MAURY MICROWAVE
CORPORATION

16 March 2005

Tuner Instantaneous Bandwidth, Linear Network Distortion, and Intermodulation and ACPR Loadpull Characterization

Authors: John Sevic, MSEE; Automated Tuner System Technical Manager, and Richard N. Wallace, System Configuration Lead, Maury Microwave Corporation

Abstract: *Characterization and optimization of intermodulation mixing products, such as* IM_3 *and ACPR, is a common application of Maury ATS. While there are many physical mechanisms responsible for the generation of intermodulation mixing products, generally, it is the frequency response of the device embedding network that determines their behavior with respect to instantaneous modulation frequency. For example, a common manifestation of the effect of the frequency response of the device embedding network is intermodulation mixing product asymmetry. Therefore, during loadpull characterization, one would prefer the effect of source and load tuners, fixture networks, and bias networks to be transparent in order to observe the true response of the intermodulation mixing products under the specified impedance and bias conditions.*

This application note illustrates how a linear network can induce asymmetry in intermodulation mixing products as a consequence of nonlinear phase response with respect to frequency. This effect, due to a non-constant group delay over the modulation bandwidth, is often referred to as linear distortion. A method is described for characterizing Maury's ATS tuners to quantify their instantaneous bandwidth, resulting in identification of a maximum modulation bandwidth. It is shown that in most circumstances, Maury tuners are transparent at modulation bandwidths suitable for wideband applications such as 3GPP and 802.11x. Guidelines are also provided to minimize the induced asymmetry of linear networks commonly used in loadpull, such as bias networks and fixture networks.

Group Delay and Linear Distortion

Group delay is a measure of the time delay imparted to a signal passing through a network, such as a transmission line, bias network, or impedance transformation network. Since group delay can be shown to be the first derivative of instantaneous phase change with respect to frequency, it is a useful metric for characterizing linear distortion, often manifested as asymmetry in intermodulation mixing products, such IM_3 and ACPR. While it may seem counterintuitive that a linear network, such as a bias network, can induce nonlinear distortion, it is indeed the case.

To illustrate the physical mechanism of linear distortion, consider **Figure 1**, showing a linear network excited from the output of a nonlinearity composed of two fundamentals and upper and lower IM_3 mixing products. Note that the upper and lower IM_3 products are asymmetric after passing through the linear network. To demonstrate how asymmetry happens, consider **Figure 2**, showing the phase response of a hypothetical linear network at some arbitrary center frequency. The straight line shown through the linear region represents the linear phase region of the network. Since group delay is the first derivative of phase with respect to frequency, we note that this region will have constant group delay.

An immediate consequence of this relationship is that all spectral components of a signal passing through this network will experience a proportionate phase shift with respect to frequency, thereby maintaining the temporal relationship of the signal's Fourier components. This fact is fundamental to understanding how linear distortion can induce asymmetry in IM_3.

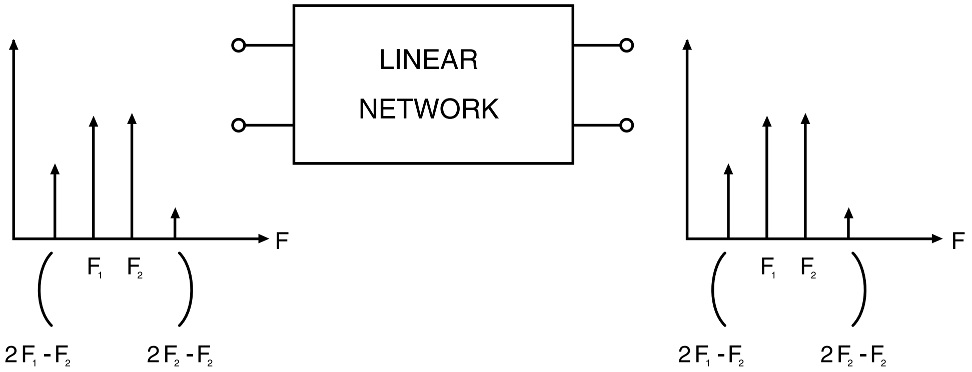


Figure 1. Linear Network Illustrating Asymmetry of IM_3 Due to Linear Distortion.

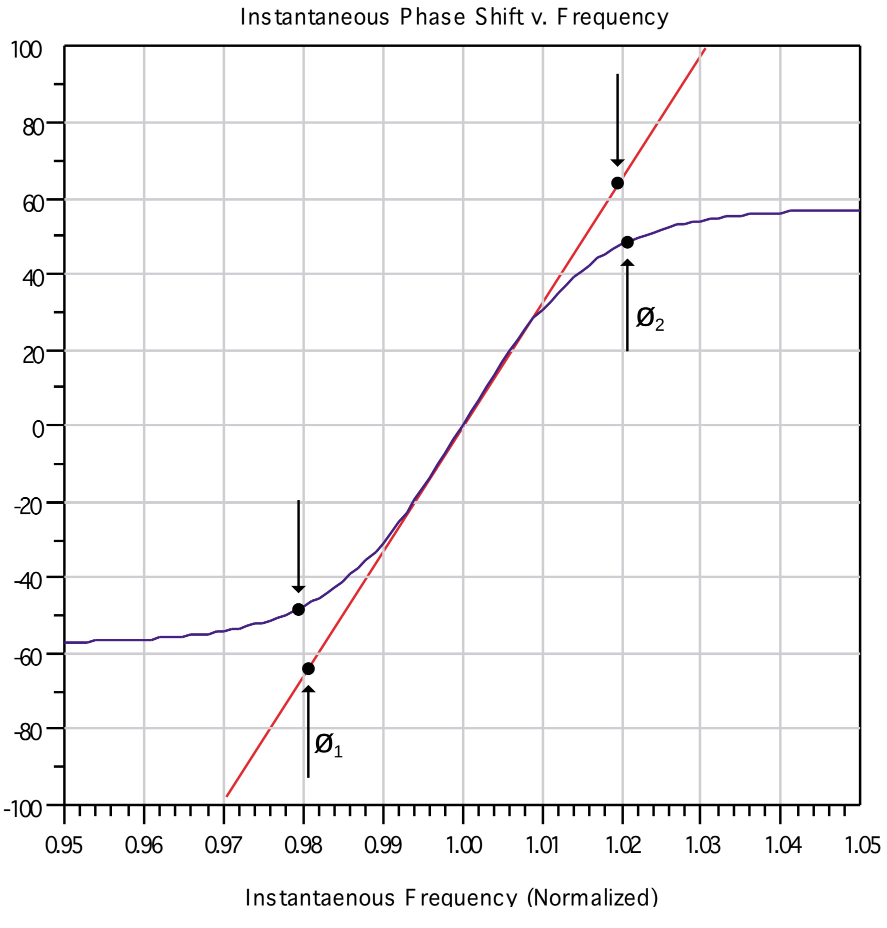


Figure 2. Instantaneous Phase Response of a Linear Network Versus Frequency. The Straight Line Represents the Linear Phase Constant Group Delay Region of the Network. No Linear Distortion is Imparted as Long as the Signal Bandwidth is Constrained to this Region. Note ^{1} and ^{2} Represent the Phase Advancement and Retardation, Respectively, from Linear Phase, for the Lower and Upper IM_3 Mixing Products. This is the Physical Mechanism Responsible for IM_3 Asymmetry in a Linear Network.

It is well-known that IM$_3$ mixing products are composed of linear, quadratic, and cubic nonlinearities[1], and that each of the components add as vectors, yielding the composite IM$_3$ that is ultimately measured with a spectrum analyzer. This fact is what leads to, for example, the unexpected, and significant, influence of the bias network on IM$_3$.

Consider in **Figure 3**, where upper and lower IM$_3$ mixing products are shown in vector form, with linear and cubic components only, to simplify the present analysis. Note that the phase of the linear component with respect to the cubic term, ϕ, is identical for both the upper and lower IM$_3$ mixing products. Now, if the tone separation for each of these IM$_3$ mixing products is such that we are out of the linear phase region of the linear network, as shown in **Figure 2**, then we see that each of the components will experience a different relative phase shift. In fact, the lower IM$_3$ mixing product will have it's relative phase advanced while the upper IM$_3$ mixing product will have its relative phase retarded, with respect to the linear phase response.

Figure 3 also shows the resultant output of the linear network, showing the effect of advanced and retarded phase on the linear phase component of each of the IM$_3$ mixing products. An immediate consequence of the non-constant group delay is that the composite upper and lower IM$_3$ have each a linear component now that is different in phase with respect to the cubic term, leading to a difference in the length of the composite vector, which is manifested as asymmetry in IM$_3$. While this example is a simplification, it is the essence of asymmetry due to linear distortion.

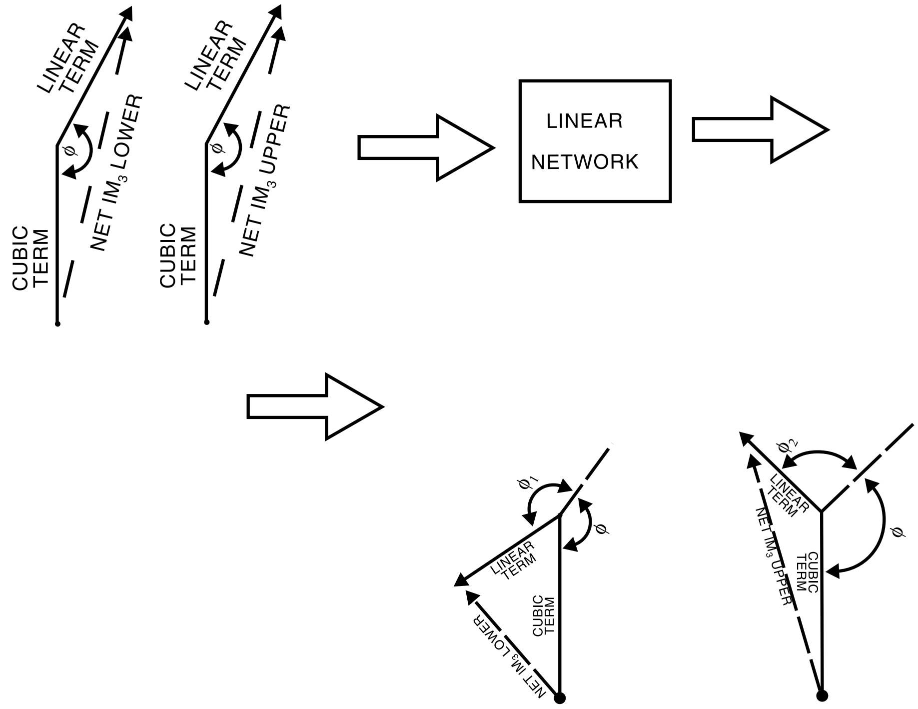


Figure 3. Vector Decomposition of IM$_3$ Mixing Products at the Input of a Linear Network Illustrating the Phase Relationship of the Linear Component with Respect to the Cubic Component at Input of Linear Network. At the Output of the Linear Network, the Vector Decomposition of the IM$_3$ Mixing Products Illustrates the Resultant Phase Relationship of the Linear Component with Respect to the Cubic Component. Note that the Resultant Phase of the Linear Term with Respect to the Cubic Term of the Lower IM$_3$ Mixing Product is Different than the Associated Phase of the Upper IM$_3$ Mixing Product.

Figure 4 shows an ADS simulation using an FDD to represent a cubic nonlinearity with the linear distortion function shown in **Figure 2**. **Figure 5** shows the resultant IM_3 asymmetry versus tone separation. Note that for tone separation within the constant group delay region of **Figure 2** that the asymmetry is negligible, meaning the relative phase shift of the linear term of each IM_3 mixing product is the same.

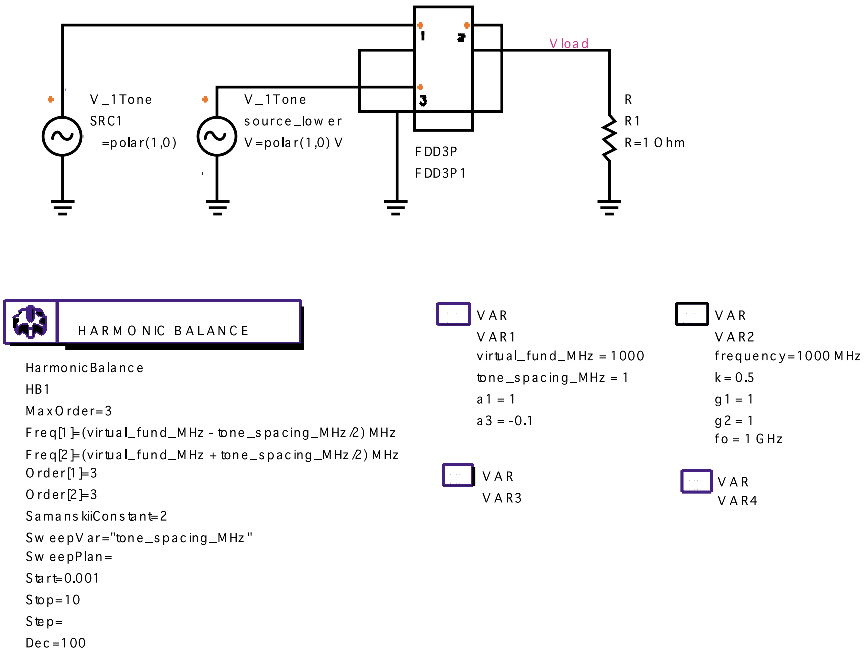
Tuner Characterization to Quantify the Effect of Linear Distortion IM and ACPR

Figure 6 shows an ATS based recommended block diagram to characterize a linear network's effect on IM and ACPR, the linear network in this case being a Maury tuner. A two-tone signal, of suitable spectral purity, is applied to a reference PA, creating intermodulation mixing products. Setting the drive level to generate mixing products of approximately -30 dBc is a good starting point. The output of the reference PA is routed through a pad and to the input of the linear network, which, in the present example is a Maury MT982E30 tuner.

The output of the tuner is applied to a directional coupler and then a pad (or power sensor). The coupled port of the directional coupler is applied to a spectrum analyzer. The incident power of the spectrum analyzer should be low enough to ensure no additional mixing products are created.

First, perform a standard two-tone power calibration with ATS, and proceed to the Power Measurement view. From the <Measurements> menu, select Two-Tone Swept Frequency. At the dialog box, enter a frequency span. The frequency span should cover the modulation bandwidth of the signal that will be used in the final loadpull characterization. Starting

Simulation Analysis to Illustrate the Effect of Nonlinear Group Delay (Linear Distortion) on IM Asymmetry



HarmonicBalance
HB1
MaxOrder=3
Freq[1]=(virtual_fund_MHz - tone_spacing_MHz/2) MHz
Freq[2]=(virtual_fund_MHz + tone_spacing_MHz/2) MHz
Order[1]=3
Order[2]=3
SamanskiiConstant=2
SweepVar="tone_spacing_MHz"
SweepPlan=
Start=0.001
Stop=10
Step=
Dec=100

virtual_fund_MHz = 1000
tone_spacing_MHz = 1
a1 = 1
a3 = -0.1

frequency=1000 MHz
k=0.5
g1 = 1
g2 = 1
fo = 1 GHz

Figure 4. Agilent ADS Simulation, Using an FDD, to Demonstrate Asymmetry Induced by the Linear Network with the Nonlinear Instantaneous Phase Response of Figure 2.

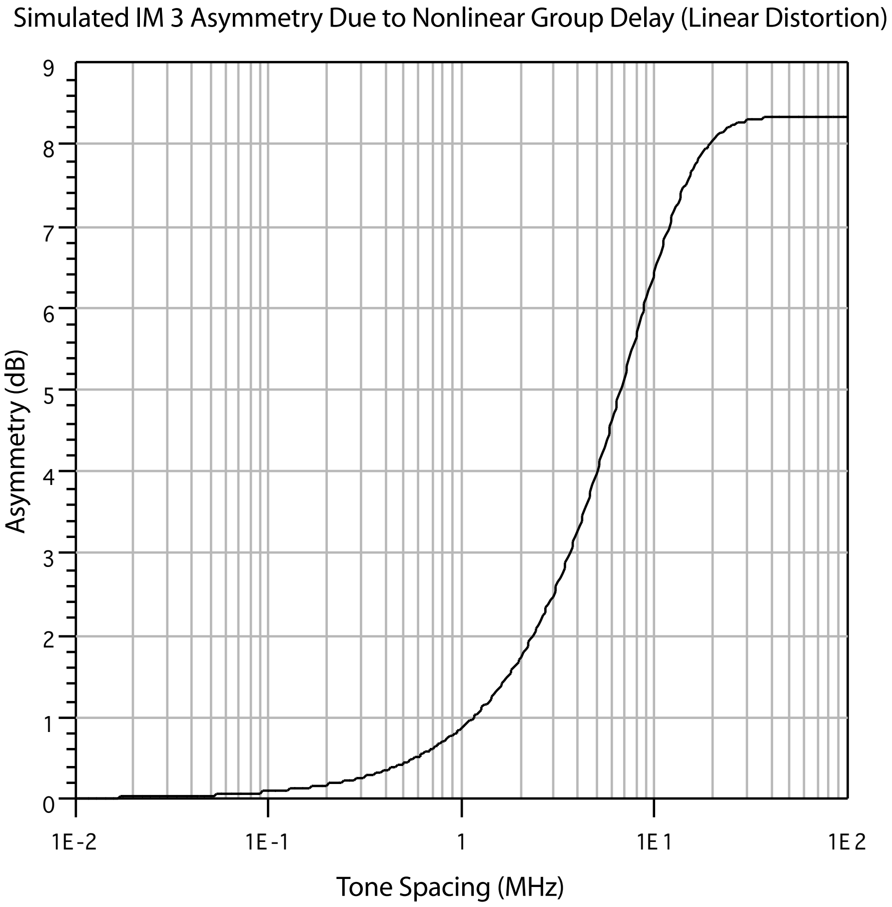


Figure 5. IM_3 Asymmetry Versus Tone-spacing for the Linear Network of Figure 2. Note that over the Linear Phase Region that the Asymmetry is Zero.

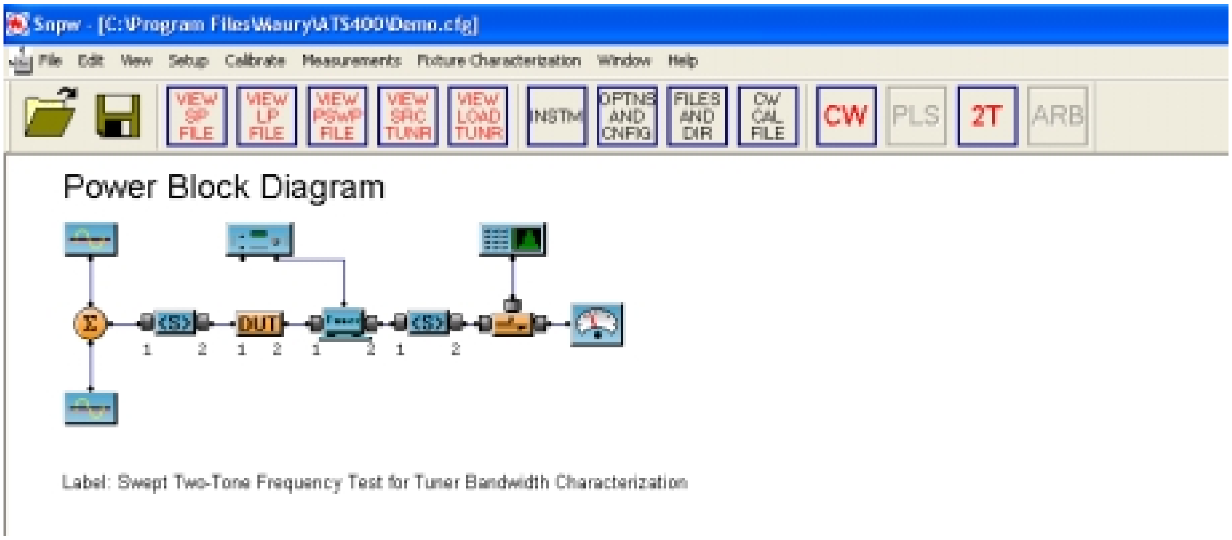
with the tuner at 50 Ω, start the frequency sweep, ensuring that the appropriate measurement parameters have been chosen, e.g., IM_3. Repeat the sweep for various impedances around the Smith chart.

Figure 7 shows the measured IM_3 asymmetry versus tone-spacing and tuner VSWR for the Maury MT982E30 tuner. We note that this tuner has exceptional bandwidth, inducing only a 1.2 dB asymmetry at a tone-spacing of 100 MHz and VSWR of approximately 55:1. These results illustrate that this tuner, optimized for common wireless applications, is virtually transparent for all common wireless standards, including ultra-wideband standards such as 3GPP and 802.11x.

Summary of MT982 Modulation Bandwidth Analysis

From the forgoing theoretical analysis and empirical analysis, it has been established that a linear network can induce intermodulation mixing product asymmetry due to non-constant group delay[2]. Therefore, to minimize the effect of linear distortion on intermodulation mixing product asymmetry, it is necessary for the linear network to have constant group delay over the modulation bandwidth.

Each of Maury's tuners have a tuning mechanism specifically designed to provide constant group delay over very wide modulation bandwidths, as the present analysis of the MT982E30 tuner illustrated. Virtually



Label: Swept Two-Tone Frequency Test for Tuner Bandwidth Characterization

Figure 6. Maury ATS Configuration for Characterizing the Instantaneous Bandwidth of a Maury Tuner.

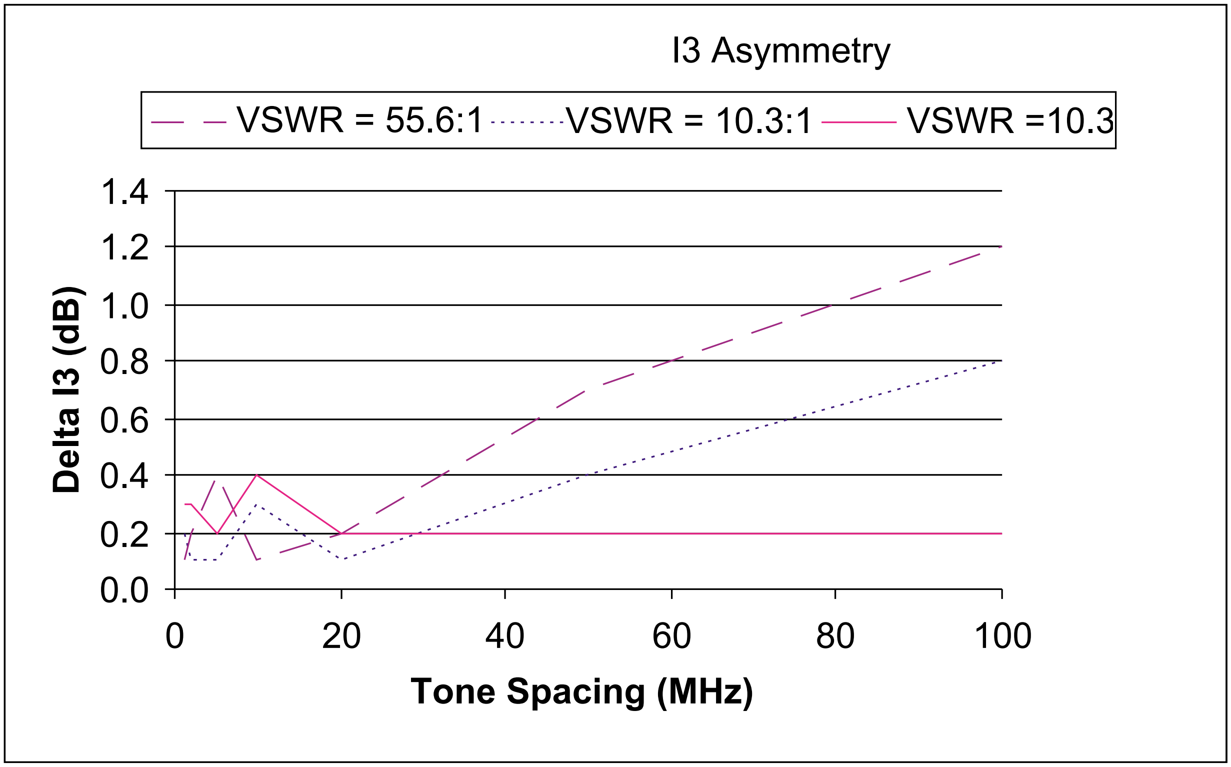


Figure 7. Maury ATS Configuration for Characterizing the Instantaneous Bandwidth of a Maury Tuner.

no asymmetry was observed up to 100 MHz, at maximum VSWR, ensuring a nearly transparent tuner influence on IM/ACPR measurements for common wideband standards such as 802.11x, as well as 3GPP and multi-carrier applications.

Guidelines for Minimizing the Influence of Linear Distortion on IM and ACPR Measurements

It has been established that constant group delay over a signal's modulation bandwidth will eliminate intermodulation mixing product distortion induced by a linear network. Therefore, during loadpull characterization, use of impedance transformation networks, bias networks, and tuners with constant group delay over the modulation bandwidth is essential. Each of Maury's tuners have exceptionally flat group delay over modulation bandwidths for nearly all current wireless standards, including 3GPP and 802.11x.

Important guidelines to consider for transparent loadpull characterization are:

- Understand the nature of the signal being used in the loadpull characterization, particularly its modulation bandwidth.
- Ensure that all bias networks have constant group delay over the modulation bandwidth at the associated RF carrier frequency. Note that an optimum bias network design often is based on Bessel-Thompson filter synthesis methods, since this filter has constant group delay over a specified bandwidth.
- Arbitrary insertion of bias network electrolytic capacitors and unnecessarily long bias feeds are the single most significant contributor to intermodulation mixing product asymmetry, due to the associated low frequency resonances that are usually within the modulation bandwidth of the signal. For example, an electrolytic capacitor above resonance appears as an inductor, which can resonate with a smaller capacitor, precipitously included for mid-band decoupling. The resultant resonance assures a region of non-constant group delay.
- Attempt to minimize bias network inductance by using two bias feeds each for drain/collector and gate/base. This is frequently done anyway, unintentionally, with remote sensing feeds, which are often terminated with a series resonant capacitor and resistor, and, finally, the remote-sense line.
- Use on-fixture bias networks when feasible (this is difficult in on-wafer applications). External bias networks exhibit excessive inductance, leading to non-constant group delay. Inclusion of current-mirror circuitry and other associated active bias networks is also recommended.
- Perform a swept-frequency analysis of each bias network to identify regions where group delay is non-consistent. Ensure any resonances are moved out of the base-band and RF modulation bands.
- Use of a quarter-wave impedance transformation networks is a common, and powerful method of increasing DUT VSWR. Perform a simulation of the quarter-wave transformer to ensure its group delay its center frequency is relatively constant over the required modulation bandwidth. If it is not, add more sections, if possible, or adopt an alternative transformer response. The Dolph-Chebyshev response is optimum in terms of constant group delay for a given transformation ratio and electrical length.
- If you are using a tuner different than the one in the present analysis, repeat the experiment using your own signal, to ensure the group delay is constant over the modulation bandwidth of your signal.

- As a final check, assemble the entire loadpull system, and after performing a ΔG_t test, apply a swept two-tone signal to identify the modulation bandwidth of your loadpull system. It is better to know than to guess.

Notes

[1] In general, IM_3 mixing products can be composed of higher-order mixing products as well.

[2] Note that non-constant group delay is not the only physical mechanism responsible for intermodulation mixing product asymmetry. For example, thermal modes can induce asymmetry. Thermal modes are generally lower in frequency (longer time constant) than linear network modes, unless the linear network has relatively large capacitance or inductance present. In fact, if one can assume a linear network has constant group delay over the modulation bandwidth, then a useful method of identifying thermal modes results, using chirp signals.