About the Oscillator Basics and Low-Noise Techniques for Microwave Oscillators and VCOs

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Abstract: - Microwave oscillator design is based on the principle of generating a negative resistance to compensate for the losses of the resonator. Several circuit combinations, including one- and two-port oscillators, are possible. In this discussion, we will first evaluate the conditions of oscillation for the Colpitts and Clapp-Gouriet oscillator. We will then evaluate a 19-GHz SiGe-based oscillator by assuming values, backed up by available S parameters and dc I-V curves, that we assigned to the nonlinear BFP520 model. So far it has been difficult to obtain complete documentation on modeling for the SiGe transistors, but our approximation appears to be justified. Next, we will evaluate a ceramic-resonator-based oscillator and show its performance. Going up to higher frequencies, we will introduce a 47-GHz lumped-resonator oscillator and a VCO at the same frequency that uses GaAsFETs as varactors. In all cases, we will give a thorough treatment of the circuits and their performance.

Key words: Oscillator circuit; RF; microwave transistors; microwave oscillators ;VCO oscillators

1. Introduction

This presentation will give an overview of both bipolar and GaAsFET-based oscillators, including ceramic-resonator oscillators (CROs). Its purpose is to show not only the linear/nonlinear mathematics, but also how the actual design should be considered, as well as commentary on the results. Many of the predictions can only be obtained by using appropriate software; for this purpose, we have used a harmonic-balance simulator by Ansoft. We also will show some practical circuits, both from the circuit design as well as the actual chip design. In the assumptions we have taken, we have avoided shortcuts so that the approach remains general in nature. It further needs to be pointed out that throughout this discussion, we will assume that each oscillator is followed by an isolation stage that can handle the input power, has at least 10 dB of amplification, and provides isolation of more than 30 dB. An FET amplifier is ideal because it will load the oscillator very little.[3,7,9,10].

2.TheCeramic-Resonator-Based Oscillator (CRO)

It is fairly difficult to build high-Q resonator circuits at the frequency range above 500 MHz. Printed circuit board implementations are lossy, and radiate a lot. Also, they are microphonic. A better choice is a resonator like a rigid cable, which is based on a piece of ceramic that is silver-plated, looks like a small tube, and has one end electrically short-circuited. Since values of ε_r from 38 to 88 are available in high-performance ceramics, the actual physical size of the ceramic resonator becomes very small, resulting in a very low impedance (low L-C ratio). In the case of ε_r = 88 material, the required length in millimeters is $8.2/f$, leading to a significant reduction in physical length. The obtainable Q is in the vicinity of 400. For smaller ε_r values, the Q will go up to 800. Figure 1 shows a photograph of a typical CRO.[11,14]

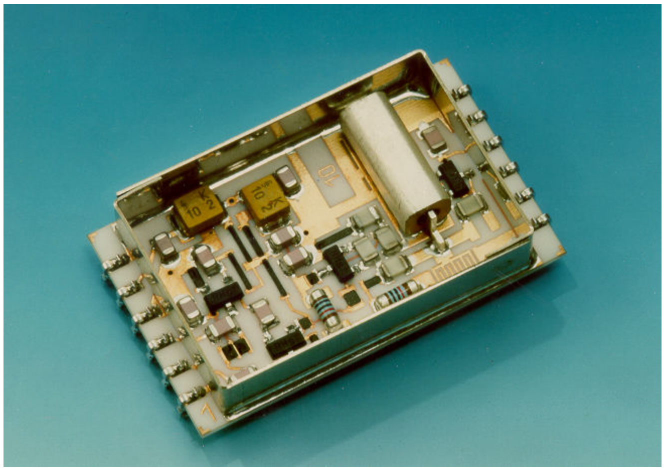

Fig. 1--Typical CRO

Its schematic is not much different from the Colpitts oscillator, as can be seen in Figure 2.

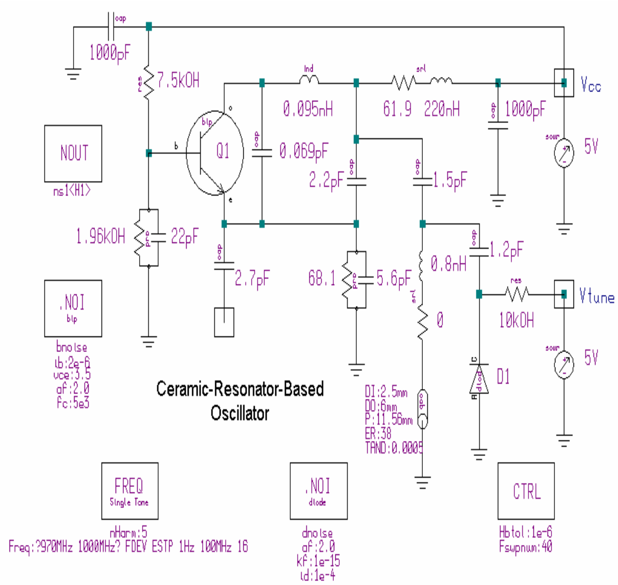

Fig. 2--Typical ceramic-resonator-based oscillator.

It may be of interest to know that most of the far-out noise comes from the tuning diode and is not related to the Q of the resonator. This is a frequently misunderstood fact. This noise contribution is also not due to the Q of the diode, but to its inherent equivalent noise resistance. Reducing the value of the 10-kΩ resistor in the diode's V_{tune} line will further reduce the noise contributed by the diode portion of the circuit to that produced by the diode it self.

This oscillator circuit is similar to the Clapp oscillator. It operates in the grounded-base configuration, and the feedback is formed by the 2.2-pF capacitor between the collector and emitter, and the 5.6-pF capacitor between the emitter and ground. The 900-MHz resonator is coupled to the oscillator with 1.5 pF, and a tuning diode with 1.2 pF. The ceramic resonator is about 11 mm long and 6 mm in diameter, and the ε_r is 38, resulting in an unloaded Q of 500. Because this type of oscillator is mostly operated between 500 MHz and 2 GHz, the base grounding capacitor is very critical. Since the values of the feedback capacitances are fairly high, taking the output from the emitter is tolerable; a better way would have been to split the 5.6-pF capacitor into two series-connected values that give the same amount of coupling[4,6,8].

Now we want to see whether the oscillator will actually "take off," and the picture of the test current components (Figure 3) shows that the crossover point for the imaginary component of the test current is at 982 MHz, but the real current stays negative up to about 990 MHz, so the oscillator can be tuned over a wider range.

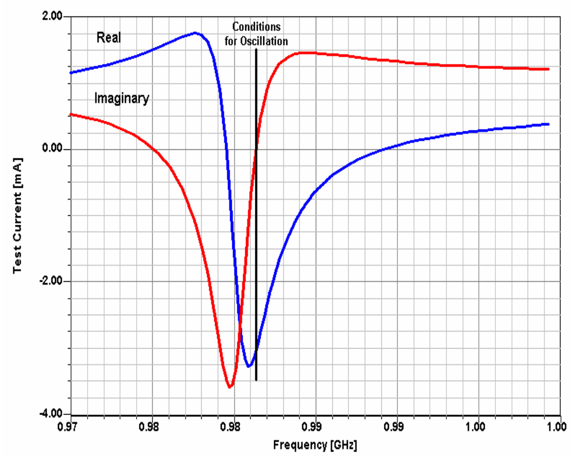

Fig. 3--The steepness of the curve

The test currents indicates a high operating Q that results in low phase noise. The steeper the slope at the changeover from inductive to capacitive reactance, the higher the resonator Q.

Since we are using a high-Q oscillator, we can expect very good phase-noise performance, as the simulated phase-noise curve of Figure 4 shows. The curve also shows the breakpoint for the flicker noise. We measured the actual oscillator and found that the difference between simulation and measurement was less than 2 dB. This is valid from 100 Hz from the carrier to 10 MHz off the carrier. At frequency offsets greater than this, the measurement becomes quite difficult[1,2,5].

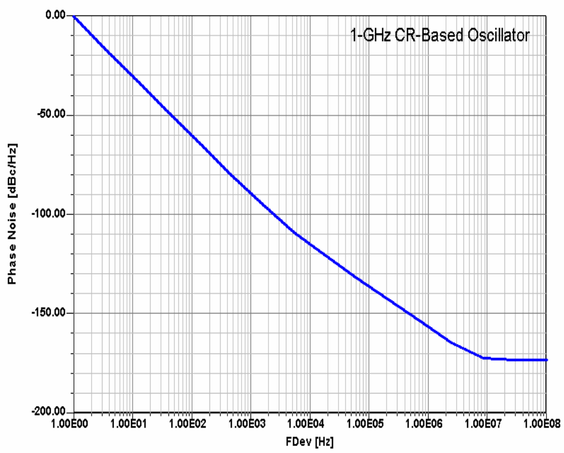

Fig. 4-- SSB phase of a typical ceramic-resonator-based oscillator operating around 900 MHz.

The breakpoint at about 5 kHz is due to the transistor's flicker noise contribution. The ultimate phase noise (breakpoint near 10 MHz) is due to KT_0 (−174 dBc/Hz),however, the tuning diode coupling is only about 10MHz per volt, and therefore, does not add to the modulation noise. For test purposes, this is an LC circuit with a loaded Q of 50 measured at about 500MHz, however the IC operates up to 3GHz.

3.The Microwave Oscillator

We have seen a variation of the Colpitts oscillator that, by adding a capacitor in series with the main inductance, is preferred in microwave applications.

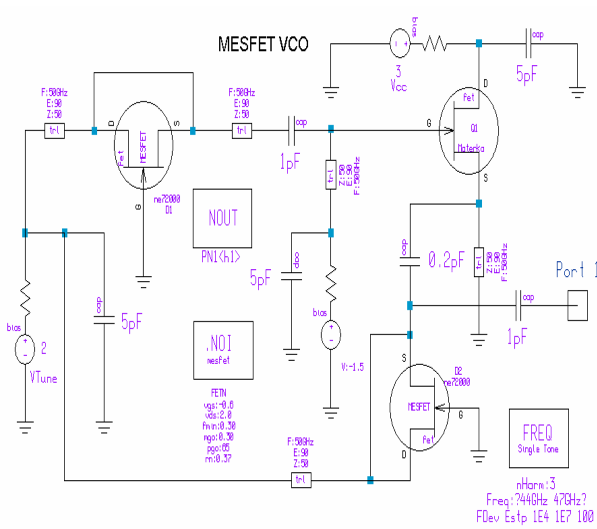

Fig. 5-- Schematic of the 47-GHz MESFET oscillator.

This oscillator type is called the Clapp-Gouriet, and most microwave engineers probably have never heard this name. Figure 5 shows the schematic of such an oscillator, which uses transmission lines for its resonator and several RF chokes. That oscillator using transistors instead of varactor (tuning) diodes--a nontrivial case for the harmonic-balance simulator.

The varactors are actually obtained by using the paralleled source-gate and drain-gate capacitances of additional GaAsFETs. This type of varactor, as well as the pure GaAs varactor, is always noisy.

It must be remembered that the noise contribution of such a "tuning diode" highly depends on its equivalent noise resistance--a value that cannot be measured with an ohmmeter. For microwave oscillators, the best way to determine this is to first build the oscillator without the varactor attached, measure its phase noise, and then measure the phase noise with the "diode" connected. The resulting deterioration is the contribution of the tuning diode.

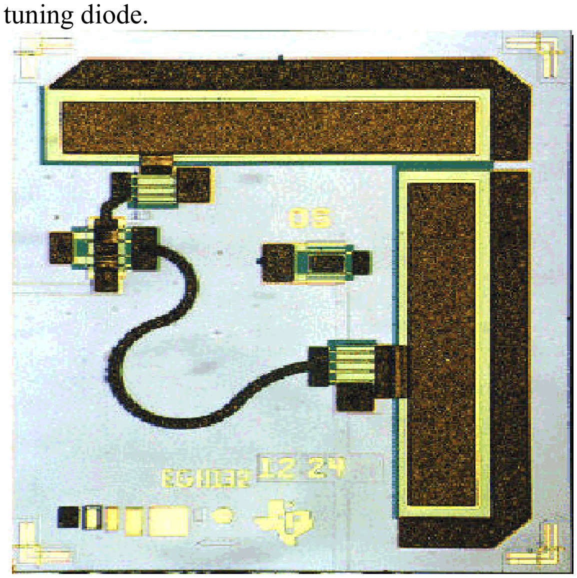

Fig. 6--MESFET-based oscillator.

An early example of the dual-varactor type oscillator is shown in Figure 6. The transistor is at the upper left; the resonator inductance goes to one "varactor," and the second "varactor" is above the transistor. This oscillator operated at 20 GHz and was designed by Texas Instruments[10,12,13].

The *S*-shaped transmission line acts as the resonator, and the circuit uses two tuning diodes for wider tuning range. Both GaAs varactors, as well as GaAsFETs used as varactors, have a high contribution to the resulting phase noise and limit the performance of the circuit.

Analyzing our Clapp-Gouriet microstrip-based oscillator, which we have optimized for 47 GHz, we obtain the phase noise as shown in Figure 7.

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This is an oscillator circuit; to change it into a VCO, tuning diodes, which will make it noisier, must be added. The curve has the familiar breakpoint, which is caused by the flicker noise of the transistor. It is a misconception to assume that the flicker corner frequency and the breakpoint will coincide.

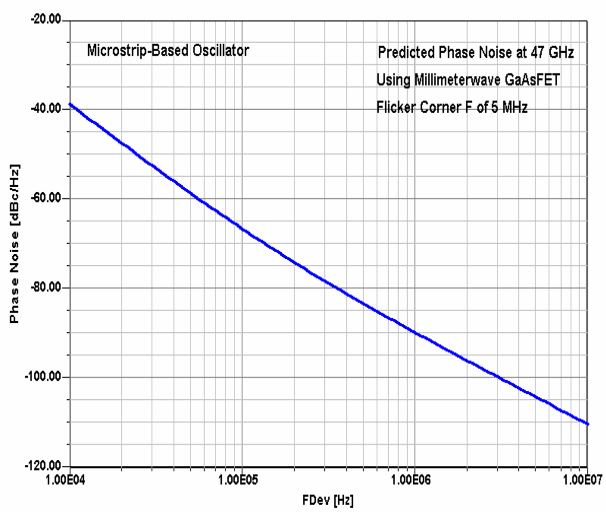

Fig. 7--Assuming a flicker corner frequency of 5 MHz, we can predict this phase noise response. The flicker frequency is responsible for the bend in the curve.

Because of the resonator Q, the breakpoint always occurs closer to the carrier. Only for very low Qs will the two values be the same.

In the same fashion, we have used Ansoft Serenade's Oscillator Design Aid to predict the oscillation frequency. The resulting curves (Figure 8) are quite startling because of the discontinuities in the real and imaginary portions of the test current. They indicate the severe nonlinearities introduced by the GaAsFET oscillator transistor and the two "tuning diodes." Also, this time the peaks in the test current components are below the oscillation point. It clearly indicates that the oscillator has not been optimized for best operating Q--a task we gladly leave to the reader as a good challenge.

The actual linear prediction is 46.3 GHz; the large-signal condition then shifts the result towards 47 GHz. The strange curves are due to the highly nonlinear operation, including the two transistors acting as tuning diodes.

The next logical step is to look at the output spectrum (Figure 9). The attenuation of the second harmonic is the familiar 20 dB. The output was taken from the resonator circuit via the familiar capacitive divider.

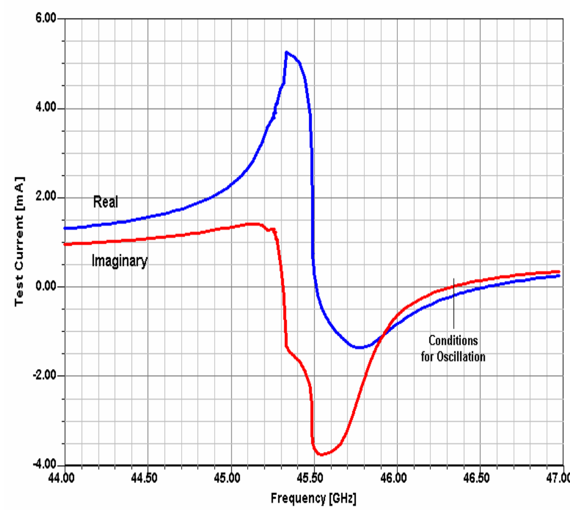

Fig. 8--Test currents for finding the oscillating conditions of the 47-GHz oscillator.

The drawback of this implementation will vary as a function of the capacitance of the varactor. A smarter, though somewhat complicated, way would be to magnetically couple from the resonator. This way, one obtains the best phase noise and has control over the loading. It is unclear why this method is not used for MMICs, while it is popular in circuits built with lumped elements and transmission-line resonators.

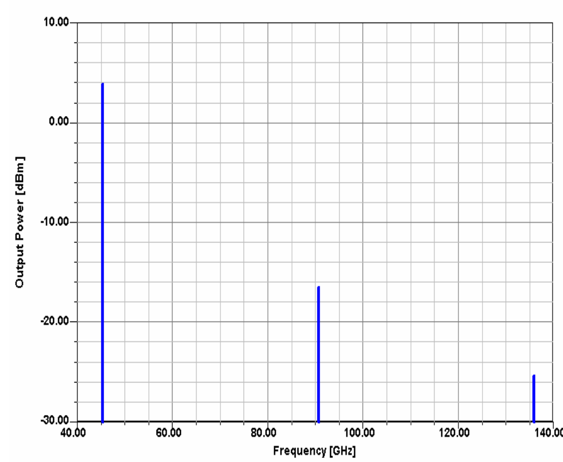

Fig. 9--Predicted output spectrum for the 47-GHz FET-based oscillator.

The resulting phase noise, as anticipated, is poor and is characterized by a straight-line response (Figure 10). This is due to the diode noise contribution . The phase noise of the oscillator is by far not state-of-the-art because the flicker noise and the diode noise are excessive.

Current research in oscillators using SiGe transistors or even GaAs HBTs will result in much better phase noise performance.

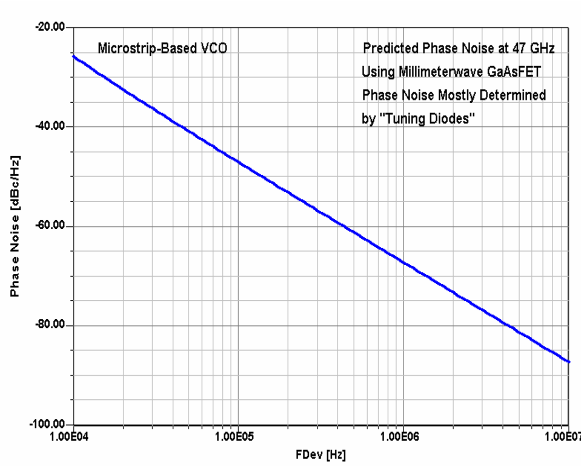

Fig. 10--Predicted phase noise of the 47-GHz millimeterwave oscillator using GaAsFETs as tuning diodes. They are notoriously noisy.

Compared to Figure 7, we have lost our good phase noise performance.

Finally, we let the circuit simulator provide us with the oscillator transistor load line (Figure 11). By inspecting it, we see that the resulting ellipse is not limited either by current or voltage, which leads to low-distortion operation for the transistor. On the other hand, our previous examination showed strong nonlinearities.

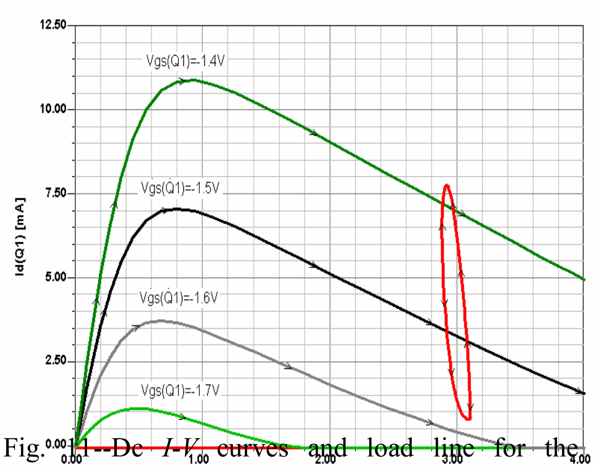

Fig. 11--Dc *I-V* curves and load line for the oscillating FET in the 47-GHz VCO.

The reason why the ellipse is not distorted has to be the loose coupling, and yet the Q is low because of the resonator elements--specifically, the transistors used as varactor diodes.

These diodes have their own load lines, since both dc and ac voltages are fed to them.

Figure 12 shows the resulting load lines. The reason for the difference in their diameters has to do with the fact that power levels at the two points are different.

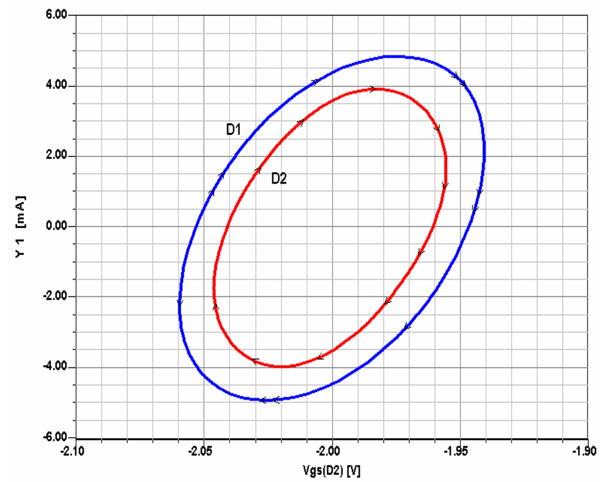

Figure 12--Load lines for the "tuning diodes"

The diodes D1 and D2, in reality are GaAsFETs with source and drain tied together.The round shape indicators that the "varactors" are both operating in their linear regions, but the devices themselves are highly nonlinear.

4. Conclusions

Designing microwave and millimeterwave oscillators still involves the use of some black magic, but a good understanding of their theory of operation, including a good simulator, does help. We have covered both bipolar transistors and GaAsFETs and point out their unique behavior. The oscillators we have used to demonstrate the design process were single-stage types.

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