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# An Empirical Design Technique for Microwave Oscillators

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***Abstract* — A large-signal design technique for series-type microwave oscillators using three-terminal active devices is described. Using this technique, the characteristics of the embedding circuits required for maximum output power are measured directly under actual oscillation conditions. A "two-signal" technique is used in the measurement to establish the required oscillation conditions and to prevent oscillation at unwanted frequencies. The design technique has been verified by the construction of a 2.7-GHz bipolar transistor oscillator.**

## I. Introduction

A variety of techniques have been proposed for the large-signal design of oscillators using three-terminal active devices. One approach is to use large-signal parameters (such as *S*- or *Y*-parameters) or a nonlinear physical model to predict the performance of the active device under actual oscillation conditions. The characteristics of the embedding circuits required for maximum output power at the desired frequency are then calculated [1]–[6]. Another approach uses a two-step procedure [7]–[12]. A one- or two-port circuit that exhibits negative resistance is first designed using small-signal parameters. Estimates of the large-signal performance of the device are often used along with small-signal parameters in the design of this circuit to maximize the available power. This circuit is then characterized under actual oscillation conditions using a large-signal reflection coefficient measurement or a load-pull measurement to determine the circuit terminations that allow maximum power to be delivered to the load.

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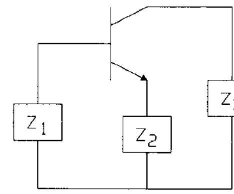


Fig. 1. The basic oscillator topology. One impedance is the output load impedance and two are purely reactive.

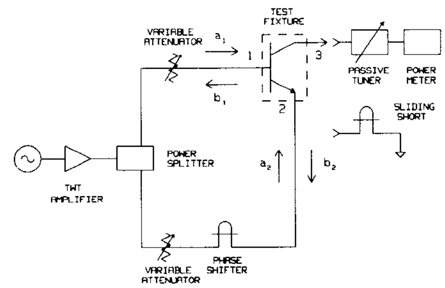


Fig. 2. Simplified test system for establishing oscillation conditions.

Presented in this paper is an alternative design technique for series-type oscillators. The first step in the design is a large-signal measurement that simulates the conditions that would exist during actual oscillation at the desired frequency. In this measurement, the impedances seen by the three terminals of the active device that are required for maximum output power are determined. Circuits are then designed using conventional techniques that present these impedances to the active device.

One advantage of this technique over those described above is that it is a completely large-signal design that does not require a large-signal model. A disadvantage is that the measurement is fairly time consuming and the results are applicable only to the specific conditions established during the measurement. However, for a fixed frequency series-type oscillator, this technique may be preferred since the validity of a nonlinear physical model or large-signal parameters need not be established.

## II. Design Technique

The basic oscillator topology is shown in Fig. 1. The embedding circuits for the oscillator consist of three terminating impedances; two are purely reactive and the third is the output load impedance. A simplified test system for simulating oscillation conditions for this topology is shown in Fig. 2. The active device is mounted in a three-port test fixture. One of the ports is terminated with a conventional passive tuner or with a sliding short; the tuner is capable of presenting an arbitrary impedance (within its tuning range) to the device and the sliding short can present an arbitrary reactance. The three-port test fixture, combined with the passive tuner or sliding short, can be thought of as forming a new two-port circuit with characteristics that vary with the impedance established by the tuner or sliding short. The effective impedances presented to the ports of this circuit are established by injecting a signal at the desired frequency into *both* of the ports. Power for the waves incident on the two ports comes from a high power source and power splitter. The amplitude of the two waves are set with the variable attenuators and the relative phase of the two waves is adjustable with a phase shifter.

Characterizing a two-port circuit by injecting a signal into both ports is often called a "two-signal" technique [13]–[16]. By adjusting the amplitude and relative phase of the two incident waves conditions can be established that are nearly identical to those achievable with a conventional test system with passive tuners and a signal applied to only one port. For the special case of an oscillator there is either zero net power leaving or entering a port (the reflected power equals the incident power) or there is net power leaving a port (the reflected power is greater than the incident power). With a conventional test system, this condition is equivalent to terminating both ports with passive tuners without applying an external signal to either port. The accuracy of the simulation depends on the characteristics of the active device. For a single frequency "two-signal" test system to accurately simulate conditions achievable with passive tuners, the device must be only weakly nonlinear in the sense that the fundamental voltages and currents in the device are not affected appreciably by the characteristics of the terminating impedances at harmonic frequencies. This is a reasonable assumption for typical microwave FET's and bipolar transistors and it is required for most of the fundamental oscillator design techniques described above.

The advantage of the "two-signal" technique in this application is that arbitrary impedances can be simulated at the frequency of interest, and at other frequencies the impedances presented to the test fixture are resistive. This resistance is typically 50 Ω (the impedance of the source), and this broad-band resistance at two of the test ports is usually sufficient to prevent the active device from oscillating.

There are two possible test configurations. If the output port is chosen to be the port with a conventional passive tuner, then the "two-signal" part of the test system must simulate purely reactive impedances at the other two ports; the output power is measured with a conventional power meter. If a sliding short is used instead of a tuner, then the "two-signal" part of the system must simulate a pure reactance at one port and an output load impedance at the remaining port. Measuring the output power with this configuration requires taking the difference between the reflected power and the incident power at the output port. Either configuration will give valid results but the configuration with the sliding short is easier to use. For convenience, the port that is connected to the passive tuner or sliding short will henceforth be identified as Port 3 and the two ports connected to the "two-signal" part of the system will be identified as Port 1 and Port 2 as shown in Fig. 2. In the configuration with the sliding short, Port 1 will be identified as the output port and Port 2 as the second port requiring a purely reactive termination. The actual orientation of the active device in the test fixture will depend on which terminal is selected to be the output terminal.

The complete test system is shown in Fig. 3 for both configurations. Two reflectometers (consisting of dual-directional couplers and phase shifters) are used in the "two-signal" part of the system in conjunction with four power meters and two network analyzers to measure, respectively, the incident and reflected power and the complex ratio of the incident and reflected waves. The difference between the incident and reflected power is displayed on a single meter by connecting the recorder outputs of the power meters to a differential amplifier. Since the losses along the various paths between the device and power sensors are usually different, it is convenient to adjust the recorder output of each power meter with a potentiometer so that the amplifier output is zero when the incident and reflected powers at the device reference planes are equal. While four power meters and two network analyzers are shown in Fig. 3, only one analyzer connected to one reflectometer and two power meters connected to the other reflectometer are actually required during the tuning part of the measurement (described in detail below). After the tuning is complete, the complex ratios of the incident and reflected waves can be measured at both ports by disconnecting the analyzer and reconnecting it to the other reflectometer. It should be noted that the condition of incident power equal to reflected power can be measured with the network analyzer as well as the power meters since this condition is equivalent to measuring a complex ratio with a magnitude of one.

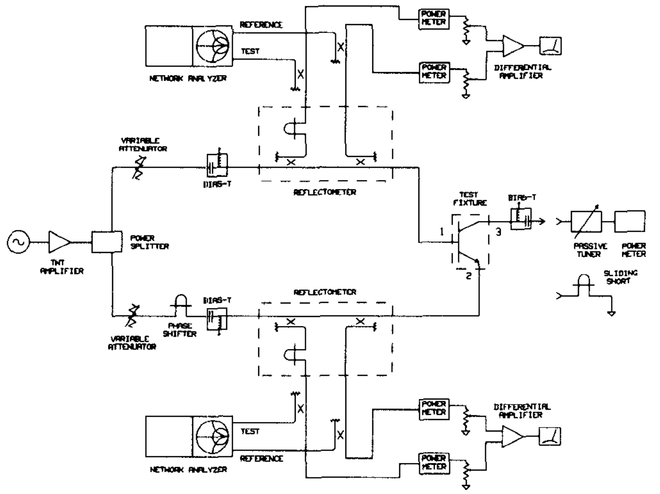


Fig. 3. Complete test system for establishing oscillation conditions, measuring the effective impedances seen by Port 1 and Port 2, and measuring the difference between the incident and reflected power at Port 1 and Port 2.

The tuning procedure differs depending on which test configuration is chosen. If the output port is connected to the passive tuner, the procedure is to adjust the output tuner, the magnitudes of the two waves incident on Port 1 and Port 2 and the relative phase of the incident waves until the measured output power is maximum. The tuning is complicated by the constraint that the incident and reflected power at Port 1 and Port 2 must be equal to simulate purely reactive terminations. One method of tuning is to fix the output tuner and adjust the two attenuators and phase shifter until the incident and reflected power at Port 1 and Port 2 are equal. If this is not possible, then the active device will not oscillate with this output load impedance. If the incident and reflected power can be made equal, the output power is noted. The attenuators and phase shifter are then readjusted until the incident and reflected power are again equal at Port 1 and Port 2 and this procedure is continued until maximum output power for that output impedance is achieved. A new output impedance is selected and the procedure is repeated until the absolute maximum output power is obtained. The complex ratios of the incident and reflected waves are then measured at Port 1 and Port 2; these ratios correspond to the reflection coefficients of the reactances required for oscillation. If the output tuner is calibrated, the output load impedance can be read directly. Alternatively, the fixture can be disassembled and the load impedance measured.

The tuning procedure for the test configuration with the sliding short is more systematic than the procedure just described. The constraint of equal incident and reflected power is automatically satisfied at the port with the sliding short. To tune for maximum output power, the position of the sliding short is first set arbitrarily and the two attenuators and phase shifter are adjusted until the incident and reflected power are equal at the port requiring a pure reactance (Port 2). The output power is then measured as the difference between the reflected and incident power at the output port (Port 1). With the network analyzer connected to the reflectometer adjacent to Port 2, the reflection coefficient of the reactance presented to Port 2 can also be measured. The two attenuators and phase shifter are then readjusted so that the identical reactance is presented to Port 2, but with a different output power. This procedure is repeated until maximum output power is obtained for these two reactive terminations at Port 2 and Port 3. In a similar manner, the maximum output power can be obtained for a different reactance at Port 2 and the reactance that yields maximum power for the particular setting of the sliding short can be found. The position of the sliding short is then changed and the entire procedure is repeated until the absolute maximum output power is obtained. The reactance at Port 2 is then measured and the reflection coefficient of the required load impedance at the output port is measured with the network analyzer as the complex ratio of the incident wave and the reflected wave at Port 1. If the sliding short is calibrated, the reactance presented to Port 3 can be read directly. Alternatively, the fixture can be disassembled and the reactance measured.

These manual tuning procedures can be fairly time consuming but they can typically be completed in an hour for a single-frequency measurement. It is convenient to have two network analyzers for the configuration with the sliding short as this allows the simultaneous measurement of the reactance of Port 2 and the output load impedance at Port 1. It is then a straightforward procedure to measure the reflection coefficient of the output impedance as a function of output power for any pair of reactances at Port 2 and Port 3. While the measurement of these nonoptimum load impedances is not necessary for a design for maximum power, it may be of interest in an oscillator design for minimum noise. It has been suggested that the intersection of the curve generated by these impedances on the Smith Chart as a function of the amplitude of the wave incident on the output port and the curve of the impedance of the output circuit as a function of frequency should be orthogonal for minimum amplitude and phase noise [17].

The final step in the design of the oscillator is to design embedding circuits, using conventional techniques, which have the required reflection coefficients at the frequency of interest. While the reflection coefficients are specified at only one frequency, it is worthwhile to consider other frequencies in the design of these circuits to minimize the probability of spurious oscillations. Low-frequency oscillation is of particular concern since the gain of the active device at low frequencies is typically higher than the gain at the desired frequency. It is usually possible to design embedding circuits with the aid of small-signal device parameters and a linear circuit analysis program that will prevent spurious oscillation at low frequencies.

A convenient method of calibrating the network analyzers is described by Poulin [18]. During calibration, a short or open is placed at the device reference plane and a signal is applied to the appropriate test port using the same test configuration shown in Fig. 3. To calibrate the network analyzer, the gain and phase are adjusted to display the reciprocal of the load reflection coefficient. For example, if a short is placed at the device reference plane, the analyzer display is adjusted to read a reflection coefficient of the reciprocal of $-1.0$, which is simply $-1.0$. The power meters for the "two-signal" part of the system are also calibrated with an open or short at the device reference plane to equalize the loss between the device and the power meters. A signal is applied to the appropriate test port and the voltages of the recorder outputs of the power meters are adjusted, using the potentiometers, to be equal. The differential amplifier output will now be zero if the incident power and the reflected power are equal.

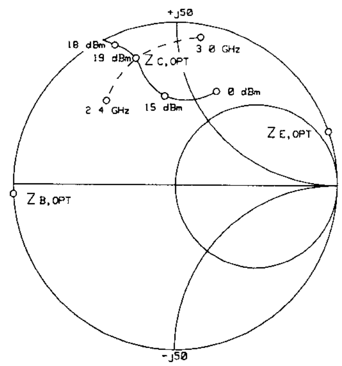


Fig. 4. The optimum impedance seen by the collector $Z_{c,\mathrm{opt}}$, the emitter $Z_{e,\mathrm{opt}}$, and the base $Z_{b,\mathrm{opt}}$ for maximum output power at 2.7 GHz. Solid curve is the collector load impedance required for oscillation at 2.7 GHz as a function of output power for the optimum emitter and base impedance as measured with the sliding-short test system. Dashed curve is the impedance of the collector circuit of the completed oscillator as a function of frequency.

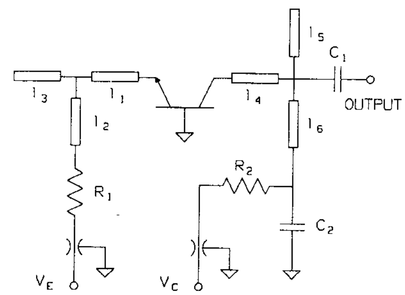


Fig. 5. Circuit diagram of complete oscillator.
$C_1 = C_2 = 12$ pF, $R_1 = 262\ \Omega$, $R_2 = 47\ \Omega$,
$l_1$: $Z_o = 50\ \Omega$, $\theta = 78°$ at 2.7 GHz,
$l_2$: $Z_o = 50\ \Omega$, $\theta = 49°$ at 2.7 GHz,
$l_3$: $Z_o = 50\ \Omega$, $\theta = 90°$ at 2.7 GHz,
$l_4$: $Z_o = 50\ \Omega$, $\theta = 55°$ at 2.7 GHz,
$l_5$: $Z_o = 50\ \Omega$, $\theta = 70°$ at 2.7 GHz,
$l_6$: $Z_o = 80\ \Omega$, $\theta = 90°$ at 2.7 GHz.

## III. Design Example

The technique was verified with the design of a 2.7-GHz oscillator. An in-house packaged bipolar transistor (not commercially available) was used for the active device. The measured maximum added power of this transistor when used as an amplifier in the common emitter configuration was 17.7 dBm. The collector was selected as the output terminal for the oscillator.

The transistor was mounted in a three-port test fixture and the conditions for oscillation with maximum output power were simulated with both test system configurations. The optimum terminating impedances predicted by both measurements were essentially identical (within the accuracy of the network analyzer) and are plotted in Fig. 4. The predicted output powers, however, differ by 1.1 dB; the maximum output power predicted by the test system with the passive tuner was 17.9 dBm and the power predicted by the sliding short system was 19.0 dBm. The difference in power is attributed to the different method of measuring output power. The power measurement that takes the difference between the reflected and incident power corrects for losses in the test fixture, and, as no tuner is involved in the measurement, it is not affected by losses that may depend on tuner position. The curve of output load impedance as a function of output power for the optimum base and emitter reactances is also shown in Fig. 4.

Embedding circuits were designed that provided the optimum collector and emitter terminations to the device. The optimum base termination is very close to a short circuit and, for convenience, the base terminal was shorted directly to ground. The circuits were fabricated on duroid using microstrip transmission lines and chip capacitors. A circuit diagram of the complete oscillator, including the bias network, is shown in Fig. 5. The measured output power of the oscillator was 17.5 dBm at a frequency of 2.69 GHz. This output power corresponds to a power-added efficiency of 32 percent.

## IV. Conclusions

An empirical design technique for series-type oscillators has been described that maximizes output power. Using this technique, the characteristics of the embedding circuits required for maximum output power are measured directly under large-signal conditions similar to those encountered during actual oscillation. These measurements are made possible by the use of a "two-signal" technique which prevents the active device from oscillating at unwanted frequencies.

A bipolar transistor oscillator was constructed to verify the design technique. The predicted oscillation frequency of 2.7 GHz was very close to the actual frequency of 2.69 GHz. The output power of 17.5 dBm was 0.4 dB lower than the power predicted by the test system with the passive tuner and 1.5 dB lower than the power predicted by the test system with the sliding short. This is reasonable agreement; it is assumed that the loss in the output circuit of the completed oscillator was similar to the uncorrected loss in the power measurement with the single power meter and passive tuner. The output power was also close to the maximum added power of the active device when used as a common emitter amplifier. These results suggest that the large-signal conditions seen by the device during actual oscillation were established during the measurement and that the output power of the oscillator was close to the maximum power that could be achieved with the active device.

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# Letters

## Comments on "The Measurement of Noise in Microwave Transmitters"

WOLFGANG FREUDE

The recent comment by Ashley *et al.* [1] as a reply to the remarks by Knöchel *et al.* [2] drew my attention to the work by Ashley, Barley, and Rast, Jr. [3], to which I would like to add three supplements. On an improved version of the frequency discriminator of Ondria [4] and Ashley *et al.* [5], the following results have been published [6].

1) As can be seen by a linearized quasistatic analysis of the setup, there is no need for a matched pair of diodes. The adjustment for optimum AM noise suppression can be accomplished by a simple LF resistive network.

2) An AM noise suppression factor was defined which is independent of irrelevant discriminator parameters.

3) The conditions for the validity of the quasistatic approximation have been stated.

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