Millimeter-wave linearity measurements: sensitivities and uncertainties

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Abstract- **Traditional linearity measurements, including compression (AM/AM and AM/PM) and intermodulation distortion (IMD), can become even more difficult with mm-wave devices and subsystems. Potential issues include lower levels of accuracy or stability on power control; mismatch effects, higher levels of spectral impurities, and less ideal combining/distribution structures. This paper will explore some of these effects at W-band and above by looking at measurement results, sensitivities, and uncertainty impacts.**

I. Introduction

Instrumentation and linearity measurement procedures have not always kept up with the bandwidth improvements in mm-wave devices/subsystems. In particular, AM/AM, AM/PM (e.g., [1]) and IMD (e.g., [2]) measurements are sometimes done with scalar tools, with signal sources or receivers of unknown purity/linearity, or with fixturing/combining structures that may not be optimal. As device and system modeling requirements increase, it may be useful to better understand these measurement challenges.

II. Gain Compression (AM/AM and AM/PM)

In terms of compression measurements, some issues include a reference measurement (i.e., the baseline from which compression is measured) that is not entirely out of the compression regime, inaccurate power calibrations, and receivers compressing in a similar range to the DUT. With bare devices and LNAs, another issue, particularly when looking at phase distortion at a given compression level, is the interaction of a variable input match with the rest of the system. The complication most often arises on structures where the input stage compresses relatively early.

Such match compression is well-known but the uncertainty impact on AM/PM at millimeter-wave frequencies is perhaps less-well-explored. The concept is that if the return loss changes with power and transmission is being measured in a scalar sense, the match change can alter the measurement. If the transmission is being measured in a corrected sense, however, then the measurement distortion is removed. An example LNA operating in F-band has a midband input match that changes from ~0.2 (linear) to 0.17 for drive levels going from -40 dBm to -25 dBm (1 dB compression point P_{1dB} ~ -28 dBm). While applying the full correction only changes the measured P_{1dB} by ~0.25 dB, it can cause 4-5 degrees of difference in measured phase distortion at compression (see Fig. 1). This multiplying effect varies with the DUT but match changes of the scale of 0.01 can routinely cause phase distortion measurement errors exceeding one degree. Since one degree may be on the order of basic measurement uncertainty of transmission phase, this added component can have significance.

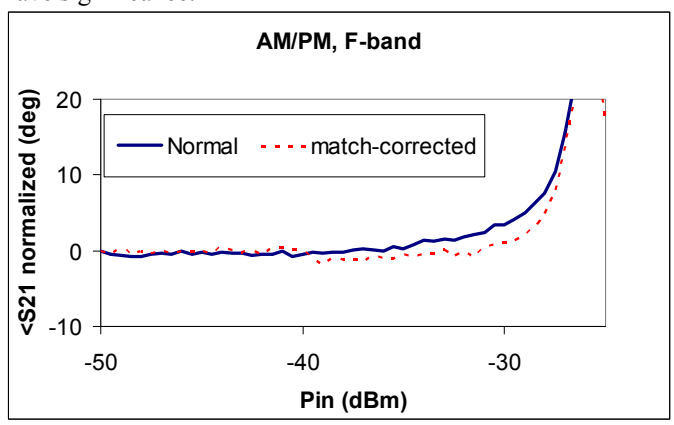

Figure 1. AM/PM behavior as a function of match correction is shown here.

Phase response steepness also produces a sensitivity to power calibration accuracy. In Fig. 2 is shown the effect of a 1 dB error in knowledge of the input power. Since power calibrations and power leveling stability in mm-wave ranges can sometimes be a challenge, this level of sensitivity can be an issue in routine measurements.

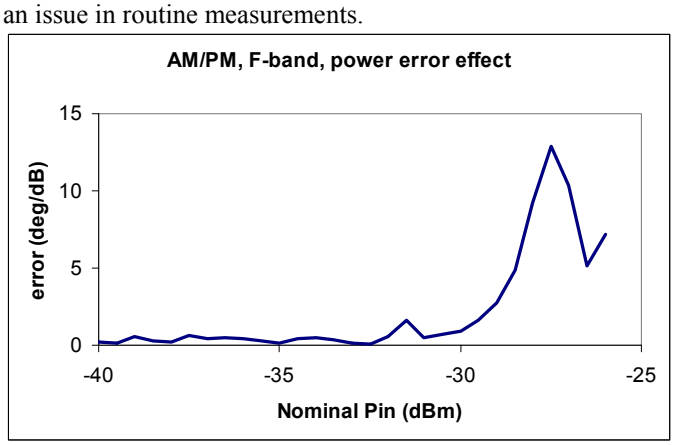

Figure 2. Power accuracy effects on AM/PM are shown here.

In some systems, reasonable power stability/accuracy over time and temperature is possible as suggested by Fig. 3 for the range 55-120 GHz [3]. In this case, accuracy could be maintained (in a relative sense) to ~0.1 dB over 24 hours and to 0.5 dB over a 90C temperature range.

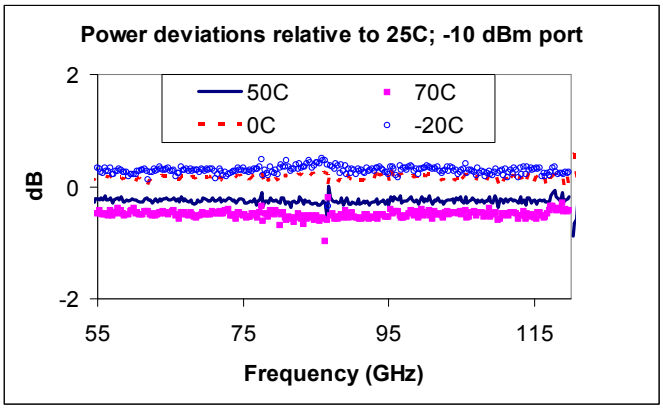

Figure 3. An example of fairly well-behaved power accuracy stability with temperature is shown here.

Another class of issues related to gain compression revolves around the spectral purity of the source. Since most mm-wave sources are comprised of extensive multiplication chains, the fractional harmonic filtering demands can be severe and there can be sometimes significant residual components. Aside from the usual integrated power issues, harmonics themselves (particularly integer harmonics) can effectively re-bias the device under test and result in anomalies. Since there has not been a large amount of published work on the sensitivity of these measurements at mm-wave frequencies, a few measurements will be considered. As an example, consider the setup in Fig. 4 where a harmonic injector is used with a broadband LNA as a DUT.

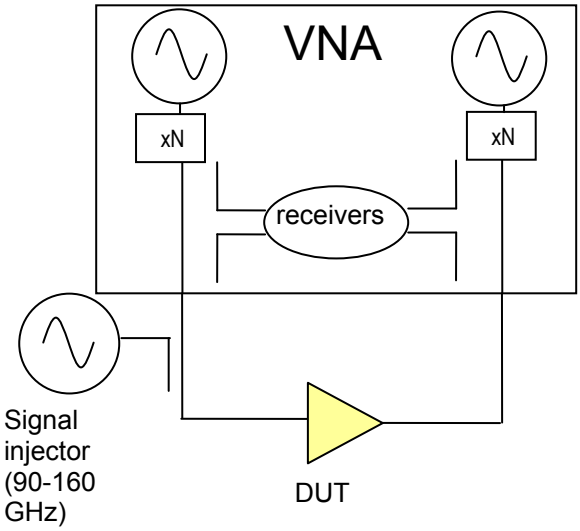

Figure 4. A setup is shown here for looking at AM/AM and AM/PM conversion with an added injection signal. The VNA may have multiple sources or may use a switching arrangement.

Here the level of harmonic injection can be adjusted and the influence on the AM/AM (see Fig. 5) and AM/PM (see Fig. 6) measurements observed. In this particular case, neither AM/AM nor AM/PM is significantly affected by even fairly high harmonic content. This may not always be true for a given device and its biasing dependencies.

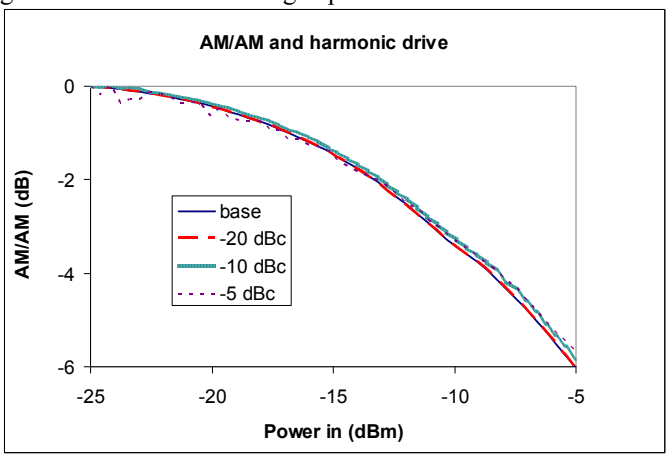

Figure 5. The effect of injected harmonics on an AM/AM measurement is shown here (fundamental at 70 GHz, injection at 140 GHz).

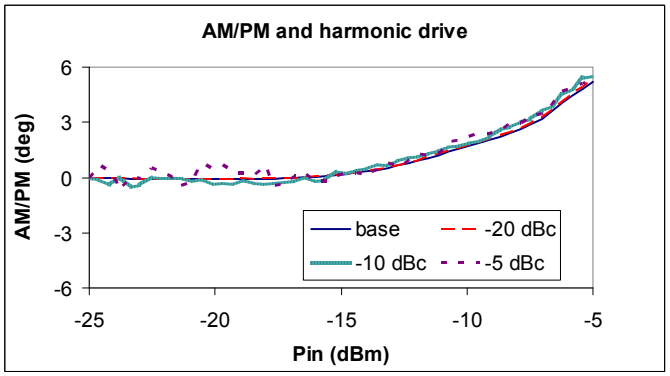

Figure 6. The effect of injected harmonics on an AM/PM measurement is shown here (fundamental at 70 GHz, injection at 140 GHz).

The introduction of other signal frequencies is, of course, possible from non-harmonically related spurs or from N/M harmonic products. The behaviors here can be considerably more complicated as has been discussed in the literature for lower frequencies (e.g., [4]-[5]). The prevalence of additional products in mm-wave systems that have not been completely filtered makes it of interest here. An example is shown in Fig. 7 for an AM/AM measurement at 100 GHz with contamination tones ranging from 90 to 109 GHz. The equivalent AM/PM measurement is shown in Fig. 8. Note that these injection levels are at or above the level at which the device starts compressing so some effects are anticipated.

As would be expected, gain compression is affected if a large enough signal is injected but it is very frequency dependent. Part of this comes from the gain profile of the DUT, part comes from the injection effectiveness vs. frequency due to port impedances and part comes from interaction of the mixing products. One does get scenarios where P_{1dB} point appears to increase.

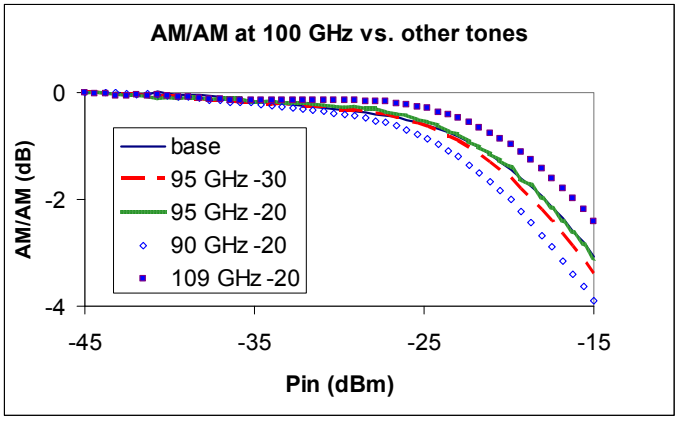

Figure 7. The effect of an injected tone on an AM/AM measurement at 100 GHz is shown here (injection at non-harmonic frequencies). The injection power level in dBm is in the legend.

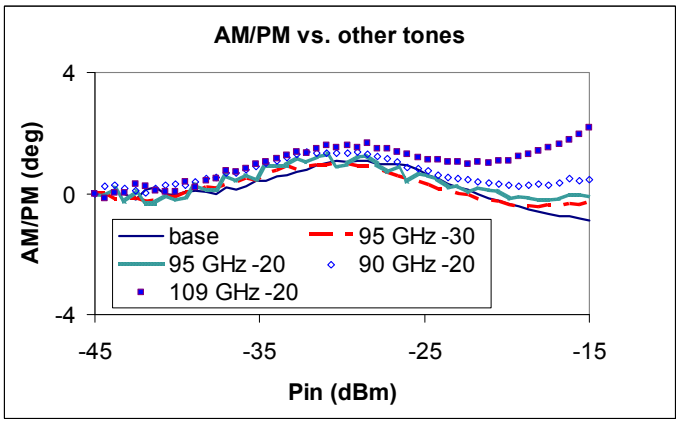

Figure 8. The effect of an injected tone on an AM/PM measurement at 100 GHz is shown here (injection at non-harmonic frequencies). The injection power level in dBm is in the legend.

In terms of phase distortion, the combination leading to the apparent P1dB increase also led to the most deviant phase excursion of about 2 degrees.

III. IMD

Intermodulation distortion measurements are sometimes performed less often at mm-wave frequencies due to the setup complexities, combining intricacies, receiver limitations and other reasons. As applications progress, however, linearity measurements at least similar in nature to IMD will likely be increasingly required. As such, we will look at a few of the potential issues.

The classical setup for this measurement is shown in Fig. 9. There are many possible technological choices for the sources but commonly they will be some synthesizer followed by a multiplication chain. Amplification (at lower mm-wave frequencies) and/or leveling circuitry and/or isolators may be present at the source output. The combiner shown is usually passive but could be coupler-based, hybrid-based or loss-based (among other choices, e.g., [6]). Due to a paucity of available power, the loss-based approach is less commonly used at the higher frequencies.

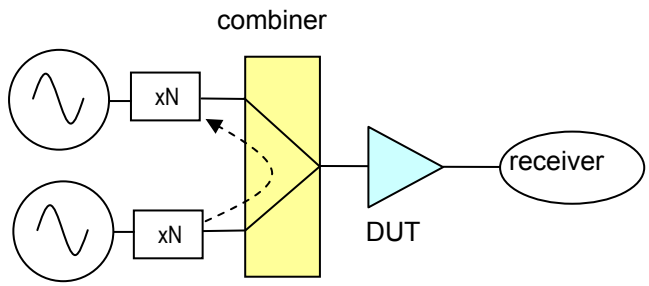

Figure 9. A classical setup for measurement of IMD products is shown here. The dashed arrow indicates a leakage path that can have some implications discussed in the text.

As with the compression measurements, signal source purity could be an issue, depending on the DUT, as harmonic components can regenerate the usual $2\omega_2$-ω_1 and $2\omega_1$-ω_2 third-order products (for input tones at frequencies ω_1 and ω_2). An additional potential issue is that, since many mm-wave receivers are based on harmonic mixers or harmonic samplers, spurious receiver responses can create faulty intermodulation measurement results. For the devices studied, these factors did not seem to be significant.

Another spectral purity issue is that of small spurs (in the form of sidebands in one of the more problematic scenarios) on the base synthesizer due to leaking reference clocks or other reasons. If these sidebands are largely amplitude-modulated onto the signal source, the multiplication process to get to mm-wave will largely just increase their offset frequency. If they are, however, largely angle modulated, then the offset frequency will be largely unaffected by the multiplication process but sideband amplitude will increase. If one unfortunately chooses an IMD offset frequency that matches this sideband offset, then an erroneous IMD result can be obtained much more easily. In the example of Fig. 10, the particular source had some small 10 MHz sidebands (reference oscillator coupling) in certain frequency ranges. These became more noticeable upon multiplication to W-band. In an IMD measurement with a 10 MHz offset, this caused problems when in the operating frequency range of ~90-95 GHz (where the sidebands were stronger). Moving to a different offset frequency produced more accurate results in this case.

Another spectral purity issue is that of multiplied phase noise. By definition, this is largely angular modulation so the amplitude of the noise sidebands will increase with multiplication number and they will always be worst close to the carrier. Thus, when making IMD measurements with very small offsets, the measurement range may be limited by the multiplied phase noise of the sources. Using one configuration, the two tone measurement at D-band with both 1 MHz and 100 MHz offsets are shown. While the point count in the plot of Fig. 11 is low, one can see the elevated noise floor. The products themselves are elevated by memory effects in the DUT (e.g., [7]) but the available range has been reduced by ~10-20 dB from noise multiplication. The general conclusion from the class of potential IMD issues so far is that

the choice of offset frequency can have a significant impact on uncertainty at least at lower product levels.

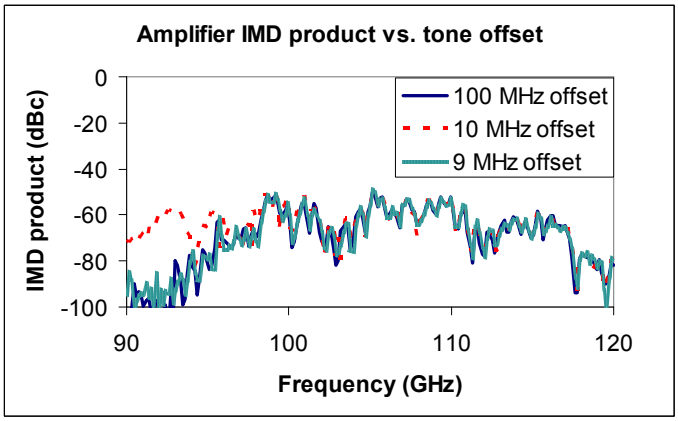

Figure 10. An example IMD measurement is shown here where the tone offset choice can make a difference due to multiplied source spurs.

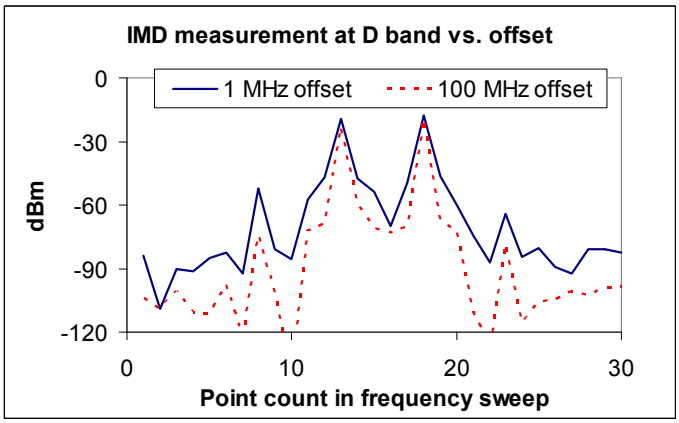

Figure 11. An example single point IMD measurement is shown here where the use of a small tone offset leads to noise floor elevation from multiplied phase noise.

Another potential issue that gets increasingly complicated at higher frequencies is the combining network for the tones. A variety of hybrids and splitters are available as discussed but the isolation between ports may not be as high as desired at all frequencies. The effects of low isolation can take several forms depending on the structure of the signal sources. Sources with relatively little buffering may be subject to frequency pulling from the other tone leaking in. More commonly, amplitude pulling occurs by the other tone interfering with a multiplier or with a leveling subsystem. The presence of the other tone generates mixing products that can re-modulate (either within a multiplier or a leveler) onto the tone producing a residual IMD product. In Fig. 12, about a 5-10 dB improvement in the result is achieved by increasing the isolation of the combining structure by ~10 dB. In this case, the isolation was improved through the use of loss and the signal source amplitude increased so the DUT saw the same main tone levels. Higher levels of isolation beyond 20 dB provided no additional benefit in this particular measurement.

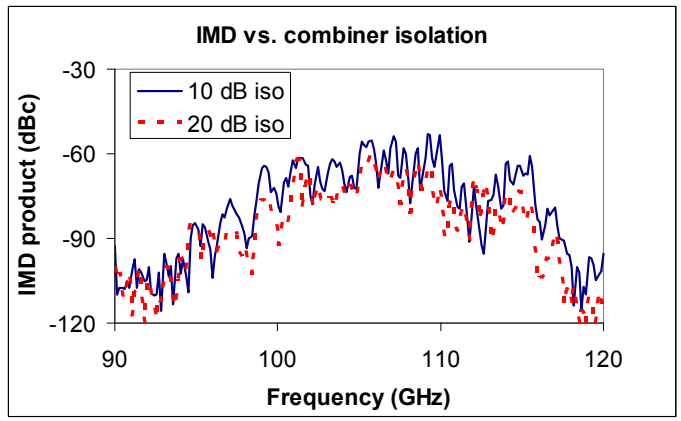

Figure 12. An example IMD measurement is shown here where the accuracy can be improved by increasing the isolation of the combining network.

One could argue that perhaps a better approach is to use a baseband multisine signal (e.g., [8]) that is then mixed up to the mm-wave band. The challenge in that case is that some of the favorable mixing products (as well as favorable internal spurs) can also end up being at IMD product frequencies. Some care is thus required with more integrated combining approaches as well.

By using a newer source structure [3] based on coupled multiplier arms, similar improvements can be made due to higher inherent isolation. In the newer structure, the leveling system detection (as well as the multiplier) is buffered from the signal source output so the 2nd tone cannot re-modulate onto the 1st tone. The resulting IMD products drop by up to 10-15 dB at some frequencies (see Fig. 13) versus those with a more exposed detection scheme. One could argue that an unleveled source may be a better option but the decrease in power stability would impact the IMD measurement accuracy (moving to different parts of the IMD curve) and making third-order intercept point (IP3) calculations less accurate.

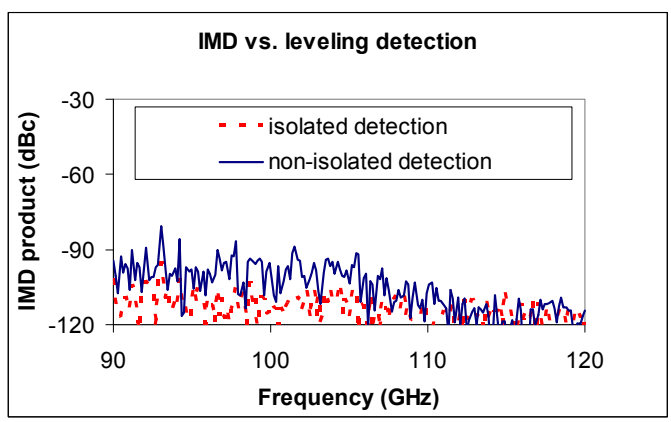

Figure 13. One mechanism that leads to isolation dependence is illustrated here: coupling of leveling systems. The use of a more isolated leveling system led to improvements in residual IMD.

To look at the power accuracy impact more closely, the primary issue is the possible extreme power dependence of the product generation process itself in some devices (e.g., [9]).

When multiple mechanisms phase, the apparent product can change dramatically hence the criticality of specifying the power at which the product is measured. An example device with such multiple mechanisms is shown in Fig. 14.

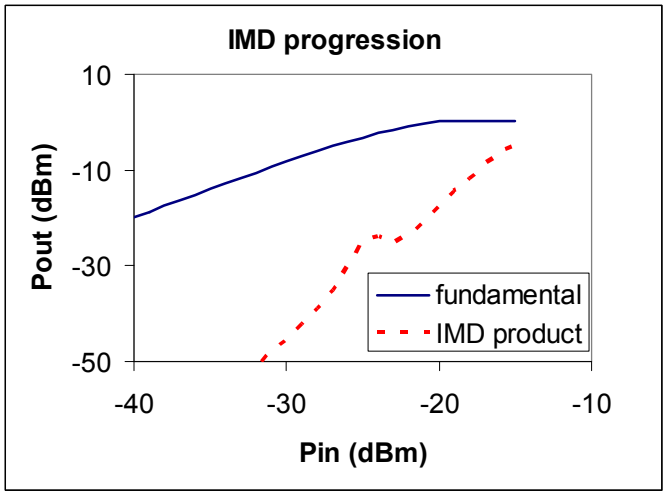

Figure 14. The power dependence of fundamental and third order product for an example DUT are shown here. The dip in the third order product is likely due to phasing of multiple third order mechanisms.

The effect of a 1 dB power accuracy error on the extracted product amplitude is shown in Fig. 15 and up to 4 dB error in the extracted IMD product could occur in this case. Above 100 GHz, power accuracy of 1 dB is sometimes challenging so this could be a significant source of uncertainty. Much above 140 GHz, traceability is potentially even more of an issue.

IV. Uncertainty comments

To make global uncertainty statements on these measurements would not be very useful because of the DUT dependence but some observations can perhaps be made. Some of the common uncertainty components are listed below along with their attributes and some common value ranges.

Compression (AM/AM and AM/PM)

Receiver compression (often < 0.1 dB below 10 dBm at receiver ports, loss after the DUT can help)

Power accuracy (effect depends on steepness of curves, can obtain <<1 dB power accuracy through W-band, may be much harder at higher frequencies)

Match effects (match compression can alter results unless full corrected, can alter P_{1dB} by ~1 dB in some cases and AM/PM by several degrees)

Harmonics and injection (may not be much of an issue unless very large or if DUT bias is very sensitive; can be significant in limiting cases)

IMD (similar comments as above plus the following)

Offset choice (spurs and phase noise multiplied up can make ~10 dB differences in residual products if chosen poorly)

Combiner isolation (can make 10 dB or more differences in residual products in some cases; consider total isolation through the source system)

Power accuracy has effects on both operating point and on intercept point calculations. Multiple dB effects are possible for 1 dB power errors.

Many of the IMD phenomena pertain primarily to the case of lower products (< -60 dBc) when system residuals and noise floor are likely to be important.

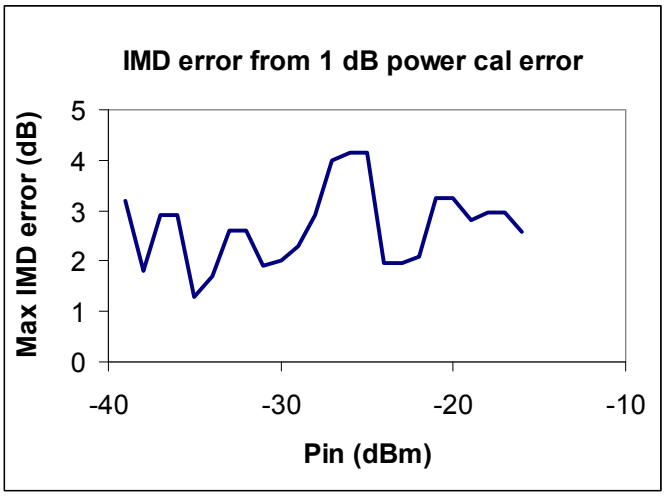

Figure 15. Based on the DUT of Fig. 14, the effect of a 1 dB power inaccuracy on extracted IMD product amplitude (dBc terms) is shown here.

V. Summary

A number of potential compression and IMD measurement issues that can be exacerbated at mm-wave frequencies have been discussed. At least within a relatively well-behaved class of DUTs, match issues and power accuracy had some the more notable impact on compression measurements (the latter of interest due to challenges with power accuracy and leveling >100 GHz) although receiver compression and spectral purity cannot always be ignored. In IMD, issues related to offset frequency selection (from spurs, phase noise or other spectral products) were among the more notable due to high source multiplication numbers that one might often encounter. Power accuracy can also play a significant role in IMD depending on the shape of the DUT's product generation curve as it may lead to an unexpected measurement definition point.

References

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