

Using PARAMETER SWEEP to design a new class of varactor diode

by Dennis Mitchell

MMICAD's exclusive PARAMETER SWEEP function opens new possibilities for RF and Microwave design engineers. This application note shows how this built-in feature of MMICAD can be used to help design a varactor diode with linear tuning characteristics.

The linearity of voltage controlled oscillators is dictated by the varactor diode tuning characteristic. Ever since the varactor diode has been in use for tuning VCOs, the VCO designer has had little to choose from. The engineer's choices were primarily limited to the abrupt junction characteristics of silicon diodes. Various varactor diodes would be tried until he happened on the diode whose C-V profile was "within spec". Hyperabrupt tuning varactors are a fairly recent innovation and offer 'faster' tuning, i.e.: a greater change of capacitance with a smaller change in voltage, but do not directly address linearity.

GaAs varactors are now also available but these new devices do not address the linearity problem and are often to be avoided when PTD (Post Tuning Drift) problems are an issue.

The engineer responsible for VCO design today can no longer afford the "hit or miss" approach to selecting varactor diodes. Production cannot afford to 'tweak' their circuits to compensate for inherently non-linear varactor diodes. Now, with MMICAD, it is possible to specify a C-V specification for a varactor tuning diode that will produce optimum results for you, the designer. Different C-V 'profiles' for this new varactor can then be used in MMICAD's simulation of a complete oscillator circuit to accurately describe the total Frequency vs. Voltage tuning characteristics.

First, we need a mathematical model which describes varactor diodes in terms of capacitance change vs. reverse bias voltage.

$$C_v = C_0 / (1 + V_r / \phi)^{\gamma}$$

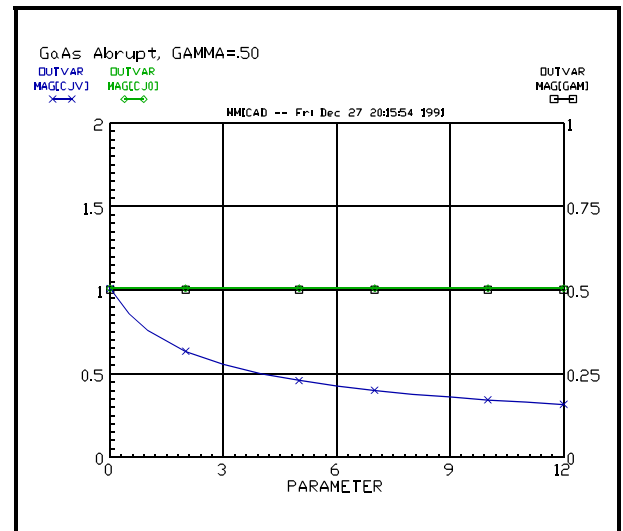


Figure 1

Figure 1 uses MMICAD to plot a typical abrupt junction varactor diode C-V curve. Only a few lines of MMICAD code were required to set up the Figure 1 graph and plot the equation. It should be noted that this equation cannot accurately describe the more complicated doping profiles such as hyperabrupts. The exponent 'γ' is typically 0.47 for Si abrupt junctions and 0.50 for some GaAs abrupt junction varactors, but can vary considerably depending upon doping profiles. GaAs varactors with 'constant γ' have been produced with γ's of 1.0, 1.25 and 1.50. These devices tend to offer 'faster' tuning rates, but offer no direct improvement in terms of controlled linearity. Figure 1 also plots γ on the right hand vertical axis and it will be shown that it is the control of γ during epitaxial growth which will yield a linear tuned varactor diode.

Solving for γ...
$$\gamma = \frac{\log[C_0/C_v]}{\log[1 + V_r/\phi]}$$

where C_0 =Capacitance at 0 volts
 C_v =Capacitance at bias voltage
 V_r =Reverse bias voltage
 ϕ ='built in' potential; Si = .7 GaAs = 1.3

When we use the abrupt junction diode described in Figure 1 in an actual oscillator circuit we can see how non-linearly it behaves. Typically, if a designer were to use this diode for a circuit which required linearity, the designer would have to select a small portion of the curve where it was most linear. In many cases, the designer is sometimes forced into a totally different circuit block diagram to compensate for a lack of linearity. Modulating at half frequency and then multiplying up is popular for FM microwave radios for example.

Figure 2 shows the Frequency vs. Tuning Voltage response from the Figure 1 abrupt junction diode.

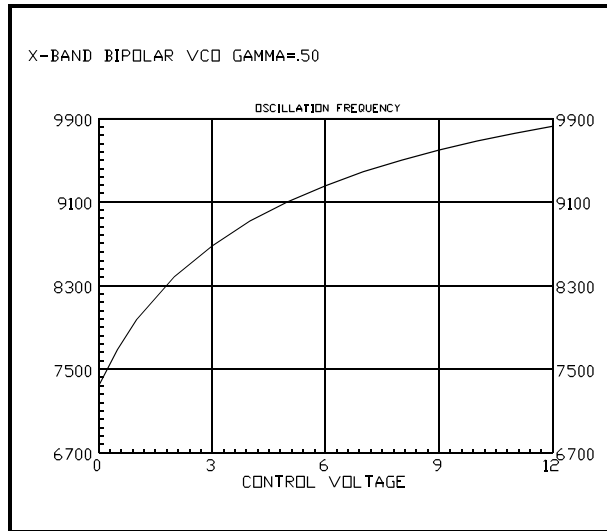


Figure 2

The sample oscillator used is an X-Band Bipolar using an NEC NE68100 chip transistor in common base, with resonator in the emitter lead and power taken from the collector. MMICAD's **MODE OSC** is used to plot F vs. V with great accuracy and simplicity. The varactor diode MMICAD code for our varactor user defined model is shown below.

```

MODVAR V=4 Cj0=1.0 !Default variable values
LOCVAR Vb=1.3      !Local variable for φ
LOCVAR Gamma=.5    !Local variable for γ
CAP 1 2 C={Cj0/(1+V/Vb)^Gamma}
DEF2P 1 2 VARAC (V Cj0)

```

It is now possible to use the new 2-Port named VARAC with the circuit description of our oscillator.

```
VARAC 20 21 0 v=PARAM Cj0=Cvar
```

Notice the keyword PARAM. This is exclusive to MMICAD and allows a parameter to be passed to VARAC which can then be swept by invoking the command in the PARAM command block.

PARAM

```
sweep 0 12 1
```

This allows the varactor to be automatically swept from the range specified within PARAM, namely 0 to 12 in increments of 1. VARAC is also passed a parameter Cvar, which is an initial variable value for the capacitance of the varactor in use, measured at Cj0.

A measure of how linear an oscillator is, and the varactor diode which dictates the response, is to compute the modulation sensitivity from the Freq. vs. Tuning voltage data. MMICAD does this automatically for the user as part of MODE OSC. By adding one more command line to the GRID block, MMICAD computes and plots Modulation Sensitivity.

GRID

```

...
...
OSC_S 0 12 0 1040

```

Here MMICAD plots sensitivity from 0 to 12 volts and 0 to 1040 MHz/V. If this device were "linear" it would have a constant modulation sensitivity. Figure 3 is non-linear but very typical of an abrupt junction varactor oscillator.

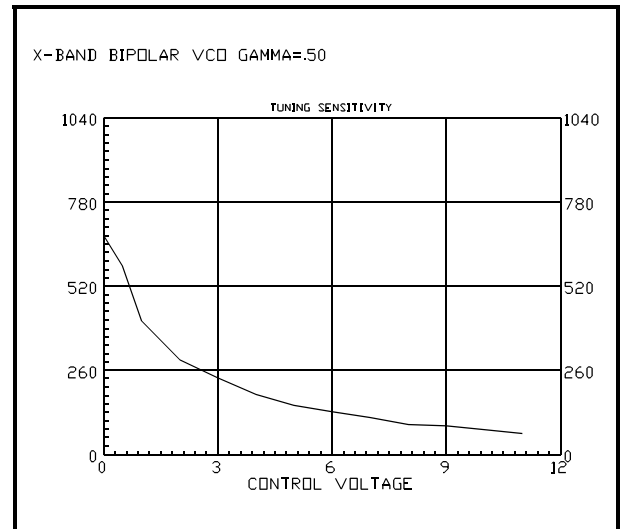


Figure 3

The accuracy of using MODE OSC with our varactor model was tested using GaAs constant gamma varactors also. The same equations which described the abrupt junction can also describe the constant gamma varactors, by simply changing gamma, γ.

Figure 4 and 5 show how this same oscillator performs when a constant gamma varactor is the only change. When gamma is increased it has the effect of making tuning 'faster' but not necessarily linear. In high volume applications, the constant

gamma diodes may present a problem with repeatability due to circuit variables having a greater effect on the higher MHz/V tuning rates of these diodes with higher constant gamma. What is required for linearity and greater repeatability of production oscillator circuits is a varactor diode that is inherently linear without compromise.

Designing a Linear Varactor

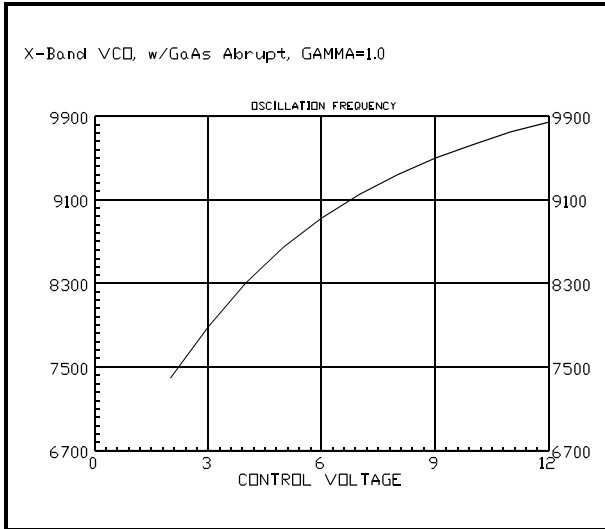


Figure 4

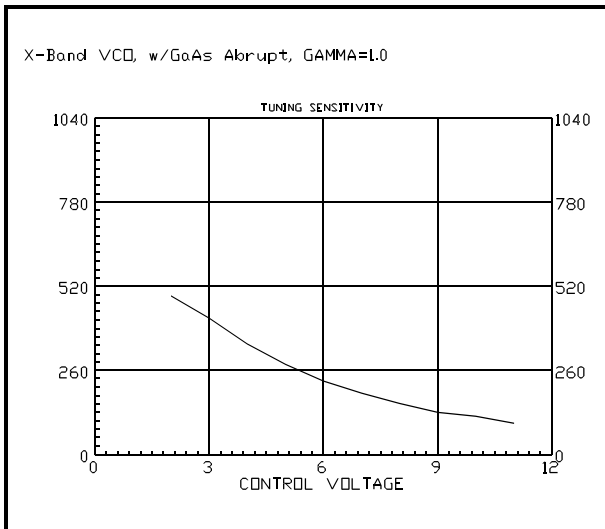


Figure 5

The resonant frequency of an LC circuit can be described in terms of a linear function with voltage:

$$f(v) = f_0(1+dV)$$

When d is thought of as the slope of the tuning curve of the C-V profile we can also describe C(v) in a similar way. Here, Cj(v) is also inversely proportional to the square of the resonant frequency linear function.

$$C_j(v) = C_{j0}/(1+dV)^2$$

This convenient linear function for frequency and Cj(v) can now be easily analyzed by MMICAD to evaluate what the tuning curve would be if we produced such a varactor diode. We can now modify our varactor diode model within MMICAD to include this change.

```

CKT                               !Varactor Diode Model, d=.15
MODVAR V=4 Cj0=.7
LOCVAR Vb=1.3
LOCVAR GAMMA={2*LOG(1+D*v)/LOG(1+V/Vb)}
CAP 1 2 C={Cj0/(1+V/Vb)^GAMMA}
DEF2P 1 2 VARAC (V Cj0)
    
```

Now we can evaluate this new type of linear varactor diode by choosing a value for d. With d=.05, we can get a very modest increase in gamma γ, which would yield ultra-linear performance over narrow changes in Cj (best for limited tuning bandwidths). With d=.20, we can get linear performance over larger tuning bandwidths.

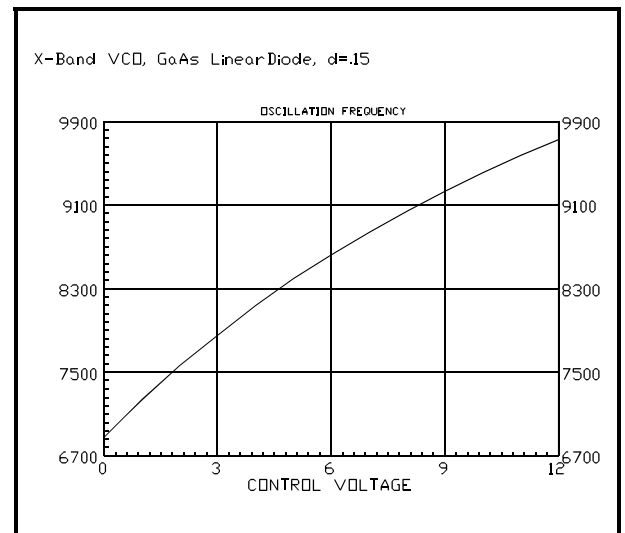


Figure 6

By the correct selection of d, it is possible to optimize linearity over a specified tuning range. This allows the designer to utilize the full tuning voltages available for his designs and to optimize not only linearity, but also tuning speed when a specific bandwidth is made part of the specification. The actual C-V plot which results from a successful MMICAD simulation

can be saved and used as a specification for a semiconductor manufacturer to produce your practical linear diode. The plots included in this note are actual plots from MMICAD imported into WordPerfect 5.1 and then sized appropriately for this application note. A plot of this new linear varactor diode is shown in Figure 6. Notice that the tuning curve end points are essentially the same as the abrupt junction diode of Figure 2, however, the linearity is greatly improved. This improvement can be seen by comparing the tuning sensitivities of the two types of diodes. Figure 7 is a plot of the linear modulation sensitivity. The slope of the modulation sensitivity plot is much flatter for this linear varactor than either the abrupt junction or even the constant gamma varactor diodes. With the correct selection of d , linearity can be optimized for any oscillator tuning bandwidth. This can be simulated ahead of time by using MMICAD to help select the appropriate diode $C_j(v)$ and doping curve represented by d .

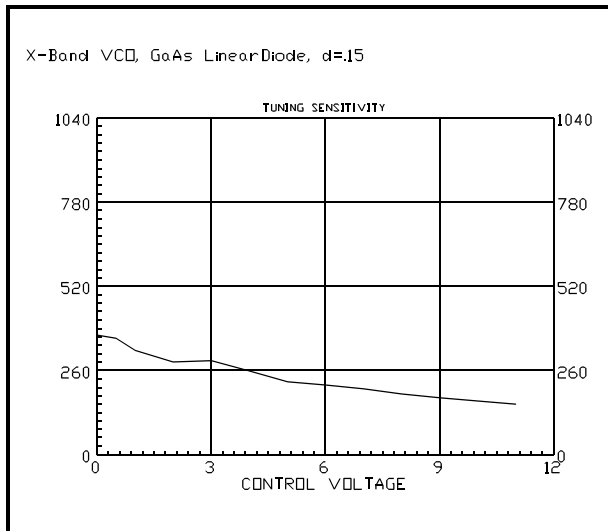


Figure 7

The doping profile C-V curve of the varactor that produced the Figure 6 frequency plot is also available from MMICAD. This allows the VCO circuit designers to physically specify a particular doping profile to a semiconductor house with confidence that it will produce the desired results. Figure 8 shows such a C-V plot of the newly simulated linear varactor diode. It can be seen that the key to producing a linear varactor diode is in controlling the rate of increase of gamma, γ .

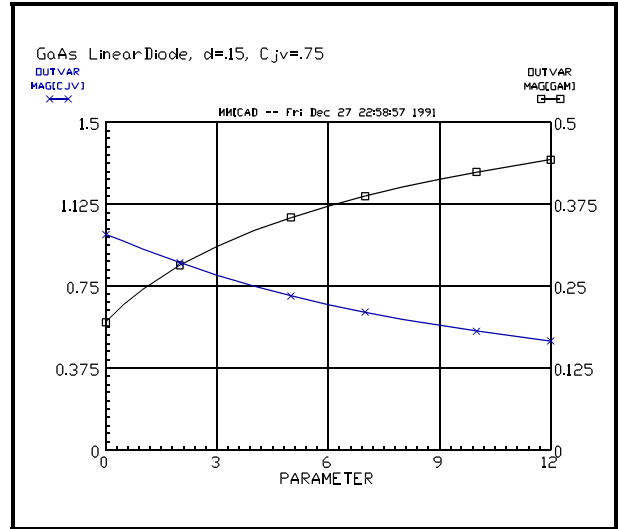


Figure 8

In our example of a linear tuned varactor diode we first used a linear function to describe the diodes behavior, then solved for gamma, in terms of this function, and then computed $C_j(v)$ using the PARAM SWEEP function within MMICAD. MMICAD allowed us to plot $C_j(v)$ and gamma using the PROC block to describe our mathematical functions, and the GRID and OUT blocks to set up our graphs. Our varactor model was described as a user defined model within MMICAD and inserted into the other parts which defined our circuit to be simulated. The MODE OSC function was invoked to view our simulation as an oscillator which automatically produces graphs for freq. vs. tuning voltage.

This note shows how powerful MMICAD can be, yet simple to use when you get your feet wet.