How to design RF circuits for high yields

A technique to eliminate minor variations that can cost big bucks in lot rejection and down production lines.

By Raymond W. Waugh

The story is familiar. The circuit designer chooses a key component based upon the performance parameters guaranteed in the data sheet and roughs out the design on a circuit simulator using the typical values from that same data sheet. The designer obtains samples of the part, builds several prototypes, performs the necessary circuit "tweaks" to bring it up to the performance predicted in the simulation, finalizes the design and turns it over to the manufacturing department. After some time, a crisis develops in production when product yields suddenly drop. A new lot of that key component was used in production, a lot with performance parameters within specification, but slightly different from the samples used to finish the design. The product design is too sensitive to variations in component values.

Had the designer been aware of certain operations, he could have made the end run bulletproof by:

- Performing a sensitivity analysis of the circuit based upon the key component's statistical data.
- Looking out-of-band for an understanding of what was happening within the frequency band of interest.
- Designing the circuit to be tolerant of variations in key component parameters.

These design practices will be examined in detail below.

Sensitivity analysis

No component is without some variation in its key performance parameters. For example, a 5.7KΩ resistor will seldom exhibit exactly 5700Ω of resistance. In fact, a large group of resistors exhibit a classic bell curve when the percent of the population with a given value of resistance is plotted against resistance, with the peak centered on the mean value of resistance. This bell curve can be described with two numerical values—the mean and the standard deviation (σ) of resistance.

Similarly, components used in RF circuits, such as diodes, transistors, FETs and ICs will exhibit some statistical variation in their key parameters as well. Furthermore, both the mean and the standard deviation will drift slowly over time, or may even suddenly change due to a process change. Such statistical data have value only if they are periodically measured.

Semiconductor manufacturers are reluctant to track the variation of their product's key parameters when the product is a low-cost, plastic packaged device. Such testing can dramatically increase the cost of a product. For the engineer who will be designing in these components, the key is to determine which parameters are important to the performance of the product in a given application. Once this is determined, only those key parameters need to be tracked. To accomplish this, however, low-cost/high-volume statistical test techniques need to be developed.

The approach

A simple example can illustrate this concept.

Consider a Schottky diode used in a small signal detector (low cost RF receiver) or a large signal detector (gain or power control circuit). Ten SPICE parameters, along with the parasitic inductance and capacitance of the diode's package, describe the behavior of the diode in either of these simple circuits. However, the measurement and extraction of some of those ten SPICE parameters is tedious. And, some are unlikely to vary from lot to lot, while others have little impact upon detector circuit behavior. Five of the SPICE parameters are key to the performance of a diode mixer or detector. They are B_V (break-

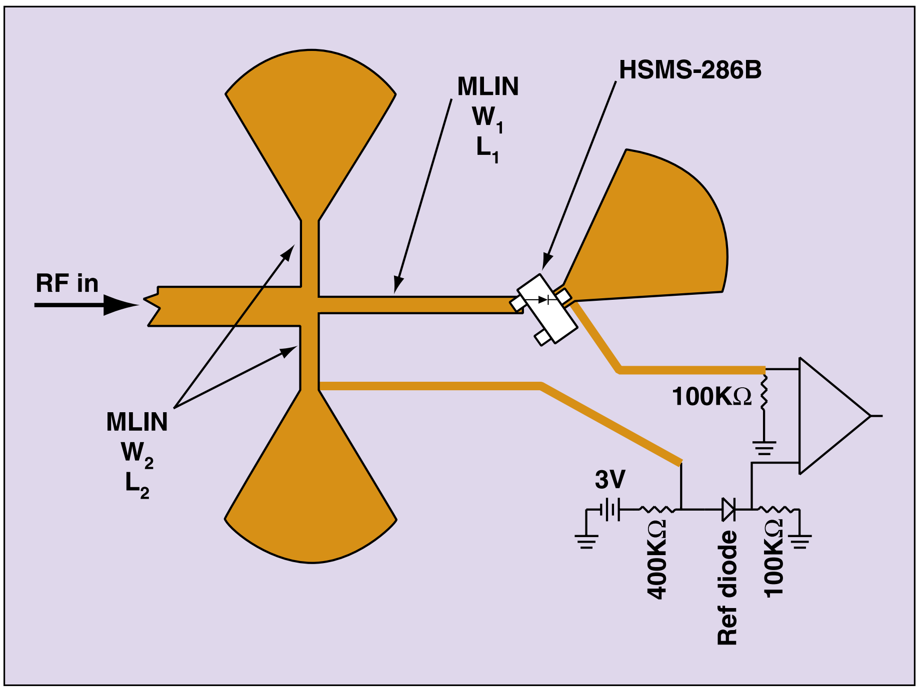

Figure 1. The detector circuit.

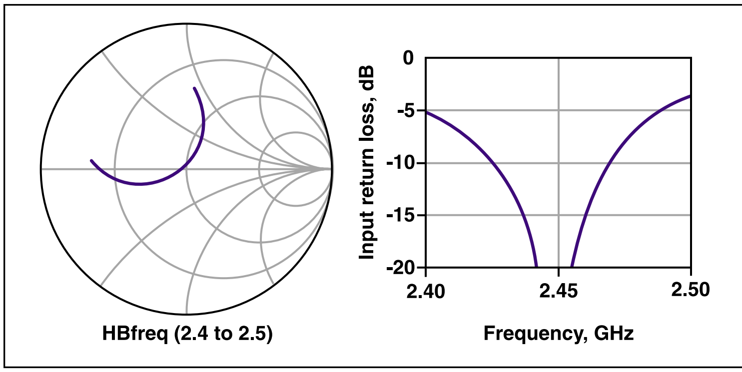

Figure 2. Input S-parameters and return loss.

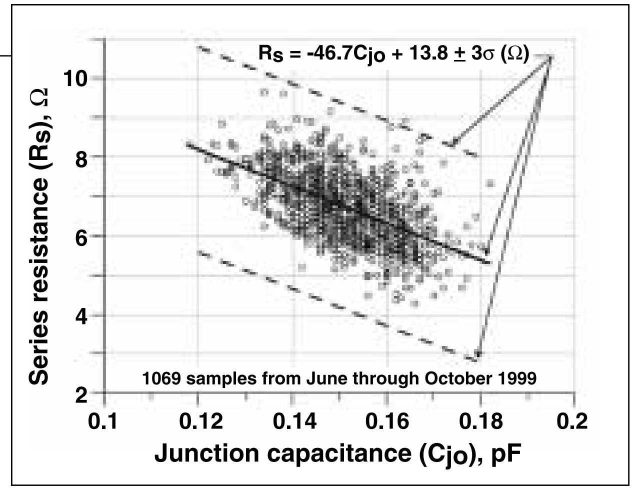

Figure 3. Statistical variation of RS with C_{J0}. HSMS-286B.

down voltage), C_{J0} (junction capacitance at zero bias), I_S (saturation current), n (ideal factor) and R_S (parasitic series resistance). With the right hardware and software, these parameters can be extracted from large quantities of diodes as they roll off the production line.

In a large signal detector with resistive input impedance matching network[1], R_S is the key SPICE parameter—variation in it will result in changes in output voltage at a given input power and temperature. Within reasonable limits, variation in the other four parameters will not produce a meaningful deviation in the output of the detector.

Analysis will show that junction capacitance is the key SPICE parameter in a small signal detector of the type used in ultra low cost receivers.[2] In such circuits, high Q reactive input matching networks are used to obtain the highest possible signal sensitivity. Consider the 2.45 GHz differential detector receiver shown in Figure 1, fabricated on 0.032" Teflon (glass reinforced) microstrip.

The diode is biased at 3μA for maximum sensitivity.[2] Line dimensions are:

W_1 = 0.017"
L_1 = 0.633"
W_2 = 0.030"
L_2 = 0.110"

These values were selected to optimize input impedance match at 2.45 GHz, as shown in Figure 2, for the nominal HSMS-286B diode, used as the reference for this article. Predicted voltage sensitivity (γ), based upon an ADS[3] simulation, is 57.2mV/μW at 2.45 GHz and 25°C, with an input power of –30 dBm.

Statistical data has been published[4] for this diode, which is summarized in Table 1. For a small signal detector, variation in breakdown voltage will have no impact upon performance, leaving but four SPICE parameters to consider. Note that, of those four, two are independent variables (C_{J0} and I_S) and two are dependent upon them (n and R_S). See Figure 3.

When each of the four parameters is varied by ±3σ, , it can be seen that only C_{J0} has a significant effect upon detector performance, permitting us to neglect the other three SPICE parameters for the purposes of this article. When C_{J0} is varied by ±30fF (±3σ), γ is calculated to be 19.7 mV/μW (+3σ) and 26.9mV/?W (-3σ), much lower than the value predicted from the nominal diode parameters. For most applications, this nearly 3:1 variation in output sensitivity is unacceptable.

Looking outside the band

When simulating an RF amplifier (or testing one on the bench), one should always look at the out-of-band response in search of potential or actual frequencies of instability. A frequency sweep outside the band of interest can provide valuable insights into the operation of any RF circuit.

We have seen that a variation of C_{J0} between mean and mean +3σ will cause a 3:1 variation in detection sensitivity, but we need to understand the reason before we can cure the problem. Setting our ADS simulation to produce a frequency sweep while varying C_{J0} will produce the plot seen in Figure 4. It is immediately seen that the variation in output voltage at 2.45 GHz is due to a large shift in the peak frequency, as well as a small shift in the peak amplitude due to the variation in R_S illustrated in Figure 3. The culprit is the change in resonant frequency of the circuit

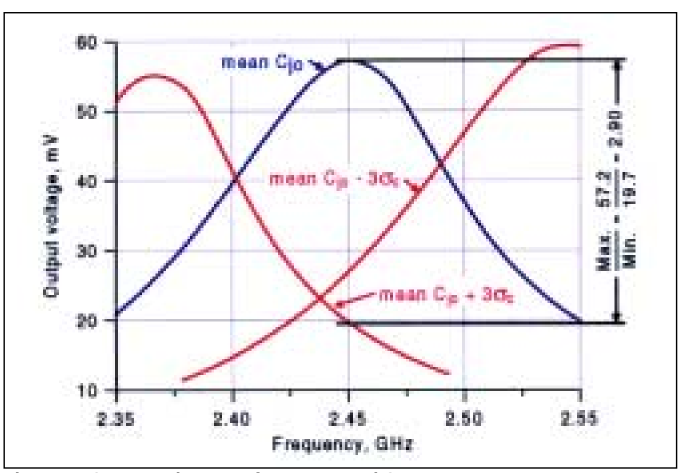

Figure 4 . Output voltage vs. frequency and C_{J0}.

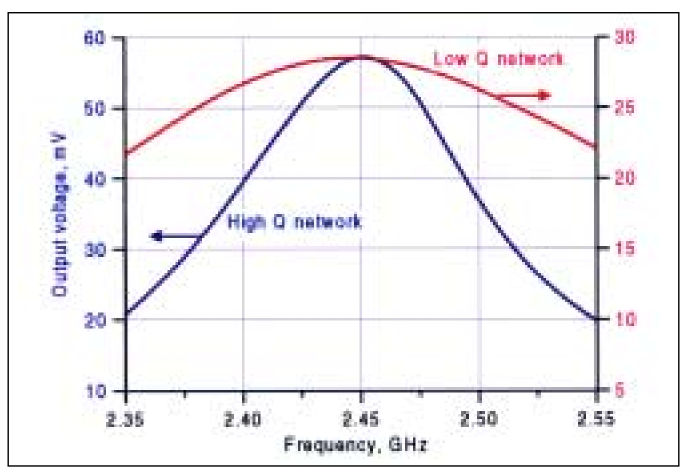

Figure 5. Output voltage vs. frequency, high and low Q circuits.

symbol	B_V	C_{J0}	I_S	n	R_S
unit	Volts	pF	Amperes	-	W
mean	9.22	0.151	3.11^{e-08}	1.0549	6.74
std. dev.	1.22	0.010	4.86^{e-09}	0.0056	0.88

Table 1. Statistical data, HSMS-286x SPICE parameters.

illustrated in Figure 1. Diode variation in C_{J0} is a given–short of finding a diode with a smaller value of σ (with approximately the same value of mean capacitance), we must find solutions in the circuit design. A study of Figure 4 suggests two approaches, one being reducing the Q of the resonant circuit; the other being reducing $\Delta f/\Delta C_{J0}$, the variation in peak frequency with C_{JO}.

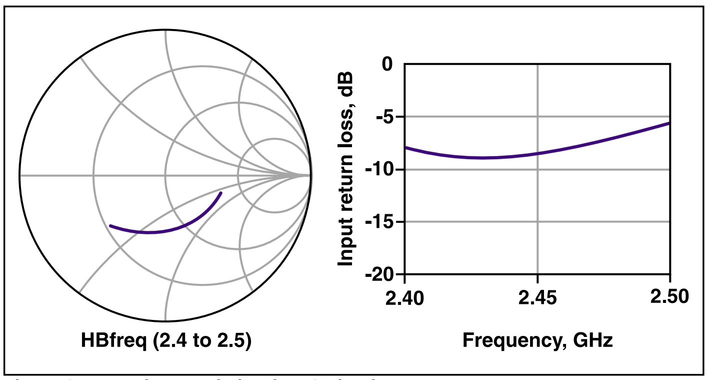

Figure 6. Input characteristics, low Q circuit.

Designing for variation tolerance

The substitution of FR4[5] for Teflon/glass as a substrate material will result in a lowering of circuit Q and a reduction in cost and size. Simulations were performed on a modified version of the circuit shown in Figure 1 (and verified on the bench), where the nominal diode (all SPICE parameters set to nominal values) produced the response shown in Figure 5. The curve labeled "High Q network" (Teflon/glass) is taken from Figure 4, while the curve labeled "Low Q network" was the response when 0.032" FR4 was substituted as a substrate material and suitable adjustments were made to W_1, L_1, W_2 and L_2. Peak amplitude is approximately half that of the circuit on Teflon/glass, but the slope of the curve is much lower, which can result in a higher value of γ for the +3σ case of junction capacitance.

It can be seen in Figure 2 that the Teflon/glass circuit was designed for peak output voltage at the design frequency, without regard to sensitivity to component parameters (or temperature). To reduce the value of $\Delta f/\Delta C_{J0,}$ is to "detune" the input match, as shown in Figure 6. In this design, W_1, L_1, W_2 and L_2 are adjusted such that the input impedance of the detector "wraps around" the origin of the Smith chart, giving up midband match in favor of bandwidth.

The application of these two techniques results in a FR4 design with:

W_1 = 0.017"
L_1 = 0.445"
W_2 = 0.021"
L_2 = 0.200"

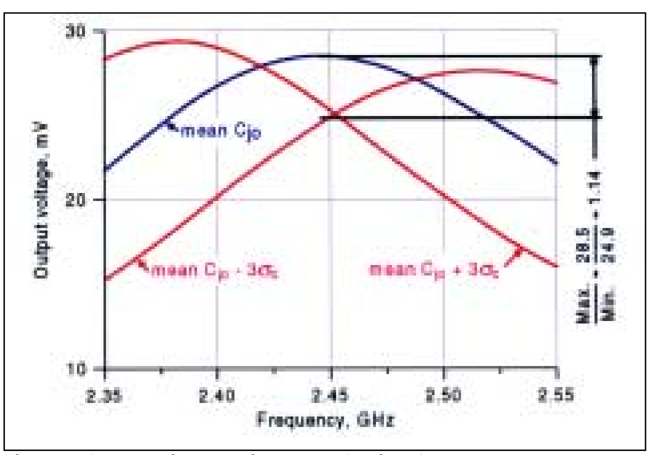

Figure 7. Output voltage vs. frequency C_{JO}, low Q.

When this circuit is analyzed over frequency with C_{J0} = mean ±3σ, the result is that shown in Figure 7. The ratio of γ_{max} (C_{J0} = mean) to γ_{min} (C_{J0} = mean –3σ) is only 1.14, much lower than that of the Teflon/glass "High Q" design. Moreover, while γ_{max} is half that of the High Q design, γ_{min} is 24.9 mV/µW, 26% higher than that for the High Q design. Since γ_{min} is the real performance spec for the detector, the lower cost/smaller size FR4 design offers superior performance.

Conclusion

It should be noted that a complete sensitivity analysis would have involved the simultaneous variation of all four SPICE parameters, using a Monte Carlo analysis. I have simplified the process to illustrate a point.

The application of three "techniques of good design" will result in superior performance, less sensitivity to temperature and component parameter variation, and higher yields in production. Sensitivity analysis, out-of-band frequency sweeps and the use of variation-tolerant design techniques are all that is required.

RF

[1] Raymond W. Waugh, *Designing Large Signal Detectors for Handsets and Base Stations*, Wireless System Design, Vol. 2, No. 7, July 1997, pp 42 - 48.

[2] Raymond W. Waugh, *Designing Detectors for RF/ID Tags*, Proceedings of RF Expo West, 1995

[3] Agilent Technologies Advanced Design System

[4] Statistical Data, HSMS-286x Family, **www.agilent.com/view/rf**

[5] Randall W. Rhea, *Designing a low-noise VCO on FR4*, RF Design, September 1999, pp 72 - 77.

About the author

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