"How to Design RF Circuits" - OSCILLATORS

Andrew Dearn *

Introduction

Oscillators can generally be categorised as either amplifiers with positive feedback satisfying the well-known Barkhausen Criteria (Ref. 1), or as negative resistance circuits (Ref. 2). Both concepts are illustrated in Figure 1. At RF and Microwave frequencies the negative resistance design technique is generally favoured.

(a) Negative Resistance Oscillator   (d) Positive Feedback Oscillator
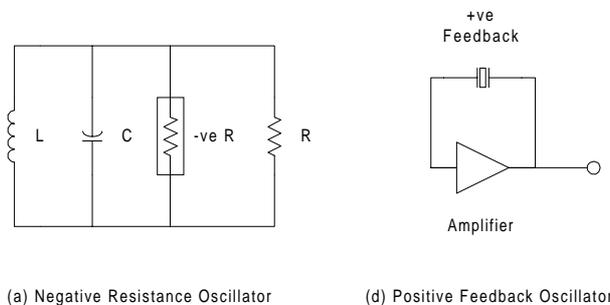
Figure 1: General Equivalent Circuits for RF Oscillators

The procedure is to design an active negative resistance circuit which, under large-signal steady-state conditions, exactly cancels out the load and any other positive resistance in the closed loop circuit. This leaves the equivalent circuit represented by a single L and C in either parallel (as illustrated) or series configuration. At a frequency the reactances will be equal and opposite, and this resonant frequency is given by the standard formula;

$$f = \frac{1}{2\pi\sqrt{LC}}$$
              … Equation (1)

It can be shown that in the presence of excess negative resistance in the small-signal state, any small perturbation caused, for example, by noise will rapidly build up into a large signal steady-state resonance given by equation (1).

Negative resistors are easily designed by taking a three terminal active device and applying the correct amount of feedback to a common port, such that the magnitude of the input reflection coefficient becomes greater than one. This implies that the real part of the input impedance is negative (Ref. 3). The input of the 2-port negative resistance circuit can now simply be terminated in the opposite sign reactance to complete the oscillator circuit. Alternatively high-Q series or parallel resonator circuits can be used to generate higher quality and therefore lower phase noise oscillators. Over the years several RF oscillator configurations have become standard. These are illustrated in Figure 2. The Colpitts, Hartly and Clapp circuits are examples of negative resistance oscillators shown here using bipolars as the active devices. The Pierce circuit is an op-amp with positive feedback, and is widely utilised in the crystal oscillator industry (Ref. 4).

* Andrew Dearn is with Plextek Ltd, London Road, Great Chesterford, Essex, CB10 1NY
  Tel: +44-1799-533200, Fax: +44-1799-533201, e-mail: awd@plextek.co.uk

(a) Colpitts

(b) Hartley

(c) Clapp

(d) Pierce Crystal Oscillator
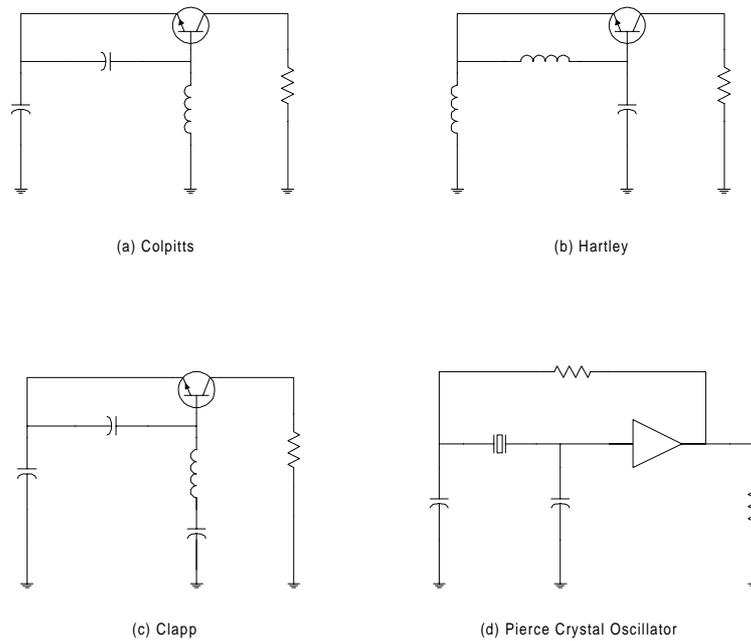
Figure 2: "Standard" Types of RF Oscillator

This paper will now concentrate on a worked example of a Clapp oscillator, using a varactor tuned ceramic coaxial resonator for voltage control of the output frequency. The frequency under consideration will be around 1.4 GHz, which is purposely set in-between the two important GSM mobile phone frequencies. It has been used at Plextek in Satellite Digital Audio Broadcasting circuits, and in telemetry links for Formula One racing cars. At these frequencies it is vital to include all stray and parasitic elements early on in the simulation. For example, any coupling capacitances or mutual inductances affect the equivalent L and C values in equation (1), and therefore the final oscillation frequency. Likewise, any extra parasitic resistance means that more negative resistance needs to be generated.

Small-Signal Design Techniques

The small-signal schematic diagram of the oscillator under consideration is illustrated in Figure 3. In this paper the Serenade® simulator from Ansoft is used. The circuit uses an Infineon BFR181W Silicon Bipolar as the active device, set to a bias point of 2 V V_{ce} and 15 mA collector current. The resonator is a 2 GHz quarter wavelength short circuit ceramic coaxial resonator, available from EPCOS. The resonator is represented by a parallel LCR model, as described in the datasheet (Ref. 5), and the Q is of the order of 350. It is important to note that for a 1.4 GHz oscillator a ceramic resonator some 15 – 40 % higher in nominal resonant frequency is required. This is because the parallel resonance will be pulled down in frequency by the necessary coupling capacitors (4 pF used) and tuning varactor etc. The varactor is a typical Silicon SOD-323 packaged device, represented by a series LCR model, where the C is voltage dependent. The load into which the circuit oscillates is 50 Ω. At these frequencies any necessary passive components must include all stray and parasitic elements. The RF models used for standard 0603 surface mount inductors and capacitors are given in Figure 4 and Figure 5 respectively. The transmission lines represent the bonding pads on a given substrate. In Figure 3 the transmission lines have been omitted for the sake of clarity.
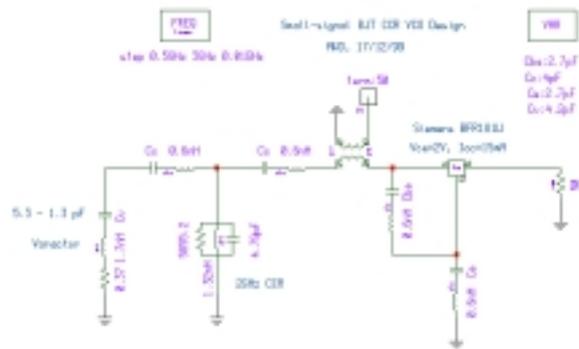
Figure 3: Schematic for Small-Signal Oscillator Design
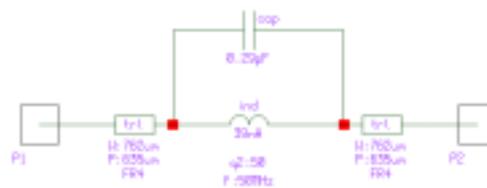
Figure 4: RF Model for nominal 39 nH 0603 Inductor
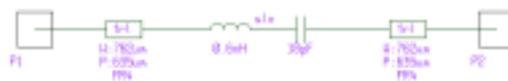
Figure 5: RF Model for nominal 18 pF 0603 Capacitor

The oscillator running into it's necessary load forms a closed-loop circuit and cannot be simulated in this form because of the absence of a port. Therefore an ideal transformer is used to break into the circuit at a convenient point, in this case, between the negative resistance circuit and resonator. It is important to note that this element is used for simulation purposes only, and is not part of the final oscillator circuit. Being ideal it does not affect the input impedance at it's point of insertion.

The first step in the design process is to ensure adequate (small-signal) negative resistance to allow oscillation to begin, and build into a steady-state. It can be seen from Figure 6 that capacitor values of 2.7 pF in the Clapp capacitive divider result in a magnitude of input reflection coefficient (S11) of 6 at 1.4 GHz. (remember |S11| > 1 implies a negative real part of the input impedance). This is more than enough to ensure that oscillation will begin.
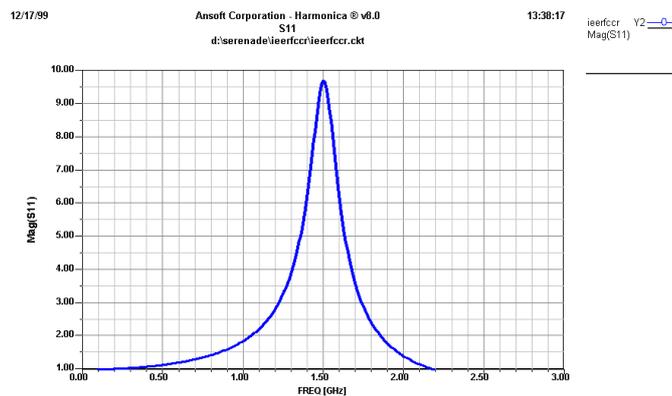
Figure 6: Result of Small-Signal Negative Resistance Simulation

The complete closed loop oscillator circuit is next analysed (small-signal) by observing the input impedance (Z11) at the ideal transformer. The oscillation condition of equation (1) is solved by looking for frequencies where the imaginary part of the impedance goes through zero, whilst maintaining an excess negative resistance. Figure 7 shows the result of simulating the complete schematic of Figure 3, with the varactor capacitance set to 4.2 pF. It can be seen that the imaginary part goes through zero at two frequencies, namely 1.35 GHz and 2.7 GHz. However, there is no net negative resistance at 2.7 GHz, whilst at 1.35 GHz there is some –70 Ω. Thus for the component values given in Figure 3 we have designed a circuit capable of oscillating at approximately 1.35 GHz.
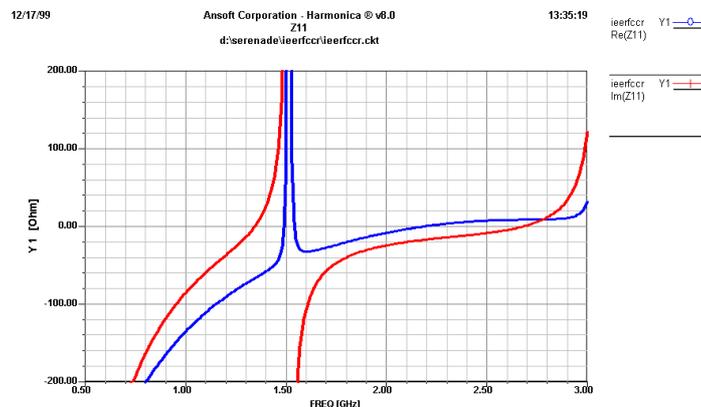
Figure 7: Result of Small-Signal Oscillator Simulation (Fixed Tuning Volts)

Large-Signal Design Techniques

For completeness the circuit is re-simulated under true large signal conditions to determine the steady-state frequency of oscillation. The circuit is modified for use in the Serenade® harmonic balance engine to that of Figure 8. The schematic is identical to that of Figure 3 except that;

- The small-signal model for the transistor is replaced by a non-linear model

- DC bias supply and necessary bias elements are added (Resistors, DC blocks and RF chokes)

- Non-linear control blocks are added, and the ideal transformer removed

Figure 8: Schematic for Large-Signal Oscillator Design

Figure 9 shows the result of the non-linear simulation with the varactor capacitance also tuned to 4.2 pF. The true large-signal steady-state frequency of oscillation is seen to be 1.4 GHz, which is in good agreement with the previous small-signal approximation. Unlike the small-signal simulation we get several more important pieces of information such as output power (+8.8 dBm) and harmonic content. Assuming an accurate noise model is available then phase noise of the oscillator can also be simulated (Ref. 6, 7). This is illustrated in Figure 10. The flicker noise corner frequency of the device was 5 KHz.

Figure 9: Result of Large-Signal Oscillator Simulation (Fixed Tuning Volts)

Figure 10: Result of Large-Signal Oscillator Phase Noise Simulation

The tuning range of the VCO can be simulated by sweeping the control voltage on the varactor diode, from 0 to 5V. A total tuning range of 1.37 to 1.55 GHz is shown at discrete control voltages in Figure 11. The output power variation of the oscillator is approximately 1.5 dB across the band.
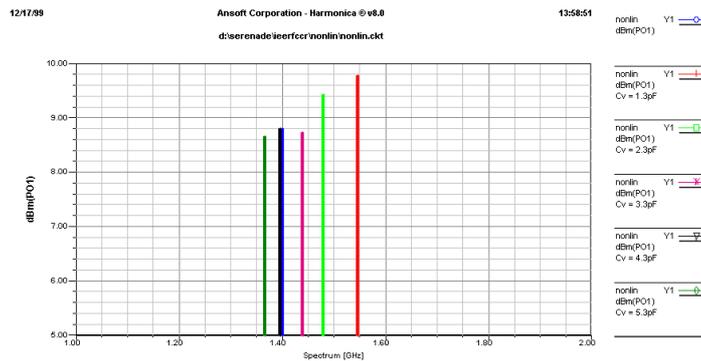
Figure 11: Result of Large-Signal Oscillator Simulation (With Voltage Control)

Measured Results

The actual circuit has been fabricated many times at Plextek, and variations have been utilised in a wide variety of practical circuits. These include GSM phones, DAB receivers and telemetry applications. A photograph of a Clapp ceramic resonator VCO used as the second Local Oscillator in a transceiver for a wireless LAN type application is shown in Figure 12. The transistor is in a SOT-23 outline, and the output is split into two buffer amplifiers, both using the same transistor. The ceramic resonator dominates the oscillator size. The measured oscillator frequency and power are generally within 5–10 % of predictions.

Figure 12: Photograph of SMT Ceramic Coaxial Resonator VCO

Conclusions

Readily available harmonic balance simulators can be used to accurately predict the frequency, output power and harmonic content of RF and microwave oscillators. Phase noise can also be simulated, although values are highly dependent on the flicker noise parameters within the non-linear model. Many manufacturers still choose to omit flicker noise data in their supplied models. In the absence of a non-linear simulator, a relatively cheap small-signal simulator can still be used to predict frequency. Output power can be estimated by assuming 10-20% DC-to-RF efficiency. In reality, the small-signal simulation is vital to ensure that adequate negative resistance is available for start-up of oscillation. As a rule of thumb a negative resistance some 20% greater than the sum of the total positive resistances should be created. The small-signal simulation also illustrates the potential for unwanted or spurious frequencies of oscillation, at which the presence of negative resistance must be avoided.

References

1. "A Practical Introduction to Electronic Circuits"
    Jones, M. H.; © Cambridge University Press, 1982

2. "Oscillator Design and Computer Simulation"
    Rhea, R. W.; © Noble Publishing, 1995

3. "Design of Amplifiers and Oscillators by the S-parameter Method"
    Vendelin, G.;© John Wiley & Sons

4. "Crystal Oscillator Circuits"
    Matthys, R. J.; © Krieger Publishing Co., 1992

5. Epcos (Formerly Siemens Matsushita) "Ceramic Coaxial Resonators" Datasheet/Application note

6. "Phase Noise in Signal Sources"
    Robins, W. P.; © IEE Publication, 1984

7. "Microwave and Wireless Synthesizers"
    Rohde, U. L.; © Wiley-Interscience, 1997