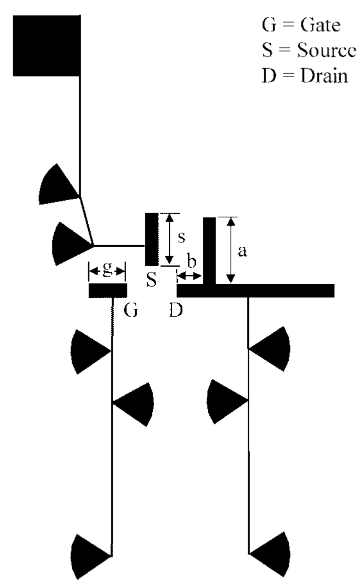

Fig. 11. Circuit layout of *Ku*-band oscillators.

the pHEMT exhibited a strong resonance around 16.2 GHz. Since decreasing the oscillation frequency typically results in higher efficiencies, the circuit was altered to oscillate from 14 to 16 GHz.

Fig. 11 shows the circuit layout for the 14- to 16-GHz oscillators. Table II gives the dimensions and measured results

TABLE II
Ku-BAND OSCILLATORS. *TYPICAL BIAS FOR ALL CASES IS $V_{gs} = -0.3$ V AND $V_{ds} = 2$ V. **BIAS IS $V_{gs} = -0.4$ V AND $V_{ds} = 2.5$ V

Dimensions (mm)				Measured Parameters			Simulated f_{osc}
g	s	a	b	Efficiency (%)	P_{out} (mW)	f_{osc}	
1.6	2.2	2.13	1.1	52	6.5	14.25	15.88
1.6	2.2	1.93	1.1	55	8.3	14.35	15.98
1.6	2.2	1.73	1.1	56	9.0	14.41	16.07
1.6	2.2	1.45	1.1	60	15.6	14.50	16.17
1.6	2.2	1.33	1.1	57	12.1	14.58	16.21
1.3**	1.8	1.4	0.9	60	23.5	15.04	16.54
0.75	1.3	1.2	1.1	48	10.6	16.0	17.20

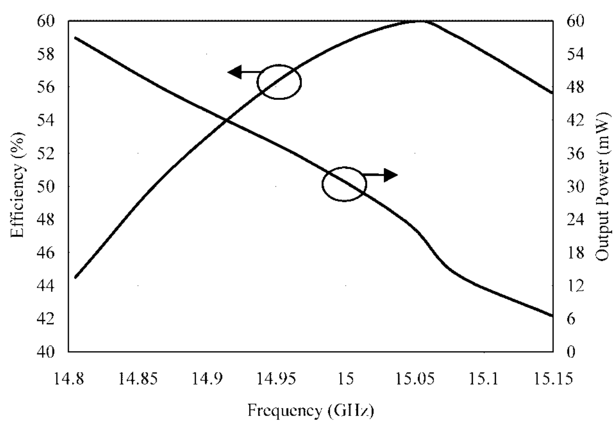

Fig. 12. Efficiency and output power for 15-GHz oscillator. A constant dc bias of $V_{gs} = -0.4$ V is applied with $V_{ds} = 1.5$ to 4.0 V and $I_{ds} = 8$ to 32 mA.

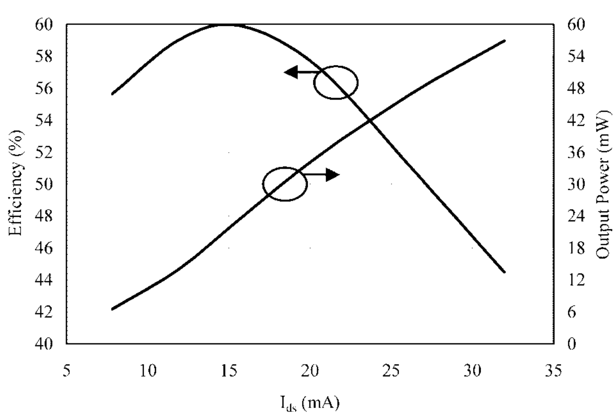

Fig. 13. Efficiency and output power versus I_{ds} for 15-GHz oscillator at a bias of $V_{gs} = -0.4$ V.

from the oscillators. The maximum efficiency is given for each oscillator circuit with the associated RF output power. Also shown are the simulated oscillation frequencies using the measured pHEMT small-signal S-parameters near pinchoff ($V_{gs} = -0.39$ V) and the IE3D simulations of the actual circuit. Two oscillators obtained 60% efficiency, one at 14.5 GHz and the other at 15.04 GHz. Both circuits were etched twice using different Kukje pHEMT's to verify the performance. Measured results revealed identical efficiencies and oscillation frequencies. Figs. 12 and 13 show the efficiency and output power of the 15-GHz oscillator. At the 60% efficiency level, the drain current is 15.7 mA or, approximately, 30% I_{dss}. At the peak output power of 57 mW, the bias is set to $V_{ds} = 4$ V and $I_{ds} = 32$ mA.

V. CONCLUSION

Ku-band oscillators using a pHEMT device have been measured with high dc-to-RF efficiencies. The efficiencies achieved include 60% at 14.5 and 15 GHz, 48% at 16 GHz, and 41% at 17.1 GHz. The simulated oscillation frequency, based on small-signal pHEMT S-parameters, revealed a large difference from the measured oscillation frequency. A large-signal model of the device and a model of the device package is needed to accurately predict the oscillation frequency, efficiency, and output power.

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Kai Chang (S'75-M'76-SM'85-F'91), for photograph and biography, see this issue, p. 1551.