A 5-GHz High-Efficiency Class-E Oscillator

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***Abstract*—A 5-GHz high-efficiency feedback oscillator using a class-E amplifier is presented. The oscillator is designed at 5.0 GHz for maximum conversion efficiency using only quasilinear simulation techniques. A maximum conversion efficiency of 59% is measured with an output power of 300 mW. The oscillator can also be biased for a maximum power of 600 mW with a conversion efficiency of 48%.**

I. Introduction

WHILE A GREAT amount of work has been done to improve the efficiency of microwave amplifiers, little has been done to address the same problem in oscillators. Achieving high efficiency in microwave oscillators is important for the same reasons as in amplifiers—increasing the output power, battery lifetime, and reliability of transmitters. Microwave oscillators have demonstrated 67% conversion efficiency with 250 mW of output power at 1.6 GHz using a class-F amplifier in a feedback oscillator [1]. Here, feedback is added to a class-E amplifier similar to the one presented in [2]. The oscillator is designed using a quasilinear approximation of large-signal operation. A hybrid oscillator indicating class-E operation was fabricated and characterized.

II. Class-E Oscillator Design

A feedback oscillator configuration with a high-efficiency class-E amplifier is used in the design. The oscillator design approach described in [3] is performed with a linear circuit simulator. The feedback length is adjusted for an oscillation frequency of 5.0 GHz and the amount of coupling is optimized for the correct compression point. An asymmetric microstrip branch-line coupler is used to provide the feedback through a length of microstrip transmission line. The circuit layout is shown in Fig. 1.

The class-E amplifier is a resonant switched-mode circuit in which a switch (transistor) turns on at zero voltage and zero derivative of voltage. Ideally, the product of the switch voltage and current is zero, resulting in 100% efficiency. In practice, the efficiency is limited by the drain-to-source saturation resistance of the transistor and other losses in the circuit. The MESFET is driven as a switch and the surrounding circuitry is designed to give class-E operation. Device parasitic reactances are included in the resonant circuit design.

The class-E amplifier in Fig. 1 uses a Fujitsu FLK052 MESFET. The input match is designed for gain by measuring s_{11} in saturation. The output circuit has a fundamental impedance for class-E operation of

$$Z_{\text{net}} = \frac{0.280\,15}{\omega_s C_s} e^{j49.0524^\circ}$$

where ω_s is the fundamental frequency, 5 GHz, and C_s is the transistor switch output capacitance, 0.4 pF [4].

The circular function [3], C, which is similar to the closed-loop gain, is used in the simulations and is given by

$$C = \frac{s_{11}s'_{11} + s_{21}s'_{12} - (s_{11}s_{22} - s_{12}s_{21})(s'_{11}s'_{22} - s'_{12}s'_{21})}{1 - s_{22}s'_{22} - s_{12}s'_{21}}$$

where s_{ij} are the small-signal s-parameters of the class-E amplifier and s'_{ij} are the s-parameters of the feedback network. Oscillations occur where the phase of the circular function crosses zero degrees with a magnitude greater than one. The MESFET saturates to the point where $|C|$ is exactly one. Device saturation is simulated by reducing the magnitude of s_{21}. This is shown in [5] to be a reasonable approximation of the large-signal operation of a FET for small levels of saturation.

The class-E amplifier achieves maximum power-added efficiency when it is operating approximately 4 dB into compresion [4]. The amount of coupling is adjusted in the simulations so that 4 dB of compression reduces $|C|$ to unity at 5.0 GHz. The feedback length is then adjusted to make $\angle C$ equal to zero degrees at 5.0 GHz. Since these simulations are based on small-signal s-parameters, the feedback line length is made to be tunable.

After fabrication, the feedback length is experimentally tuned to produce an oscillation at exactly 5.0 GHz. The first design was intended to couple −5.7 dB of the amplifier output power to the feedback loop and −1.4 dB to the load. This oscillator achieved an output power of 210 mW with 43% conversion efficiency and was operating too far into compression. We believe that too much coupling was predicted in the simulation because the effects of large-signal operation on the input and output match are ignored. Nonlinear simulations show that in some cases when $|s_{21}|$ compresses by 25%, $|s_{11}|$ decreases by 33%. A second oscillator was designed and fabricated with reduced coupling in order to increase the power and efficiency. The second design couples −6.5 dB of the output power to the feedback loop and −1.1 dB to the load. Experimental results for this design are presented in the following section.

Fig. 2 shows the simulated circular function for this oscillator with no saturation taken into account. Only the frequency ranges where the oscillation conditions are met are shown here. This simulation shows a low-frequency oscillation near 600 MHz, which appears to be more compressed than the desired

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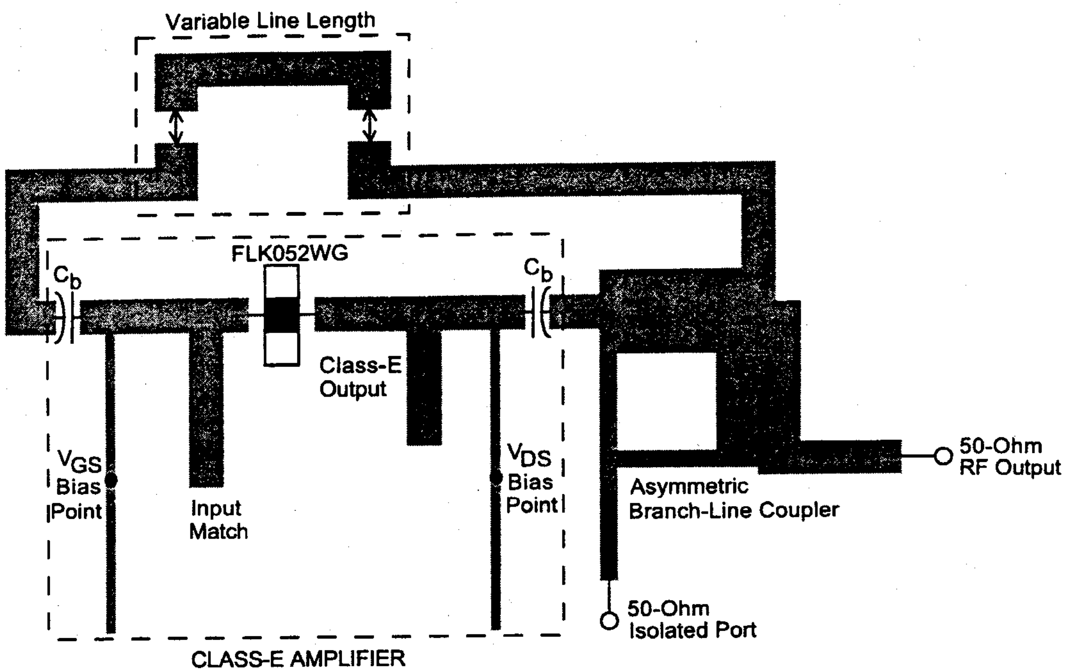

Fig. 1. Class-E oscillator in microstrip.

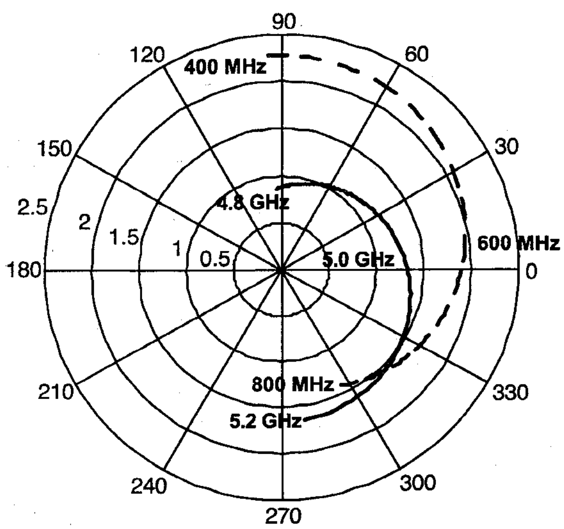

Fig. 2. Simulated circular function for unsaturated class-E oscillator. Dashed line shows oscillation near 600 MHz and solid line shows oscillation near 5 GHz.

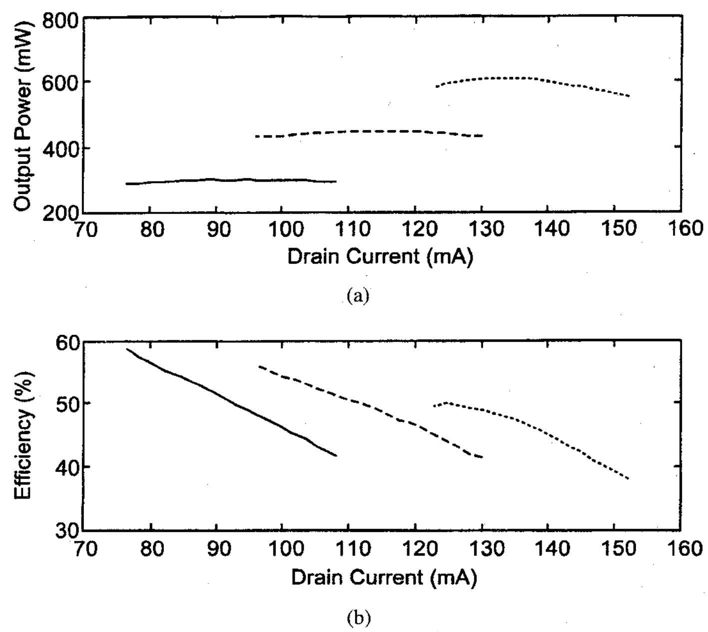

Fig. 3. Output power and conversion efficiency versus drain current, I_{DS}, for $V_{DS} = 6.5$ V (solid line), $V_{DS} = 8$ V (dashed line) and $V_{DS} = 9.5$ V (dotted line).

5-GHz oscillation. The high level of saturation for the 600-MHz mode is verified experimentally by the large number of harmonics produced by this mode. This low-frequency oscillation is supressed in the circuit by lowering the value of C_b in Fig. 1. The measured oscillation frequency of the 5-GHz mode differs less than 3% from simulation.

III. Experimental Results

Fig. 3 shows the measured output power and conversion efficiency of the oscillator versus drain current for three different values of V_{DS}. The lines on the plot represent the range over which the oscillation remains stable. The plot shows that as the drain current increases, the efficiency decreases while the output power remains the same, so there is no advantage in raising the drain current over the minimum level. The maximum efficiency is 59% for $V_{DS} = 6.5$ V and 300 mW of output power. The maximum output power is 600 mW for $V_{DS} = 9.5$ V and 48% conversion efficiency. The oscillation frequency varies less than 1% over the entire biasing range shown here.

Table I compares the class-E amplifier and the oscillator presented here for the same bias point. Neglecting losses, the expected output power of the oscillator is the power added by

TABLE I
COMPARISON BETWEEN CLASS-E AMPLIFIER AND CLASS-E OSCILLATOR. SECOND ROW SHOWS IDEAL OSCILLATOR PERFORMANCE BASED ON AMPLIFIER MEASUREMENTS. THIRD ROW SHOWS MEASURED OSCILLATOR DATA

	V_{DS}	I_{DS}	Power	Eff
Amplifier	8 V	93 mA	27.8 dBm	72%
$Oscillator_I$	8 V	93 mA	27.3 dBm	72%
$Oscillator_M$	8 V	96 mA	26.7 dBm	56%

the amplifier. The expected efficiency is equal to the power-added efficiency of the amplifier at this bias point. As the table shows, the efficiency is lower than the ideal level. Some of the difference is due to losses in the circuit, but most is believed to be caused by the oscillator still operating too far into compression. This can be corrected in the design if the large-signal characteristics of the MESFET are known accurately. These results show the need for good nonlinear models when designing oscillators for high efficiency.

The class-E amplifier used here is designed to present an open circuit to the second harmonic at the drain. Class-E operation of the oscillator is suggested by noting that the output power is -36 dBc at the second harmonic and -27 dBc at the third harmonic.

IV. CONCLUSION

The class-E approach to obtaining high efficiency is shown to be applicable to oscillators. A maximum conversion efficiency of 59% is measured with an output power of 300 mW. A quasilinear design approach is shown to be accurate for predicting oscillation frequency, but nonlinear analysis is necessary when designing oscillators for maximum efficiency. Since the feedback network consists only of a microstrip transmission line, this oscillator is fairly noisy—approximately -70 dBc/Hz for a 100-kHz offset. A high-Q resonator may be added in the feedback network to improve this figure.

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