# LINC2 Software Enhances the Design and Analysis of VCOs and Other Tunable RF and Microwave Circuits

By Dale D. Henkes, ACS

The most commonly used simulation programs and methods have become popular for good reasons; they have become essential tools for enabling the circuit designer to be more productive and to practice the trade successfully. SPICE based programs are appropriately used to analyze transient and circuit start-up behavior as current or voltage waveforms in the time domain. RF and microwave circuit simulation programs commonly display the circuit's s-parameters (or quantities related to these s-parameters) in the frequency domain. More advanced circuit simulation software will include additional methods of analyzing the circuit or viewing the resulting simulation data.

In addition to the customary frequency response analysis, this article will demonstrate a few other methods and simulation tools for enhancing the design and analysis of RF and microwave circuits. The LINC2 RF CAE (Computer Aided Engineering) software suite from ACS (Applied Computational Sciences, Escondido, CA) will be used to demonstrate the following:

- **Swept Variables and Circuit Component Parameter Sweeps**
  A circuit or component parameter can be swept through a range of values by assigning a variable to the parameter and performing a variable sweep. The circuit response can be viewed against the variable at any fixed frequency point.
- **User Defined Equations**
  New component models can be created or existing component models modified by user defined equations that formulate new relationships between variables and circuit parameters.
- **Special Output Functions for Post Processing Simulation Data**
  These special intrinsic functions provide new ways of processing and viewing simulation results. For example, finding and tracking the frequency point at which the maximum value of a circuit response occurs or tracking the frequency point for zero transmission phase during a variable parameter sweep.

In the following example, the design of a voltage-controlled oscillator (VCO) will be analyzed using these special simulation and analysis tools.

## Voltage-Controlled Oscillator (VCO) Example

The crystal oscillator circuit of Figure 1 has been reconfigured in Figure 2 so as to enable the oscillator to be analyzed by linear Bode (gain and phase response) techniques. The modifications include breaking the feedback path through the crystal, removing the crystal and connecting input and output ports at the circuit nodes where the crystal was attached. Breaking the feedback path and attaching source and load measurement ports allows for analyzing the oscillator as a phase shift network and amplifier cascade.

The oscillator will oscillate at the frequency where the total open loop phase shift equals zero degrees as long as there is sufficient positive gain (> 0 dB) in the vicinity around this zero-phase crossover point. Since the circuit can potentially oscillate at frequencies where the phase shift is multiples of 360 degrees, care should be taken to ensure that there is no positive gain (< 0 dB) at any undesired frequency where the loop phase shift is 0 or multiples of 360°. The frequency selective tank circuit formed by L1, C1, C2 and C3 ensures that the circuit meets the oscillation criteria at only the desired frequency.

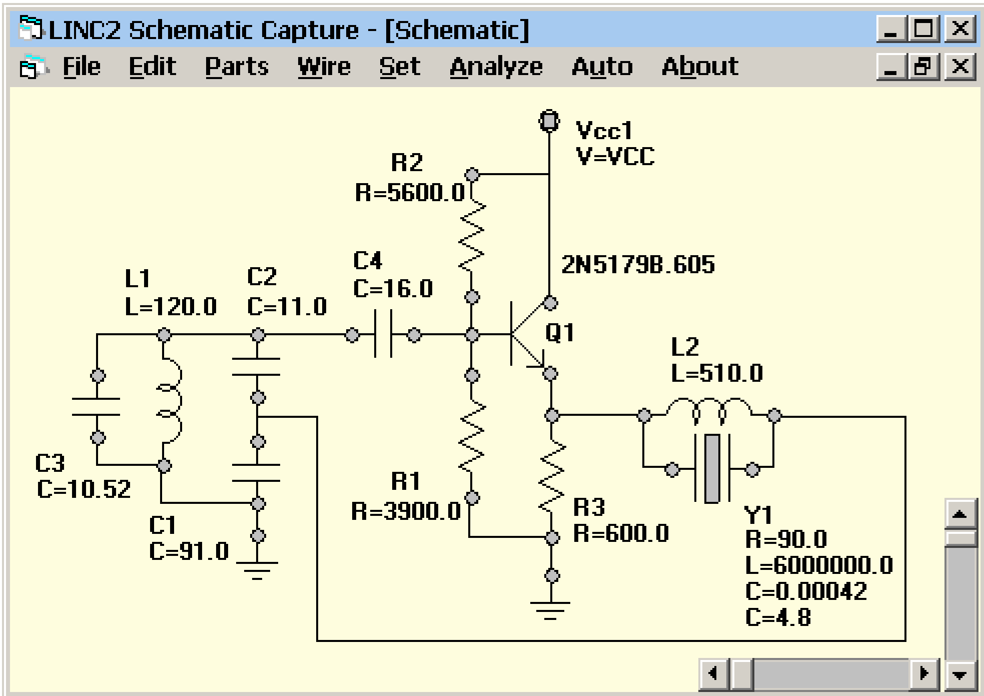


**Figure 1, 100 MHz Butler Crystal Oscillator**

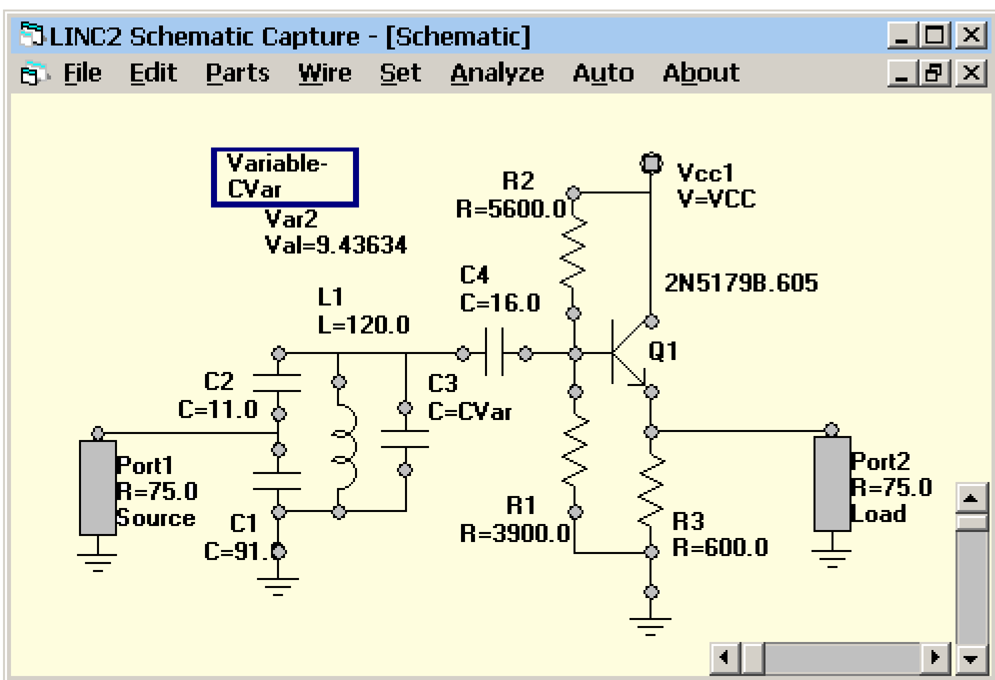


**Figure 2, LINC2 Schematic Setup for Oscillator Analysis**

In Figure 2, the crystal has been removed to allow for tuning the oscillator over a relatively wide frequency range. The tuning range for this example, using a varactor tuning diode, is around 30% (+/- 15% of the center frequency). The tuning range using other tuning methods may be larger.

**Circuit Simulation Using Variables for Tuning Control**

In LINC2 a named variable can be placed on the schematic page and assigned to one or more component parameters as needed. In this example, the variable CVar is given an initial value of 9.44 pF and assigned to the VCO tuning capacitor C3. This sets the oscillator's center frequency to 100 MHz. With the oscillator configured as in Figure 2, the linear gain/phase swept frequency response is displayed in Figure 3 for several settings of the variable tuning capacitor C3.

Interactive real-time tuning is convenient and easy to perform in a LINC2 graph window. Simply selecting the variable from the Tune menu and tapping the up or down arrow key increases or decreases the value of the variable while the plotted circuit response is immediately updated. With the variable CVar assigned to the capacitance value for C3, tuning CVar varies the frequency of oscillation (zero phase point) as shown in Figure 3.

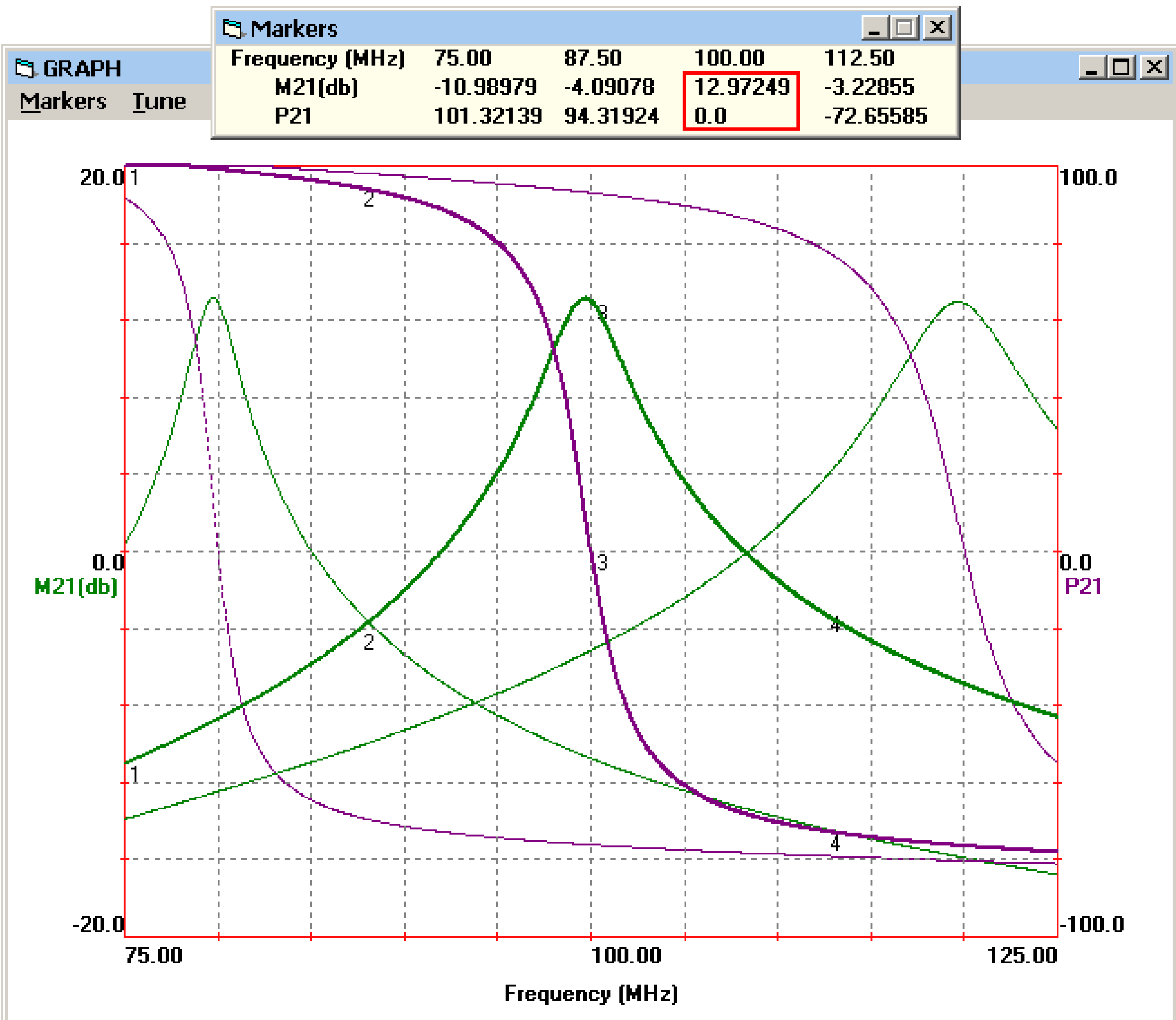


**Figure 3, LINC2 Oscillator Gain-Phase Frequency Response**

As is the case for a well designed oscillator of this type, the gain peaks at nearly the same frequency point at which the open loop transmission phase becomes zero. In Figure 3, the three gain peaks and phase zero pairs occur at 80 MHz, 100 MHz and 120 MHz for CVar (tuning capacitor C3) values of 21.4 pF, 9.44 pF and 3 pF respectively. This suggests the following way to determine the VCO tuning range for a given range of tuning capacitance:

Set the variable CVar to its largest value and note the resulting frequency corresponding to zero open loop transmission phase (P21 = Phase Angle[S21] = 0). Then, set CVar to its smallest value and again note the frequency at which P21 = 0. The difference between these two frequency points is the tuning range.

For CVar = 21.4 (pF), P21 = 0 occurs at 80 MHz. When CVar is tuned to 3 (pF), the P21 = 0 point shifts upward to 120 MHz. The result is a 40 MHz frequency range (centered at 100 MHz) for tuning capacitance ranging from 3 pF to 21.4 pF. This amounts to a 40% tuning range over frequency for a 7 to 1 ratio in tuning capacitance. A more direct and automatic method for determining the VCO tuning range will be demonstrated next, after introducing the use of swept variables.

### Using Swept Variables in Circuit Simulations

Instead of manually tuning a component parameter using a variable as in the previous section, the variable can be set up to automatically sweep over its entire range of values while the circuit response is plotted as a function of the swept variable. As shown in Figure 4, the LINC2 program provides a checkbox for enabling a variable parameter sweep, resulting in an ordinary variable being converted to a swept variable. The parameters of a swept variable are its nominal value, the starting value, the stop value and number of sweep points.

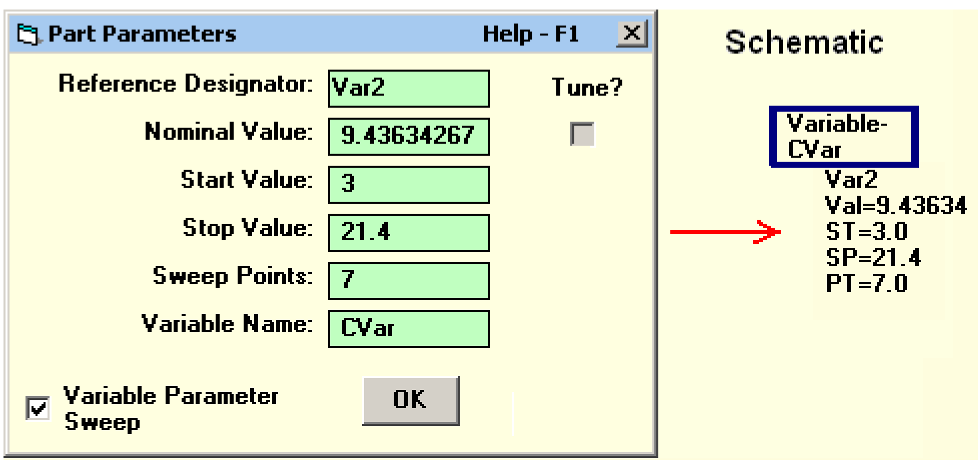


**Figure 4, LINC2 Swept Variable Setup**

### Variable Parameter Sweeps and LINC2 Special Output Functions

There are a number of special built-in functions in the LINC2 program for post processing of the simulation data. The **Zero[Data]** function finds the frequency at which the selected data has a value of exactly zero. The function continues to find all frequency points corresponding to zero data values in the simulation data for each value of a swept variable, thus generating an array of frequency points. The result is a plot of frequency (vertical axis) versus a selected variable (horizontal axis). The meaning of “frequency” in this example is the frequency of oscillation (Frequency[P21 = 0]) for each value of the tuning capacitance.

As just described, the **Zero[P21]** function will be employed in this example to plot the VCO oscillation frequency as a function of the tuning capacitor's swept capacitance value (CVar). Since the P21 = 0 value (zero transmission phase point) shifts in frequency as the swept variable (CVar) is automatically stepped through its values, plotting the frequency of zero P21 against this variable will plot out the VCO's tuning response. This unique LINC2 function produces the oscillator's tuning response to the tuning capacitance CVar as shown in Figure 5.

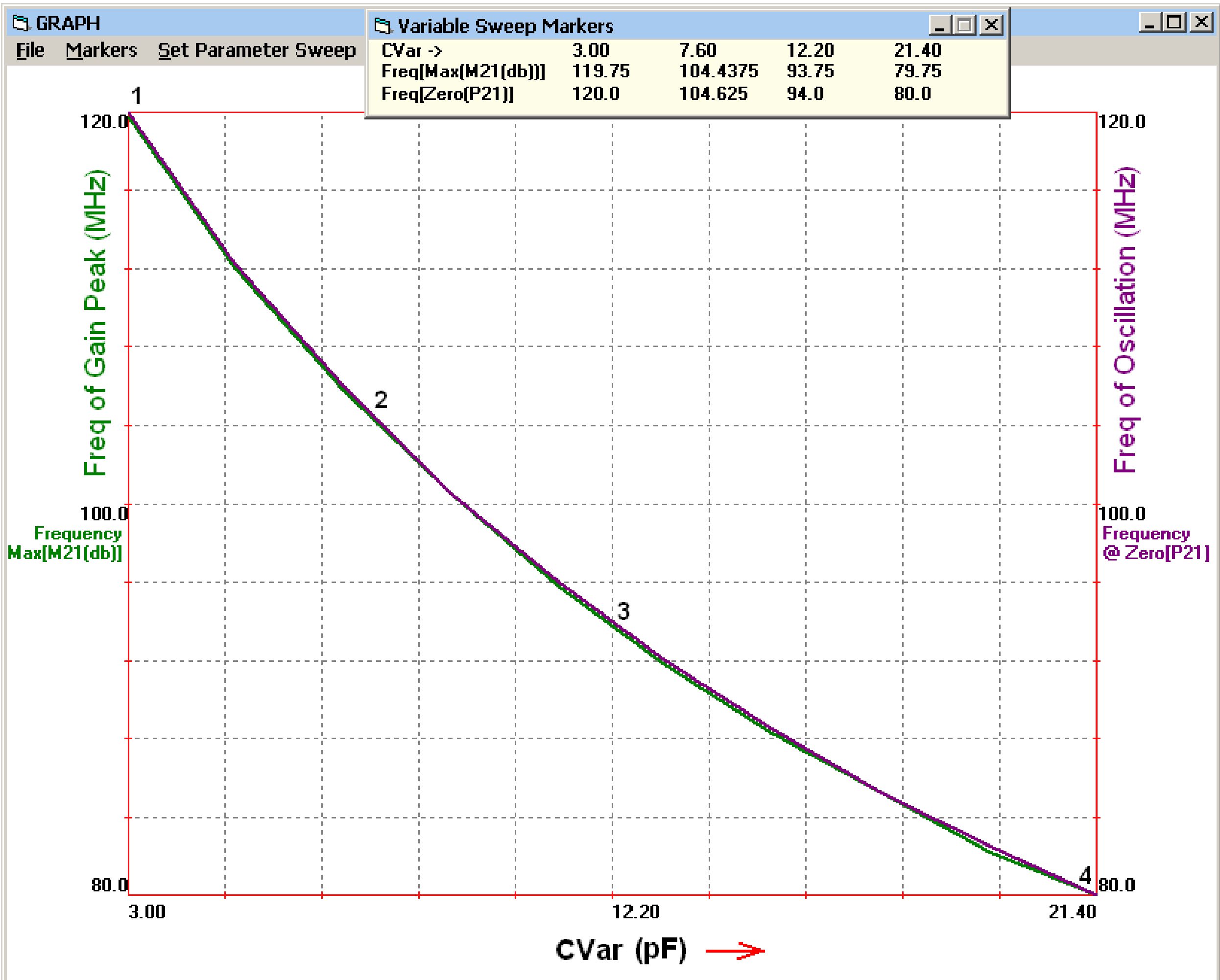


**Figure 5, The VCO's Oscillation Frequency as a Function of the Tuning Capacitance**

The oscillation frequency (Freq[P21=0]) is plotted on the right vertical axis while the frequency at which the gain peaks is plotted on the left vertical axis as a function of the tuning capacitance (CVar). These two plots almost completely overlap because the gain peaks (Max[S21(dB)]) occur at nearly the same frequency as the zero phase point (see Figure 3).

Comparing Figure 5 to Figure 3, Figure 5 shows the VCO's tuning response to the tuning capacitance in a much more direct and clearer way. In Figure 5 the oscillator's tuning characteristics are captured and displayed in a simple easy to visualize graphical format.

**Creating New Circuit Models with User Defined Equations**

The tunable oscillator schematic in Figure 2 uses a variable (CVar) to control the tuning capacitance (C3). The variable capacitor C3 might be implemented in a number of different ways. This example will use a varactor tuning diode to accomplish voltage-controlled tuning of the oscillator, making it a VCO (or Voltage-Controlled Oscillator). The diode's capacitance as a function of its tuning voltage can be simulated by using a user defined equation in LINC2. A useful approximation for the varactor diode's voltage to capacitance transformation is given by [1]:

Equation 1) $C(V_R) = C_{J0}/(1 + V_R/V_J)$^M + $C_P$, where $C_{J0}$ is the diode's zero-bias junction capacitance, $V_R$ is the applied reverse DC bias voltage, $V_J$ is the junction potential, M is a device dependant constant called the grading coefficient, and $C_P$ is the device package capacitance.

Using an equation to model the diode may be preferred over using a built-in schematic model because it defines the function explicitly and there is almost no limit to the model details and complexity that can be embodied in the equation. Moreover, it is easy to edit the equation model to accommodate the characteristics of a different device. Figure 6 shows a LINC2 schematic of the VCO with the varactor (represented by C3) modeled by equation CVarEqn.

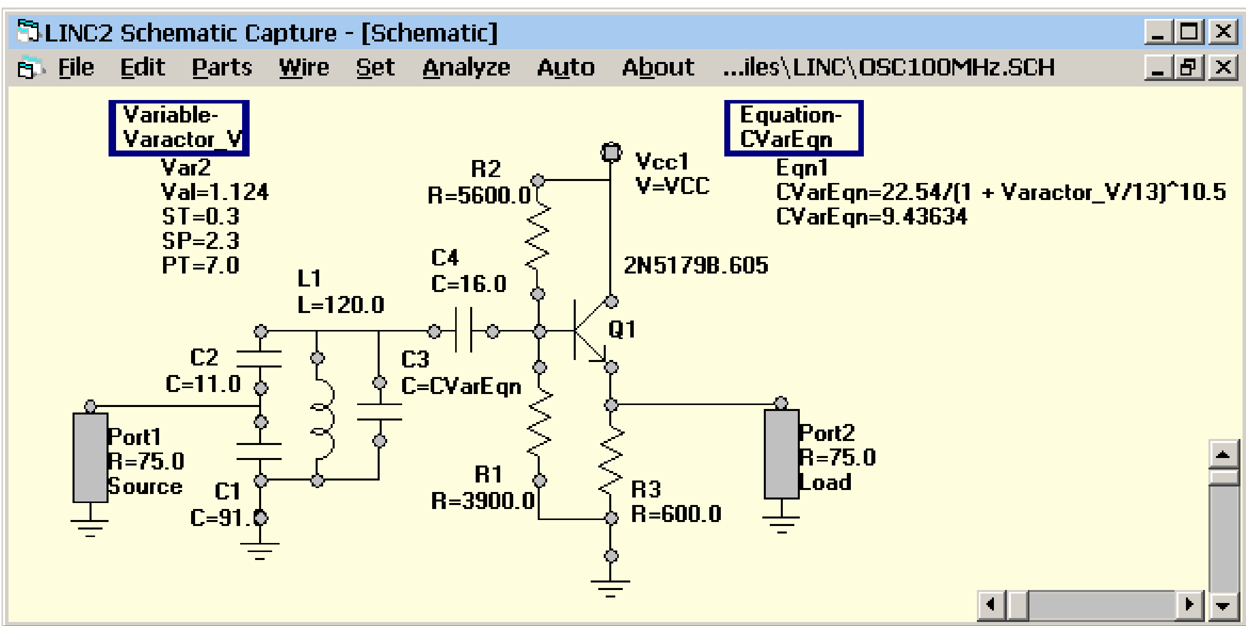


**Figure 6, LINC2 VCO Schematic with Varactor Equation Model**

In the schematic (Figure 6), the variable CVar (from Figure 2) has been replace with the equation CVarEqn that models the varactor's capacitance as a function of its DC bias voltage. The equation uses the model parameters given in [1] for the SMV1248 diode. The diode model parameters were extracted from measured $C_V(V_R)$ data. More complete models may include at least some series resistance and package inductance and these parasitic components could also be included explicitly on the schematic.

A simulation run on the circuit in Figure 6 will produce a conventional frequency response plot as in Figure 3 with the exception that, instead of varying the capacitance directly, the VCO is tuned by varying the varactor voltage (via the Varactor_V variable in the schematic). However, the LINC2 simulator also produces the characteristic tuning plot shown in Figure 7. This graph window simultaneously plots the VCO's tuning response (Zero[P21]) and the equation (CVarEqn) that describes the tuning diode's capacitance, both as a function of the varactor DC bias voltage (Varactor_V).

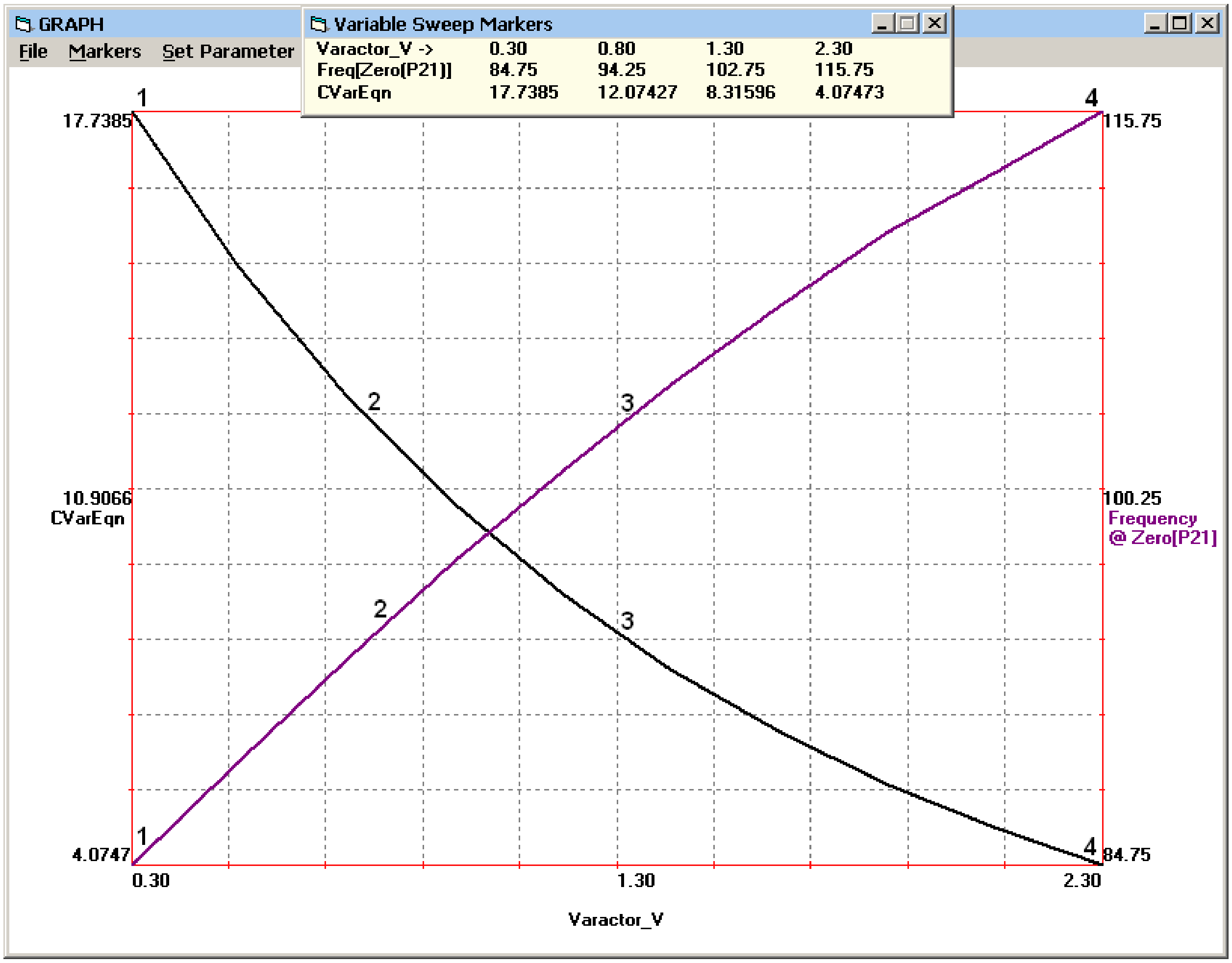


**Figure 7, The VCO's Tuning Characteristics as a Function of Varactor Voltage**

Comparing the tuning frequency response in Figure 7 to that in Figure 5, the following observations can be made. The tuning frequency slope in Figure 5 is negative because the tuning capacitance is increasing to the right, lowering the frequency of oscillation. However, in Figure 7 the tuning frequency slope is positive because it is plotted as a function of the varactor voltage. As the varactor voltage increases to the right, the varactor capacitance decreases (and the frequency of oscillation moves higher).

Figure 7 indicates that the VCO's tuning frequency is a slightly upward curving function of the tuning voltage (relative to a straight line) whereas the tuning diode's capacitance curves downward in a non-linear curve characteristic of the exponential nature of the diode's voltage to capacitance relation (Equation 1). With this plot, it can see at a glance that the VCO can be tuned between 84.75 MHz and 115.75 MHz with a tuning voltage ranging between 0.30 volts and 2.30 volts. The corresponding varactor tuning capacitance will range between 4.07 pF and 17.7 pF respectively. Markers placed on the plots have their numerical values displayed at the top of the graph for various values of varactor voltage.

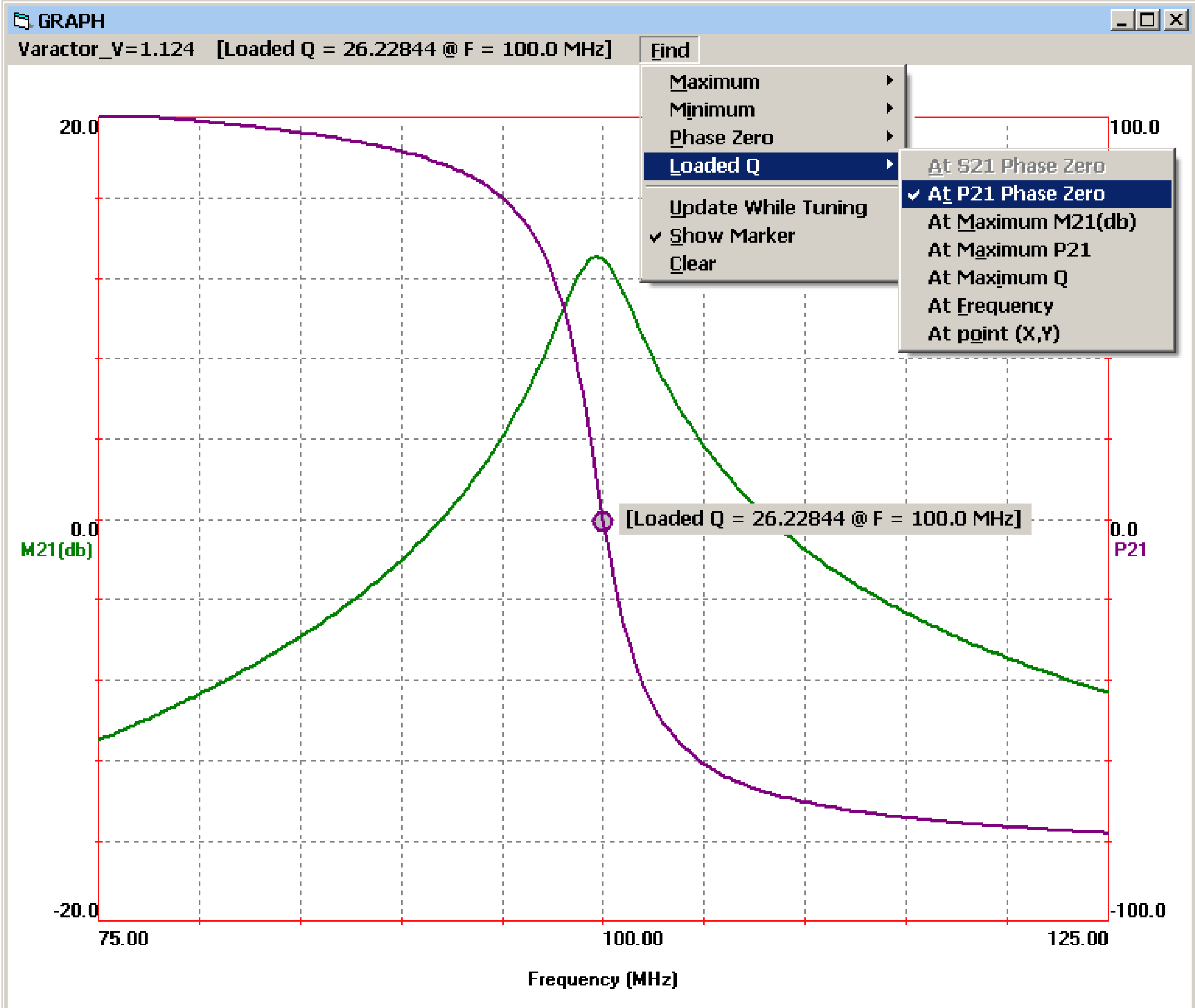


**Figure 8, LINC2 Automatically Calculates the Loaded Q of the Oscillator**

## Summary of LINC2 VCO Analysis

The LINC2 program provides new ways to analyze and characterize the VCO's response to tuning control. For example, in Figure 7 the linearity of the VCO's tuning control can be seen at a glance. The required control voltage range and tuning capacitance range can also be immediately determined from the graph by inspection.

When a user defined equation is part of a LINC2 schematic (such as equation CVarEqn in Figure 6), the equation can be plotted simultaneously on the same graph along with the simulation data. For example, in Figure 7 the plot of equation CVarEqn shows the tuning diode's $C_V(V_R)$ characteristics and how they relate to the overall tuning characteristics of the VCO.

In addition to these new LINC2 output functions and analysis techniques, the conventional frequency sweeps (as in Figure 3 and Figure 8) of S21 (Gain) and P21 (Phase) yield important additional information about the VCO and its quality of performance. For example, in Figure 8 the **Find** menu can be used to locate the frequency of oscillation and calculate the loaded Q for the oscillator. **Find > Loaded Q > At P21 Phase Zero** places a small circle on the phase (P21) curve at the frequency point where the VCO will oscillate for the given value of tuning voltage/capacitance. This is also the point where the loaded Q is calculated. The loaded Q is one of the most dominate factors in determining the phase noise of the oscillator. The LINC2 GRAPH window (Figure 8) reports a loaded Q of 26.23 for the VCO at 100 MHz.

This article has repeatedly cited the open loop phase zero point as the indicator for the frequency of oscillation. This concept can be found in reference [2] under the subject Oscillation Conditions (Chapter 1). Reference [2] refers to the closed loop phase of 0° (or a multiple of 360°) as one of the requirements for oscillation. Indeed, the loop is closed in the actual oscillator circuit. This article refers to the open loop phase zero requirement because the (amplifier-feedback) loop is broken and the cascade is simulated open-loop for analysis purposes. Reference [2] also refers to the gain condition for oscillation, which was mentioned earlier as an additional requirement for oscillation, that there should be sufficient positive gain at the zero-phase point.

The circuit theory, such as presented in reference [2], is an excellent source to acquire an understanding of the circuit operation and design requirements. Moreover, it is gratifying to verify the theory through circuit simulation and actual hardware built. The author has used the LINC2 program to design a crystal controlled version of this oscillator. The oscillator was then built and employed in an up-converter in communication equipment for a satellite uplink.

When different simulation programs are available and time permits, it is a good idea to verify the circuit using a different kind of simulator. There are many versions of the SPICE program available (and some are available free of charge). The inner workings of the way SPICE analyzes a circuit are very different from the way RF EDA programs (such as LINC2) perform circuit simulation. And yet, as one would hope and expect, the results are the same- though presented from a different viewpoint (i.e. in the time domain for SPICE and the frequency domain for LINC2). The same circuit analyzed by the LINC2 program (in Figures 2 and 6) was entered into Linear Technology's LTSpice program [3] and a SPICE simulation was run. The results are shown in Figure 9.

The SPICE simulation in Figure 9 shows the startup transient after 300 ns and continuing on until the oscillations eventually stabilize another 200 ns later. There are two complete cycles for every 20 ns time period, for a frequency of 100 MHz. An oscillation frequency of 100 MHz was exactly as predicted by the zero phase (P21=0) point on the LINC2 simulation in Figure 8. This completes the analysis of the voltage-controlled oscillator.

**The LINC2 Software Suite**

LINC2 is a high performance RF and microwave design and simulation program from ACS. In addition to schematic based circuit simulation, optimization and statistical yield analysis, LINC2 Pro includes many value-added features for automating design tasks, including circuit synthesis.

LINC2 directly interfaces to leading RF and microwave design suites, allowing it to be used stand-alone or by leveraging its capabilities with those of other major packages. LINC2 offers exact circuit synthesis, schematic capture, circuit simulation, circuit optimization and yield analysis in a single affordable design environment. More information about LINC2 can be found on the ACS web site at www.appliedmicrowave.com.

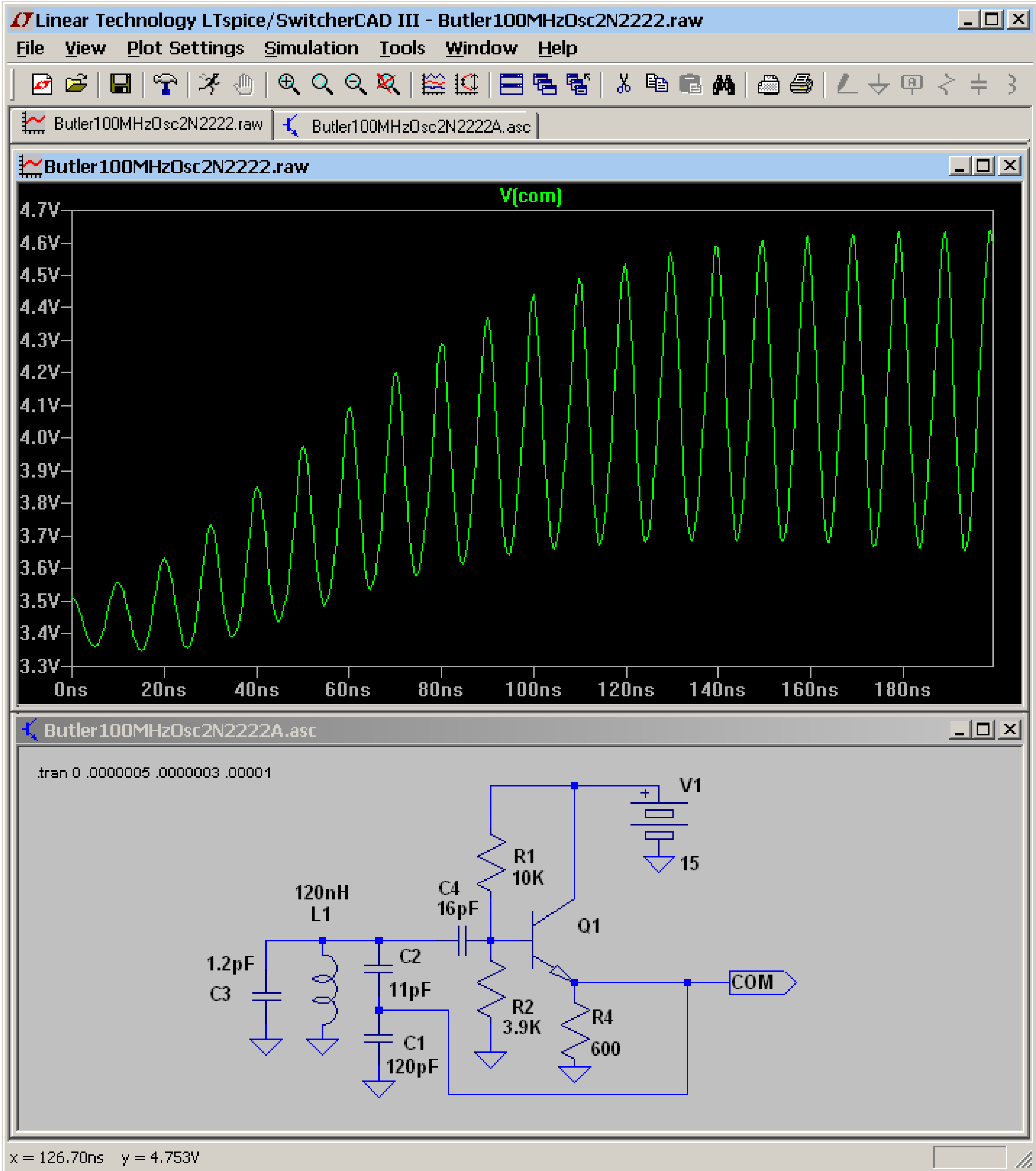


**Figure 9, LTSpice Version of the Oscillator Simulation**

**References**

1. Application note APN1004, Alpha Industries.
2. Foundations of Oscillator Circuit Design, Guillermo Gonzalez, Artech House 2007, Chapter 1, Section 1.2, Oscillation Conditions.
3. The LTSpice/SwitcherCAD III program was provided courtesy of Linear Technoloy, www.linear.com.