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APPLICATION OF CAD LOAD-PULL TECHNIQUES IN MIXER DESIGN

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ABSTRACT: *This work describes the application of a commercial CAD software to implement load-pull techniques in the design of microwave mixers. This method is used to generate conversion-loss regions when a diode is pumped and operated as a mixer circuit. Emphasis is placed on the inclusion of image and out-of-band terminations to optimize the operating conditions required to obtain low conversion loss. An X-band 5-dB conversion-loss mixer is designed and tested using this method.* © 2003 Wiley Periodicals, Inc. Microwave Opt Technol Lett 36: 320–323, 2003; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.10754

Key words: *load pull; mixers; microwaves; harmonic balance; conversion loss*

1. INTRODUCTION

Mixer analysis and design fundamentals and theory are described in detail in [1]. However, one can explore new capabilities offered by CAD tools, which allow us to adapt some of the characterization and measurement techniques by means of circuit elements and models defined as built-in features in the software. As is well known, optimum diode-mixer design requires a careful selection of the impedance terminations presented to the different mixing frequencies appearing at diode input and output ports [2]. For single tone products consisting of a single RF input signal mixing with the local oscillator the following frequencies are generated:

$$f_{IF} = M \cdot f_{LO} \pm N \cdot f_{RF}, \quad (1)$$

where f_{IF} = output signal for the mixer, f_{RF} = input signal for the mixer, f_{LO} = local oscillator frequencies for the mixer, and M and N = integers (0, 1, 2, . . .) represent the m^{th} or n^{th} harmonic of each signal.

The basis of the load-pull technique described here takes the principles of the experimental measurement systems described in [3, 4] that are oriented to amplifier design, and adapts them to a diode-mixer design. It consists in the characterization of the diode embedded between an input circulator and an output tuner in order to present several distinct loads to the diode, while it is pumped and biased to a specific operating point. Practical tuners are commercially available, easy to use, and of relatively low cost. However, they are of limited use because of their limited frequency and impedance range; in addition, the control of the impedance presented to the image and higher order harmonics is difficult. The CAD load-pull approach does not suffer from limitations in load reflection coefficient magnitude. By simulating a reflection coefficient using the one-port elements included as data elements in the simulation package, unity magnitude can be achieved, if necessary, for any physical setup and at any frequency. Phase and magnitude are controlled directly by a control box in the HB simulation menu.

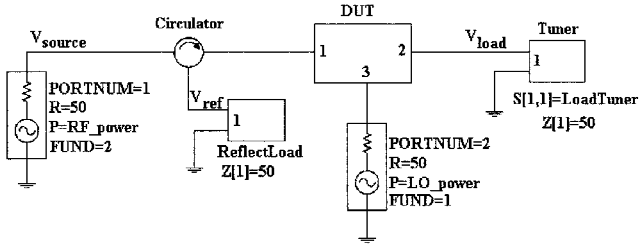

Figure 1 Load-pull simulation setup

Effective CAD load pull can be implemented if precise nonlinear device models are available (generally obtained from small signal S-parameter measurements) and then, by using harmonic balance analysis with an adequate number of LO harmonics, we can obtain the conversion loss value associated to each tuner position and, in this way, we can have a graphical view on the Smith Chart of the conversion loss capabilities for a given device and operating conditions. A CAD load-pull statistical analysis has been reported [5] to verify the optimized parameters of resistive FET mixers, and in this paper we use the CAD load-pull technique to establish conversion loss regions on a Smith Chart from which we can follow a systematic design and implementation of microwave diode mixers.

2. LOAD PULL SETUP

With the nonlinear simulation setup shown in Figure 1, we implement the load-pull method to determine the conversion loss regions. The dependency of diode performance on output impedance is examined by applying a fixed RF power and pumping the diode with a fixed LO power to set specific operating conditions and determine its conversion loss for a given number of load terminations.

In Figure 1 the device under test (DUT) includes the diode and bias structures used to provide DC voltage and current, as well as the coupling structure for RF (f_2) and local oscillator (f_1) signals. Variation of the output load is carried out by the one-port element, implemented as a tuner, which allows the definition of a set of impedances or reflection coefficients that will be presented as a load impedance to the diode at the various mixing frequencies, including the image and sum-mixing products. The DUT is pumped to an adequate power level from a local oscillator and then biased to set the operating conditions as a mixer device.

The commercial software Advanced Design System (ADS) [6] is used, mainly because it integrates the schematic and layout simulations features in the same design environment, which allows us to make linear and nonlinear circuit analysis and optimization; also, we can perform direct electromagnetic analysis of the passive structures using Momentum, the 2.5-D electromagnetic simulator included as a companion to ADS.

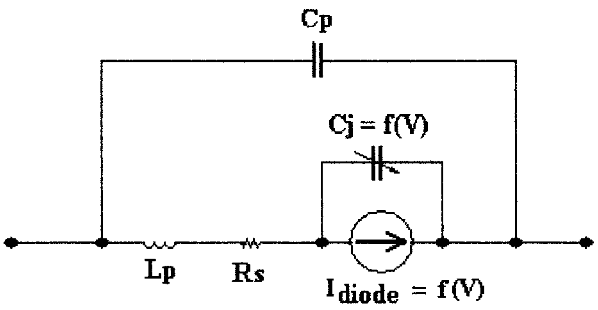

Figure 2 Nonlinear Schottky diode model

2.1 Diode Model

One essential and key element when using this approach is the diode model shown in Figure 2, which represents the behavior of the device at both DC and RF operating conditions. By using the basic diode equations

$$I_{diode} = I_{ss} \cdot \left(\exp\left(\frac{V}{nkTB} \right) - 1 \right), \quad (2)$$

$$C_j = \frac{C_{j0}}{\sqrt{1 - (V/V_{bi})}}, \quad (3)$$

we fit and optimize experimentally measured data to obtain parameter values that will be introduced in a symbolically defined device (SDD) element or, alternatively, use those parameter values directly as parameters for the resident ADS nonlinear diode model, as shown in Figure 3. These parameters in conjunction with the parasitic values extracted from measured data give us a precise and reliable device model to be used in all the nonlinear analysis and mixer simulations. By means of the Matlab function FMINS we set initial values for the parameters defined in Eqs. 1 and 2, evaluate the equations, and compare the results with experimentally measured values. We minimize the error function until a global minimum is found and then use these new parameters to evaluate the equations and compare with experimental curves. Final parameter values for MA40417 are: $R_s = 6.5\ \Omega$, $L_s = 0.13$ nH, $C_p = 10$ fF, $I_{ss} = 0.421$ pA; $C_{jo} = 0.0239$ pF, $N = 1.3$, and $V_{bi} = 0.85$ V. When those parameters are used to evaluate the model, the comparison of measured and fitted data shows very good agreement.

The equations required by the software to process the tuner functions are associated with control elements and HB analysis dialog boxes. Variables are defined to sweep magnitude and phase values between a minimum and maximum, depending on the desired region in the Smith Chart, to map load-reflection coefficients. Also, to be consistent with the basic theory on mixer design

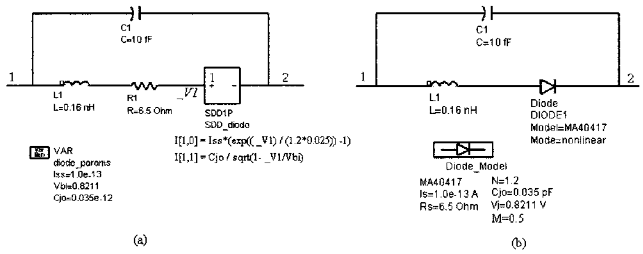

Figure 3 Nonlinear diode model for ADS using: (a) SDD; (b) diode model element

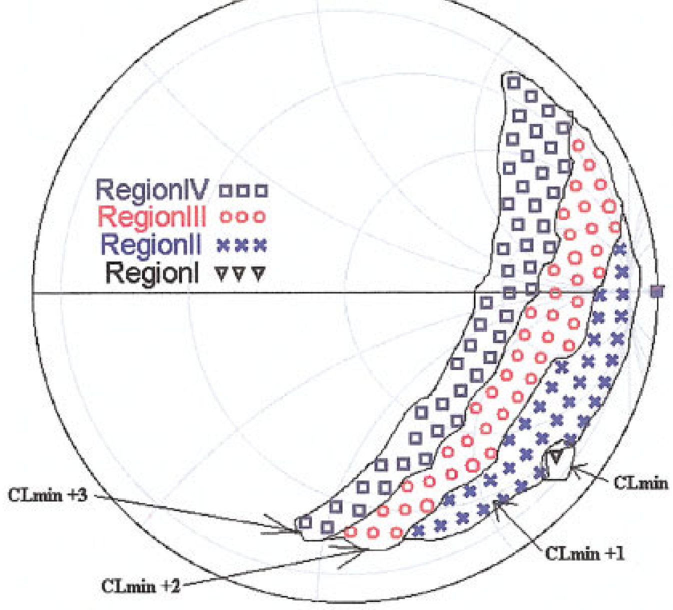

Figure 4 Conversion loss regions. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

[2], we have to present adequate load terminations at the different mixing products; this task is performed by defining the terminations (short or open circuits) associated with each known mixing product. In particular, it is known that for the "Y" type mixer defined in [1], all the out-of-band frequencies must be short circuited and the best conversion loss is obtained by terminating the image frequency in open circuit, although other terminations could be used. In fact, several combinations of short- and open-circuited terminations at those frequencies were tested to determine the best conditions for minimum conversion loss.

Regarding the block diagram in Figure 1, by means of V_{load} and V_{source} in the setup, we define conversion loss by subtracting the appropriate mixing products. This can be done directly in the circuit page by defining a measurement equation or in the data windows as a general equation, to show all graphic information needed by using the basic equation:

$$L = dBm(mix(V_{load}, \{1 - 1\})) - dBm(mix(V_{source}, \{0, 1\})). \quad (4)$$

Also, to complete the information we can get the source and load impedances associated with each conversion loss value using the appropriate indexing of the variables used to represent those quantities. We define the reflection coefficient at the input by means of:

$$\Gamma_{in} = \frac{mix(V_{ref}, \{0, 1\})}{mix(V_{source}, \{0, 1\})}. \quad (5)$$

3. CONVERSION LOSS REGIONS

By defining several values of reflection coefficients on the Smith Chart, we can plot regions of conversion loss value. Conversion loss (CL) characterization is made by applying load-pull techniques at radio frequency (RF) and intermediate frequency (IF), and sweeping the load impedance between given values. In this way, for each impedance point at the IF port, one can determine the corresponding source impedance through the input circulator

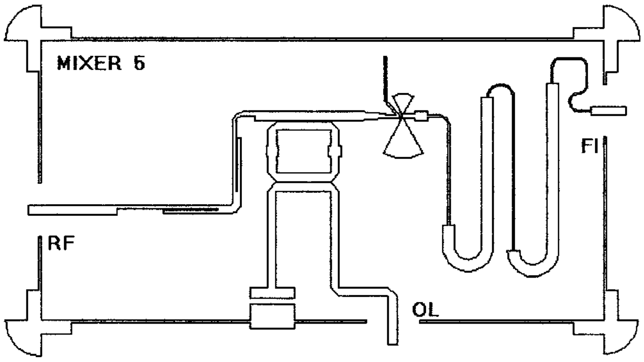

Figure 5 Layout of the X-band mixer

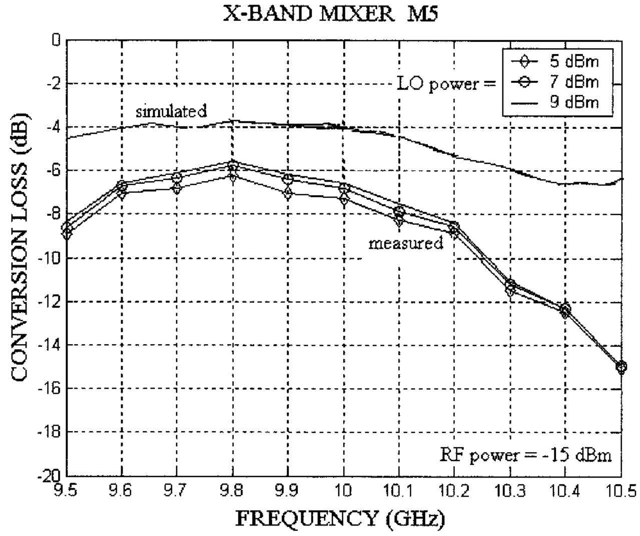

Figure 6 Frequency response of X-band mixer

as shown by V_{ref} in Figure 1. We apply this process to study the MA40417 diode whose model was obtained from DC and S-parameter measurements using a J-Micro microstrip-to-on waffer coplanar transition as described in section 2.

As can be seen, for the particular operating conditions in our example, the value for minimum conversion loss is the point marked as CL_{min}, which corresponds to a single point in the impedance chart. For conversion loss values between CL_{min} and one dB higher, we have region I, which corresponds to the locus of load impedances associated to various tuner positions. For CL values between CL_{min} and two dB higher, we have region II and, similarly, for conversion loss value from CL_{min} up to 3 dB higher, we have region III.

By knowing the source and load impedances, it is possible to synthesize matching networks so that the DUT will be able to provide low conversion loss as a mixer. The impedance values selection to obtain low conversion loss is made by means of indexing the variables in the impedance domain presented for all the tuner positions. Once this is done, the impedance information can be tabulated or saved for further processing.

4. APPLICATION TO MIXER DESIGN

With this information at hand, we can proceed to select the impedance points that meet our needs and from which we can synthesize the corresponding input and output matching networks. This means that we have to avoid impractical impedance values inside those conversion loss regions to simplify the synthesis process and obtain physically realizable networks. For example, we take a point from region III, corresponding to a conversion loss value of 4.0 dB, and synthesize the input- and output-matching networks.

To implement the mixer, in this study a two-section spurline filter is used at the RF input to reject the image frequency with less than 1-dB RF attenuation. To couple the pump LO signal, we use a directional filter centered at the local oscillator frequency and a matching and filtering structure at the intermediate frequency output. The required RF impedance is nearly real, so that it can be implemented with a tapered line transformer. A $\lambda/4$ shorted stub is placed for DC return. Two radial stubs are used to shortcircuit the diode at the LO and 2^{nd} LO harmonic frequencies. We verified the frequency response of the filters using electromagnetic analysis by means of the 2.5-D Momentum capabilities integrated in ADS to obtain very good agreement with the experimental results.

Using the software to analyze this structure, it was found that good conversion loss performance could be obtained with the application of the described methodology. Based on those results, a single diode mixer was implemented using Cuclad 10-mil substrate. The complete mixer layout is shown in Figure 5.

Experimental results shown in Figure 6 indicates that this mixer has minimum conversion loss of 5.56 dB when it is pumped at 9-dBm LO power and 11.02-GHz LO frequency. DC bias ($V_{dc} = -0.7$ V, $I_{dc} = 2$ mA) is applied through the IF port. The differences found can be attributed to slight deviations in the input filter center frequency and increased losses as can be observed in the return losses at both the RF and IF ports, as shown in Figure 7. The performance of the realized mixer is in good agreement with that predicted by the simulation setup.

5. CONCLUSION

In this paper, we presented the adaptation of a load-pull technique as a tool for mixer design. With the aid of the conversion-loss regions, one can select the most appropriate load impedance for a given conversion-loss value. A CAD technique was used to determine the load and source reflection coefficients while characterizing diode performance. The conjunction of a powerful software package that allows full nonlinear analysis and simulation with the

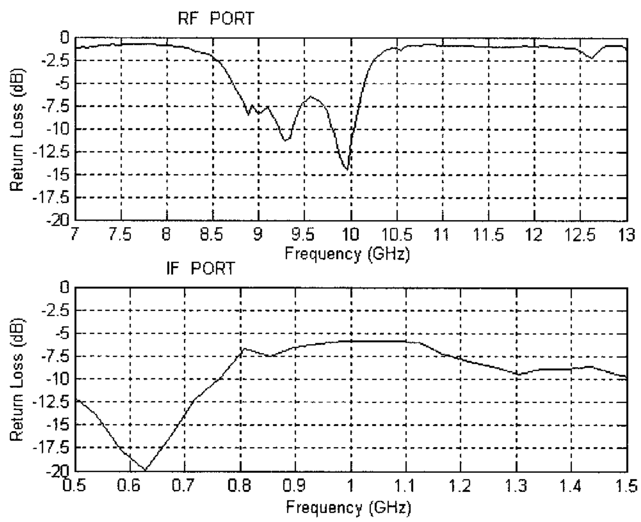

Figure 7 Return loss at RF and IF port

basic theory is a technique than can be applied to easily and quickly achieve an optimized mixer design. This method can be generalized to other mixer structures from the device's nonlinear model.

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