Software Enhances the Design and Analysis of Tunable Circuits

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> **Equations with swept variable values enable tunable components to be represented for the simulation and analysis of tunable circuits**

Modern EDA software has evolved over the years to provide some very powerful tools for the design and simulation of almost any kind of RF and microwave circuit or system. One aspect of current EDA software that makes it so powerful is the speed at which it can perform calculations, rendering simulations and detailed analysis reports in record time. Another aspect of the power and utility of this kind of software lies in the richness of the tools, capabilities and features that the software provides. Software packages with expanded toolsets, multi-function modules and collections of programs oriented toward performing different but related phases of the workflow are referred to as software suites.

These full-featured EDA software suites can be complex, making it difficult to find and use many of the less common features. Sometimes even relatively experienced users are not aware of all the features and capabilities contained in the software. This article will employ a microwave filter design example to highlight how less commonly used EDA tools and methods can, nevertheless, significantly enhance circuit analysis.

RF and microwave circuit simulation programs commonly display the circuit's *S*-parameters (or quantities related to these *S*-parameters) in the frequency domain. The more advanced circuit simulator will include additional methods of analyzing the circuit or viewing the resulting simulation data. In addition to the traditional frequency response analysis, this article will demonstrate a few other tools and simulation methods for the enhanced design and analysis of RF and microwave circuits. The LINC2 EDA software suite from ACS (Applied Computational Sciences) will be used to demonstrate the following:

- *Circuit Parameter Sweeps/Variable 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. Information related to the frequency at which maximum transmission occurs is particularly useful for analyzing tunable filters, while information about the frequency at which zero transmission phase occurs is useful for the open loop analysis of oscillator circuits.

In the following example, the design of a tunable bandpass filter will be analyzed with
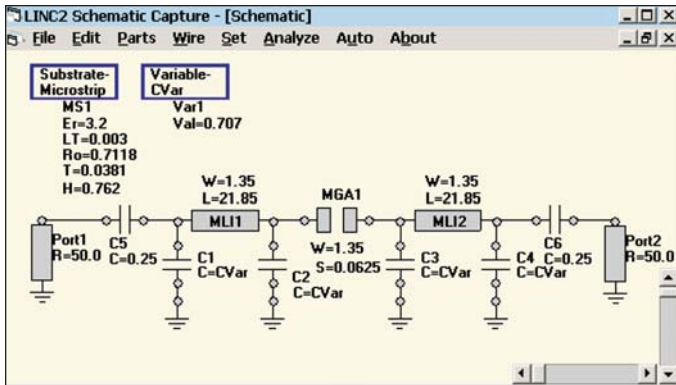
Figure 1 · End-coupled microstrip bandpass filter.

Figure 2 · The tunable filter's frequency response for three selected values of CVar.

these special simulation and analysis tools. The example will start with the usual frequency response analysis (the results of which are displayed in Fig. 2) and then contrast this view of circuit performance with the additional visualization methods.

Tunable End-Coupled Microstrip Bandpass Filter Example

The general design of the capacitive gap end-coupled microstrip bandpass filter is given in [1]. The end-coupled resonator topology was chosen for simplicity of tuning. It is easy to place shunt tuning capacitors between the ends of the microstrip resonators and ground using surface mount technology. Ideally, the coupling capacitance between resonators should also be tuned. The consequences of not simultaneously tuning both the resonators and the coupling between them is that the insertion loss and relative bandwidth will vary with frequency as the filter is tuned. The following simulation results show that these effects were observed only to a small degree. The insertion loss varied by only 1.5 dB over a 40% tuning range, while the relative bandwidth remained nearly constant.

The schematic, after optimization for a center frequency of 2.5 GHz is shown in Figure 1. In Figure 1, a microstrip gap (MGA1) is used to capacitively couple the two resonators, while C5 and C6 couple the signal in and out of the filter respectively. All physical dimensions in the schematics are in millimeters (mm).

In some designs, C5 and C6 could also be implemented as microstrip gap capacitors. However, because the required capacitance is relatively large in this case, the gap would be too narrow to fabricate reliably unless a multi-gap structure such as the interdigital capacitor is used [2].

C1 through C4 are variable capacitors that load the ends of each resonator strip to vary the effective electrical length of the resonator for tuning purposes. The tuning capacitors (C1-C4) may be implemented using varactor
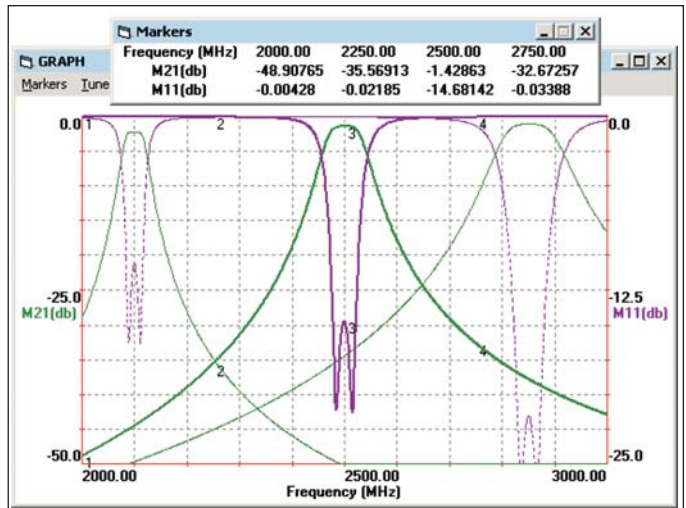
diodes. As the tuning capacitance increases, the effective resonator length is increased, resulting in the bandpass filter shifting to a lower frequency [3].

Using Variables in Simulation for Tuning Control

In LINC2 a variable can be placed on the schematic page and assigned to as many component parameters as needed. In this example, the variable CVar is given a nominal (initial) value of 0.707 pF and assigned to capacitors C1 through C4. In this way, all four tuning capacitors are ganged together and tuned simultaneously with the same value, as would be the case with four identical varactor tuning diodes all driven with the same (variable) bias voltage.

Figure 2 shows the filter response centered at 2.5 GHz for CVar = 0.707 pF. The markers show the numerical values for the magnitude of S_{21} (M_{21} in dB) and input return loss (M_{11} in dB) for the filter centered at 2.5 GHz. Figure 2 also shows the responses for CVar tuned to 1.21 pF and 0.425 pF, resulting in bandpass responses centered at 2100 MHz and 2850 MHz, respectively.

Determining the tuning capacitance range required to tune the filter's response between 2 GHz and 3 GHz is easy. This is accomplished using LINC2 by simply selecting CVar from the Tune menu and pressing the up or down arrow keys to increase or decrease its value. The filter's response moves across the LINC2 Graph Window in real time as CVar is tuned interactively. Noting the value of CVar when the filter is tuned to 2 GHz and then again when it is tuned to 3 GHz yields the range of the tuning capacitance required to tune the filter between these two extremes. The result is a tuning capacitance range between 0.3 pF and 1.4 pF.
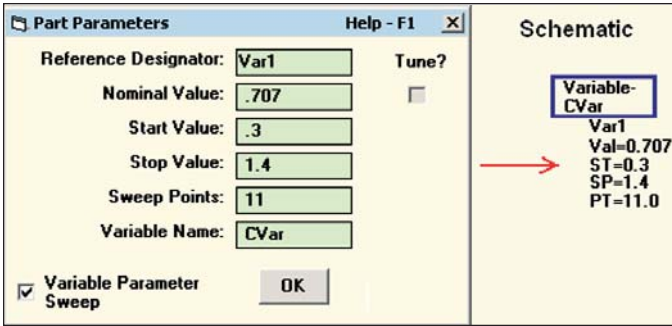
Figure 3 · LINC2 swept variable setup.

Figure 4 · Tunable bandpass filter's frequency response as a function of the tuning capacitance.

Using Swept Variables in 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 3, the LINC2 program provides a checkbox for enabling a variable parameter sweep, thus turning an ordinary variable into a swept variable. The parameters of a swept variable are its nominal value, the starting value, the stop value and number of sweep points.

Special Output Functions and Variable Parameter Sweeps

The LINC2 program provides a number of special built-in functions for post processing of the simulation data. This example will employ the Maximum function for plotting the bandpass filter's center frequency as a function of the tuning capacitor's swept capacitance value (CVar). The way this function works is that for each value of the swept variable the program finds the frequency for which the selected data is a maximum. This frequency data is then plotted as a function of the swept variable.

The data of interest for the bandpass response is the maximum value of S_{21}, which occurs within the passband of the bandpass filter. Since the S_{21} maximum value (peak in the bandpass response) shifts in frequency as the swept variable (CVar) is stepped through its values, plotting the frequency of maximum $|S_{21}|$ against this variable will plot out the filter's tuning response. This unique LINC2 function produces the filter's tuning response to the tuning capacitance CVar, as shown in Figure 4.

Comparing Figure 4 to Figure 2, Figure 4 is a much clearer way to display the tunable filter's response to the tuning capacitance value. In Figure 4, the filter's tuning characteristics are captured and displayed in a simple, easy to read graphical format.

Using Equations to Create New Circuit Models

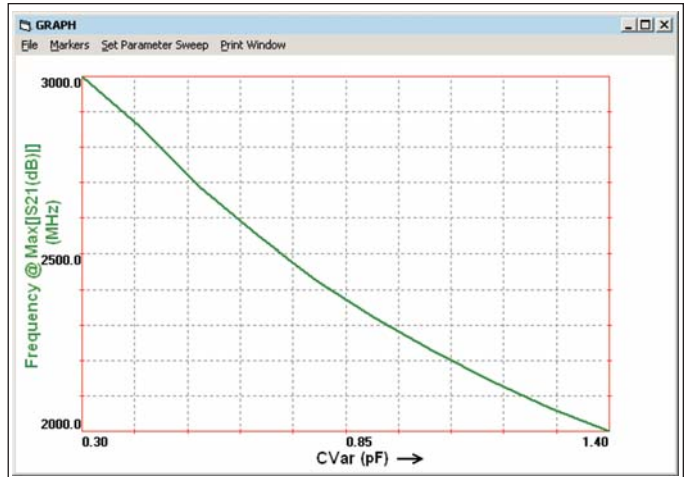The tunable filter schematic in Figure 1 uses a variable to control the tuning capacitance. However, what is needed is a physical method of controlling the tuning capacitance. Varactor tuning diodes can accomplish this. The diode's capacitance as a function of its tuning voltage can be simulated by using a user-defined equation in LINC2. A useful approximation for the varactor diode's voltage to capacitance transformation is given by [4]:

$$C(VR) = CJ0/(1 + VR/VJ)^{\wedge}M + CP \qquad (1)$$

where CJ0 is the diode's zero-bias junction capacitance, VR is the applied reverse DC bias voltage, VJ is the junction potential, M is a device dependent constant called the grading coefficient, and CP 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 5 shows a LINC2 schematic representation of the varactor tuned filter.

In the schematic (Fig. 5), the variable CVar (from Fig. 1) has been replaced with the equation CVar that models the varactor's capacitance as a function of its DC bias voltage. The equation uses the model parameters given in [4] for the SMV1248 diode. The diode model parameters were extracted from measured CV(VR) 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.

In Figure 5, L1 through L4 feed the DC tuning voltage (Varactor_V) to the four tuning varactors C1 through C4 (modeled by CVar). If the only concern is providing DC to bias the varactor diodes, then L2 and L3 are redundant.
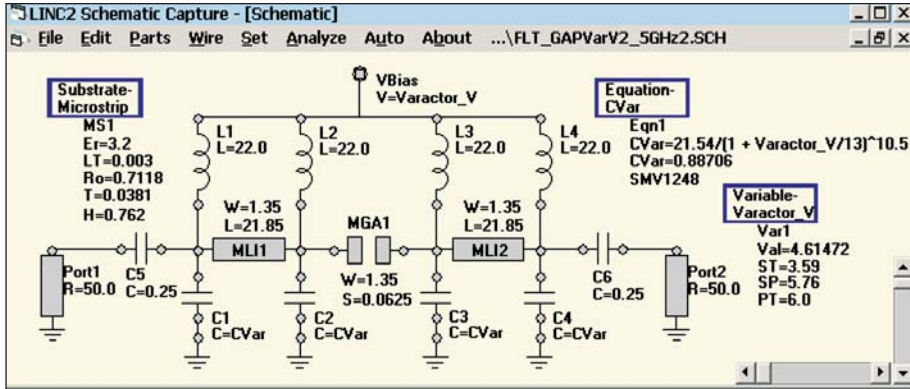
Figure 5 · Varactor tuned bandpass filter schematic for simulation.

L1 alone is sufficient to feed the DC tuning voltage to C1 and C2 through microstrip line MLI1. Likewise, L4 is sufficient to feed DC to C3 and C4 through microstrip line MLI2. However, placing all four inductors in the circuit ensures that each varactor tuning capacitor combined with the inductance (and parasitic capacitance) of the inductor produce nearly the same capacitance at each end of the microstrip resonators. A simulation was run with only L1 and L4 present with the undesirable result of reduced tuning range.

A simulation run on the circuit in Figure 5 will produce a traditional frequency response plot as in Figure 2 with the exception that, instead of varying the capacitance directly, the filter 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 6. This graph window simultaneously plots the filter's tuning response and the equation (CVar) that describes the tuning diode's capacitance, both as a function of the varactor DC bias voltage (Varactor_V).

Comparing the tuning frequency response in Figure 6 to that in Figure 4, the following observations can be made. The tuning frequency slope in Figure 4 is negative because the tuning capacitance is increasing to the right. However, in Figure 6 the tun-

ing 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 filter passband moves higher in frequency).

Figure 6 indicates that the filter's tuning frequency is almost a linear function of the tuning voltage whereas the tuning diode's capacitance is a non-linear curve characteristic of the exponential nature of the diode's voltage to capacitance relation (Eq. 1). With this plot we can see at a glance that the filter can be tuned between 2000 MHz and 3000 MHz with a tuning voltage ranging between 3.59 volts and 5.76 volts. The corresponding tuning capacitance (per diode) will range between 1.66 pF and 0.46 pF, respectively. Markers placed on the plots have their numerical values displayed at the top of the graph for various values of varactor voltage.

Tunable Bandpass Filter Summary

This completes the analysis of the tunable bandpass filter. The LINC2 program provides new ways to analyze and characterize the filter's response to tuning control. For example, in Figure 6 the linearity of the filter'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.
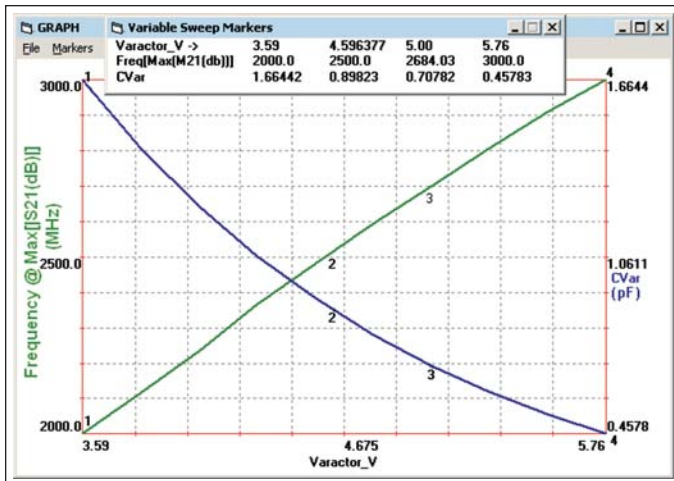
Figure 6 · The bandpass filter's tuning characteristics as a function of varactor voltage.

When a user-defined equation is part of a LINC2 schematic (such as equation CVar in Fig. 5), the equation can be plotted simultaneously on the same graph along with the simulation data. For example, in Figure 6 the plot of equation CVar shows the tuning diode's CV(VR) characteristics and how they relate to the overall tuning characteristics of the filter.

In addition to these new LINC2 output functions and analysis techniques, the conventional frequency sweeps of S_{21} and S_{11} (as in Fig. 2) yield additional important information about the filter and its response to tuning. For example, in Figure 2 it can be seen that the bandwidth grows with frequency as the filter is tuned, but the relative bandwidth (as a percentage of the center frequency) remains relatively constant. Also, Figure 2 indicates that the insertion loss and return loss improve with frequency. The insertion loss ranges from 2.5 dB at the low end of the tuning range to approximately 1 dB at the high end.

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.

References

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