Custom MMIC

Application Note 106

IP2 Measurements of Wideband Amplifiers

v1.0

Description

Application Note 106 describes the theory and method used by Custom MMIC to characterize the second order intercept point (IP_2) of its wideband amplifiers. Custom MMIC offers a large selection of wideband amplifiers as standard products with superior IP_2 levels.

Background

Distortion in amplifiers can take many different forms. One type of distortion occurs when the output signal level gets large and approaches the 1 dB compression point of the amplifier. In this case, the output waveform is compressed or even clipped, and this action generates unwanted harmonics which are added to the desired signal. A second type of distortion, which can happen at any output power level, occurs when two signals at distinct but closely separated frequencies are presented to the input of the amplifier. Nonlinearities within the active devices cause these two signals to multiply together, and this multiplication produces distortion tones at frequencies different than, but related to, the input signals. The most prominent tones generated in this fashion are known as second-order and third-order distortion, where the order refers to the particular harmonic generated by the multiplication. Third order distortion affects every amplifier, as the distortion tones are close in frequency to the desired signals, so they appear within the bandwidth of the amplifier. Second order distortion, by contrast, does not affect every amplifier since these tones are not close in frequency to the desired signals, so they can fall outside the operating bandwidth of the amplifier, especially in narrow band designs. For wideband and distributed amplifiers, however, this is not the case. Second order distortion is both a major concern of and a major differentiator between wideband amplifiers.

To illustrate the phenomenon of second- and third-order distortion, let us consider an amplifier subject to two sinusoidal input signals of equal strength at frequencies f1 and f2, where f2 > f1. Furthermore, we assume the frequency difference between the two tones is small compared to their values (f2 – f1 << f1). We can represent this scenario on a spectrum plot of frequency (x-axis) versus power level (y-axis), as shown below in Figure 1:

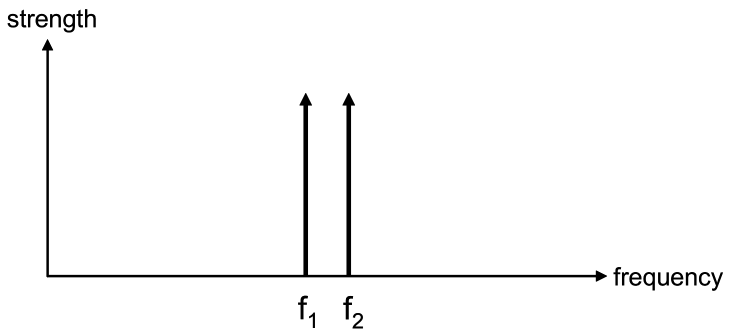

Figure 1: Spectrum plot of input signals at two distinct but closely separated frequencies, f_1 and f_2.

Let us now input these two tones into an amplifier and examine what emerges at the output. In the ideal situation, these two tones and these two tones only would emerge, albeit at a higher power level. But no real amplifier is ideal, so what emerges instead is a combination of the fundamental tones and some distortion tones. In Figure 2 below, we show the output spectrum of a typical narrowband amplifier, along with the major second- and third-order distortion tones generated by the amplifier.

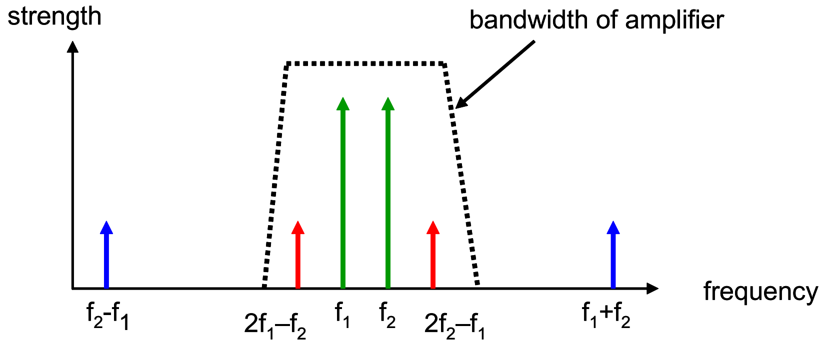

Figure 2: Output spectrum plot of a narrowband amplifier subjected to the two input tones of Figure 1. The amplifier bandwidth is shown with the dashed line.

In this figure, we have identified the fundamental output tones in GREEN, the second order distortion tones in BLUE, and the third order distortion tones in RED. The second order tones appear at the sum and difference of the two input frequencies f_1 and f_2, and these are called second order since the magnitude of the coefficients in front of f_1 and f_2 add to 2. The third order tones appear at frequencies $2f_1$-f_2 and $2f_2$-f_1, and these are called third order since the magnitude of the coefficients in front of f_1 and f_2 add to 3. Additionally in this diagram, we have added a dashed box to indicate the bandwidth of this particular amplifier. We note the third order tones, since they are very close to the desired fundamental tones, fall within the bandwidth of the amplifier, so they will be present at the output along with the desired signals. The second order tones, by contrast, are well outside the bandwidth so they will be greatly attenuated. Therefore, for this particular narrowband amplifier, third order distortion is of great importance, whereas second order distortion can likely be ignored.

In Figure 3, however, we consider the same output spectrum, only this time with a wideband amplifier. Again, we have identified the fundamental tones in GREEN, the second order distortion tones in BLUE, the third order distortion tones in RED, and the bandwidth of the amplifier by the dashed line.

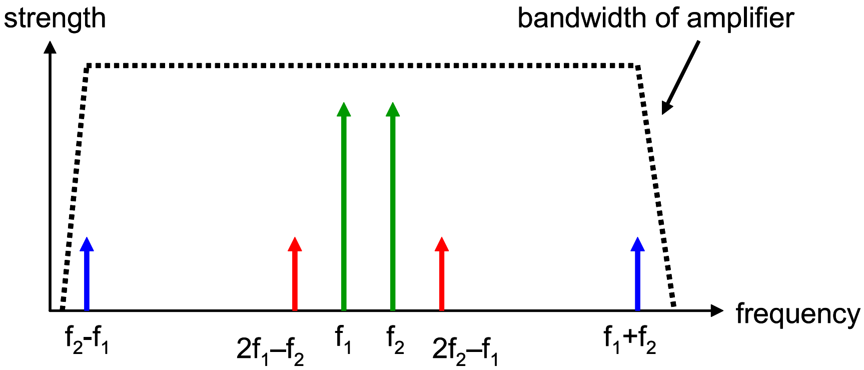

Figure 3: Output spectrum plot of a wideband amplifier subjected to the two input tones of Figure 1. The amplifier bandwidth is shown with the dashed line.

In this figure, we note the second order tones at f_1+f_2 and f_2-f_1 are now within the bandwidth of the amplifier, so they will emerge at the output at a significant level that cannot likely be ignored. So, for wideband amplifiers, we need to understand further this second order distortion and consider a figure of merit by which we can compare different circuits. That figure of merit is called the IP_2.

The Second Order Intercept Point, IP2

The intercept point is a powerful concept by which different amplifiers can be compared, for it speaks of the amplifier's linearity. The most common intercept point used as a figure of merit is the third order intercept point, or IP_3 for short. In a similar manner, we can consider the second order intercept point, which is called IP_2.

In Figure 3 above we identified the two second order tones, one at the sum frequency ($f_1 + f_2$) and one at the difference frequency ($f_2 – f_1$). However, we made no mention of the actual levels of these two tones. As can be shown through nonlinear circuit analysis and confirmed by measurement, these two second order tones have the property that in the linear region of the amplifier, their level increases by 2 dB for every 1 dB increase in the fundamental tones at f_1 and f_2. In Figure 4 below, we demonstrate this phenomenon by presenting the measurement of the fundamental and second order difference tone ($f_2 – f_1$) for the CMD192, Custom MMIC's flagship DC to 20 GHz distributed amplifier.

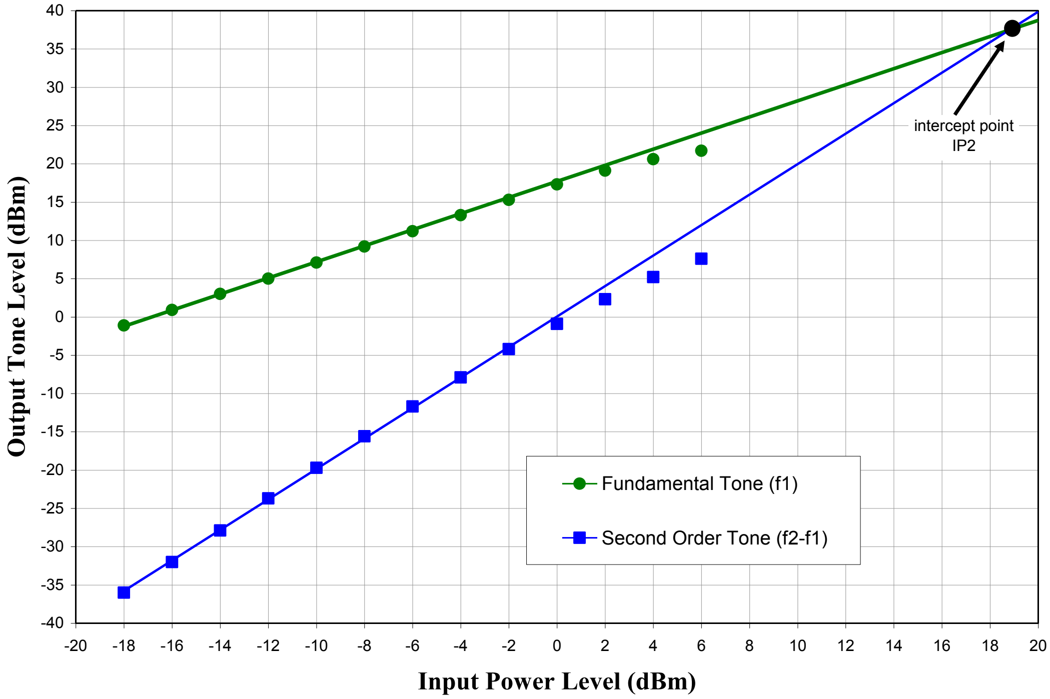

Figure 4: Output power level of the fundamental tone (f_1) and second order difference tone ($f_2 – f_1$) for the CMD192 amplifier, where f_1 = 3 GHz and f_2 = 3.8 GHz.

In this figure, we note the input power of the two fundamental tones was swept from -18 dBm to +6 dBm. The measured output power level of the fundamental tone at f_1 is shown in green, while the output level of the second order distortion tone (f_2-f_1) is shown in blue. The measurement of the second fundamental tone at f_2 was nearly identical to f_1, so it is not shown for brevity. We further note the slope of the second order distortion tone at lower (linear) input power levels is twice that of the fundamental tone, just as the theory predicts. Indeed, straight lines were drawn through the fundamental and second order responses and then extrapolated higher in power until they crossed – that intersection is precisely the IP_2 point. For amplifiers, the IP_2 is usually reported as an output power level (+37.5 dBm for this example).

On The Measurement of IP2

When measuring the IP_2 point, it is important that the levels of the fundamental and second order tones are within the linear region of the amplifier (well below its compression point), so that an accurate extrapolation of the intercept point can be obtained. For example, in Figure 4, we note that when the input power level per tone is 0 dBm or greater, the output fundamental and second order tones begin to deviate from their linear trends, which indicates the amplifier is approaching compression. Therefore, if we had started our extrapolation at an input power level of 0 dBm instead of -18 dBm, we would have arrived at an intercept point that was artificially high. Here at Custom MMIC, we always ensure the IP_2 is measured in the amplifier's linear region.

Second, we note that IP_2 is a function of fundamental frequency. This is especially true with the second order sum term (f_1 + f_2), as eventually the sum term will be above the amplifier's bandwidth and then naturally attenuated. In Figure 5 below, we show such a phenomenon by presenting the sum IP_2 for the CMD233 amplifier, a 2 to 20 GHz distributed low noise amplifier.

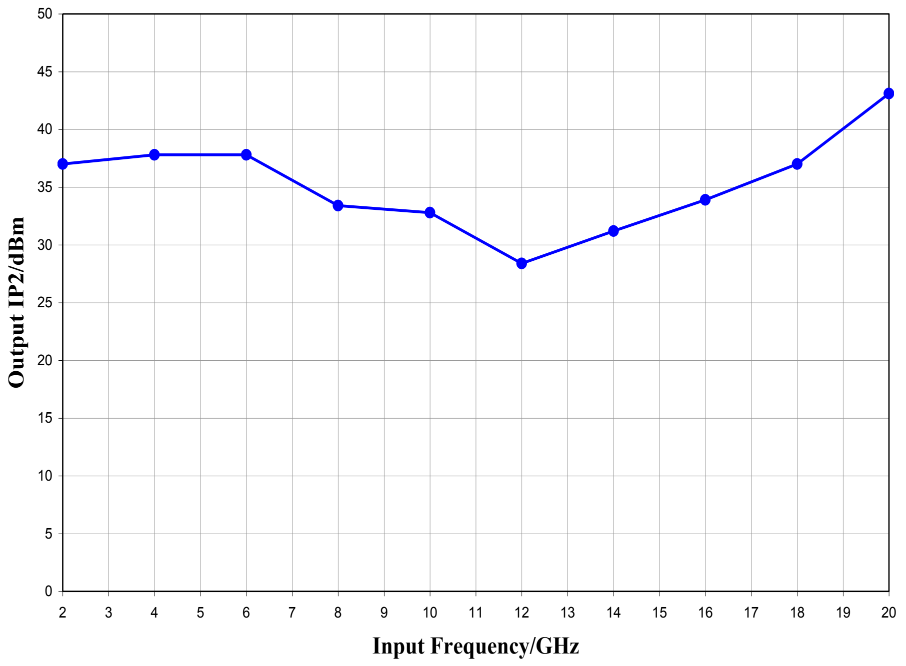

Figure 5: Output IP_2 (sum term) for the CMD233 wideband 2 to 20 GHz distributed low noise amplifier as a function of input frequency, f_1. Second input tone was $f_2 = f_1 + 100$ MHz, both tones at an input level of -10 dBm.

In this figure, we note the IP_2 of the sum term rises dramatically for input f_1 frequencies above 13 GHz (sum term above 26 GHz). This increase corresponds to the noticeable drop in the CMD233's gain above 20 GHz. Finally we note that the second order difference tone at 100 MHz (not shown) is well below the specified lower band edge of the CMD233, so it is attenuated to very low levels and can generally be ignored. Here at Custom MMIC, we measure the sum IP_2 across the operating frequency of the amplifier to determine these trends in performance, and where appropriate, we also measure the difference IP_2.

Finally, one problem which can arise in these measurements is extra IP2 distortion due to the spectrum analyzer, since such measurement equipment is inherently wideband. Most spectrum analyzers have very high IP2 intercept points, but if the output tones of the amplifier are strong enough, the analyzer can generate unwanted sum and difference signals, which will then add to the response of the amplifier. To prevent this extra IP2 distortion, attenuators can be placed between the amplifier and the analyzer to reduce the output signal level emerging from the amplifier. Experimentation may be required to determine the optimum attenuation level such that the output tones are still well within the dynamic range of the analyzer, but typically 10 to 20 dB of attenuation is sufficient.