Enhancing Second Harmonic Suppression in an Ultra-Broadband RF Push-Pull Amplifier

By Gavin T. Watkins

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Abstract

An ultra-broadband push-pull amplifier operating over a bandwidth of two and a half octaves from 50 MHz to 300 MHz is described here. The broadband second harmonic distortion suppression of the amplifier is characterized in terms of gain and phase imbalance between the two amplifier paths. By incorporating an attenuator and delay line in one of the paths the distortion suppression of the amplifier is modified so that greater than -45 dBc is achieved over the whole band. Up to 11 dB improvement in suppression was achieved using this method.

Introduction

In low power and broadband applications where amplifier efficiency is noncritical, shunt-series feedback is often used [1]. At high powers this is impractical due to the low efficiency and the parasitic strays of resistive elements used in the feedback network. Transformer-coupled push pull amplifiers are capable of efficient operation at medium and high output power levels. Since transformers can provide a purely resistive impedance transformation over their operating range, broadband operation of 1:250 is possible [2]. Some less traditional applications have also emerged like envelope tracking where extremely wide operation is again required [3].

Transformer Coupled Push-Pull Amplifier

A push-pull amplifier generally consists of four main elements: an input transformer connected in anti-phase, two single ended amplifiers (SEAs) and an output transformer to combine the outputs of the SEAs in anti-phase as shown below in Fig. 1 (a).

The output spectrum of each SEA consists of a fundamental tone and harmonically related distortion products as shown by the Volterra series:

$$y(t) = a_1 x(t) + a_2 x(t)^2 + a_3 x(t)^3 + a_4 x(t)^4 \ldots \tag{1}$$

where x(t) is the input signal and y(t) the output. Because the center tap of input transformer's secondary is grounded, one SEA will see x(t) as its input and the other –x(t). Since the $(-x(t))^2$ is equal to $(-x(t))^2$, the output y_1(t) of path one and y_2(t) of path two will be:

$$y_1(t) = a_1 x(t) + a_2 x(t)^2 + a_3 x(t)^3 + a_4 \; x(t)^4 \ldots \tag{2}$$

$$y_2(t) = -a_1 x(t) + a_2 x(t)^2 - a_3 x(t)^3 + a_4 \; x(t)^4 \ldots \tag{3}$$

y_1(t) and $y_2(t)$ are combined in anti-phase resulting in the fundamental components (FUN) and odd order harmonics adding, whereas the even order harmonics cancel [4].

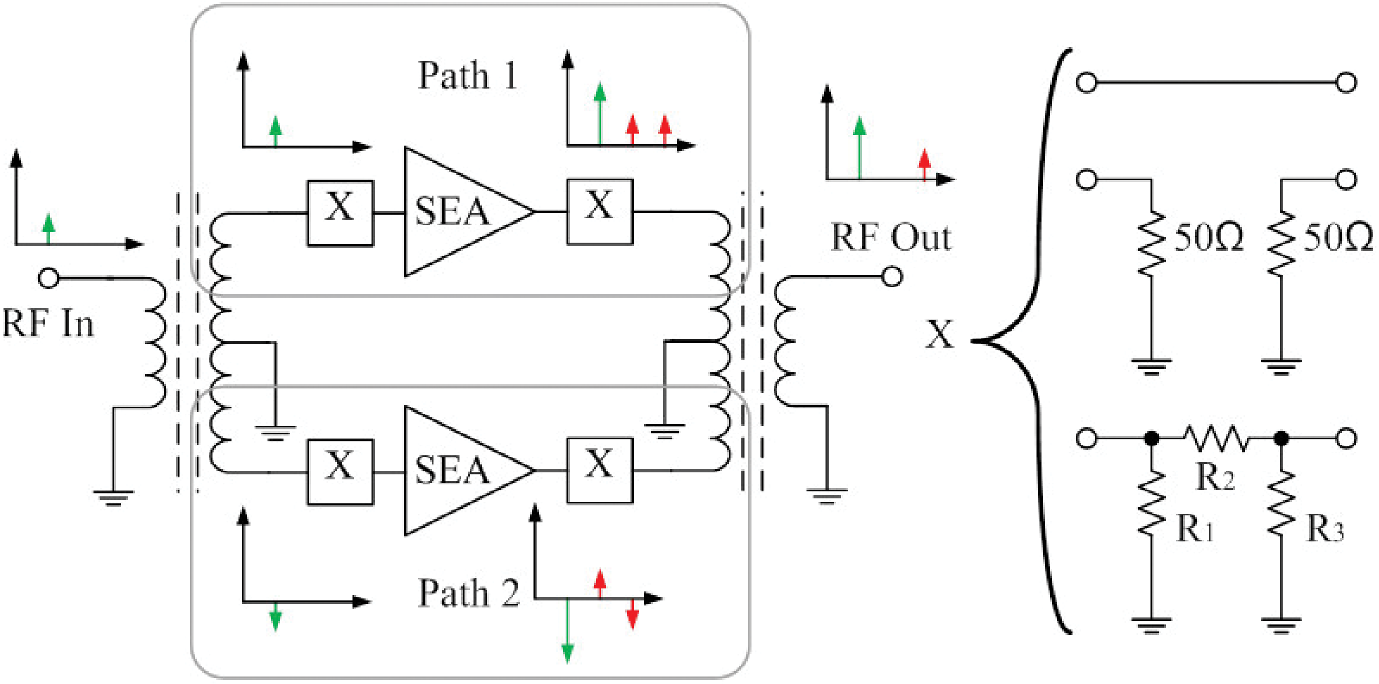

Figure 1 •Push-pull amplifier where block X can be either a short, two 50Ω loads, or a Pi type attenuator.

Second Harmonic Suppressions in Push-Pull Amplifiers

Second harmonic distortion (2HD) in transformer coupled push-pull amplifiers has previously been examined [5] [6], but no mechanisms given for enhancing its suppression. 2HD is generated by non-linear processes, but its suppression is linear. A high degree of suppression requires a very small gain and phase imbalance [7]:

$$S_{dB} = 10\log_{10}((\cos\delta\theta - \delta A\cos\delta\theta)^2 + (\sin\delta\theta + \delta A\sin\delta\theta)^2) \qquad (4)$$

where δθ is the phase imbalance between the two signals, and δA the amplitude imbalance. A phase and gain imbalance of 1° and 1 dB results in -18.8 dB suppression [8] as shown in Fig. 2.

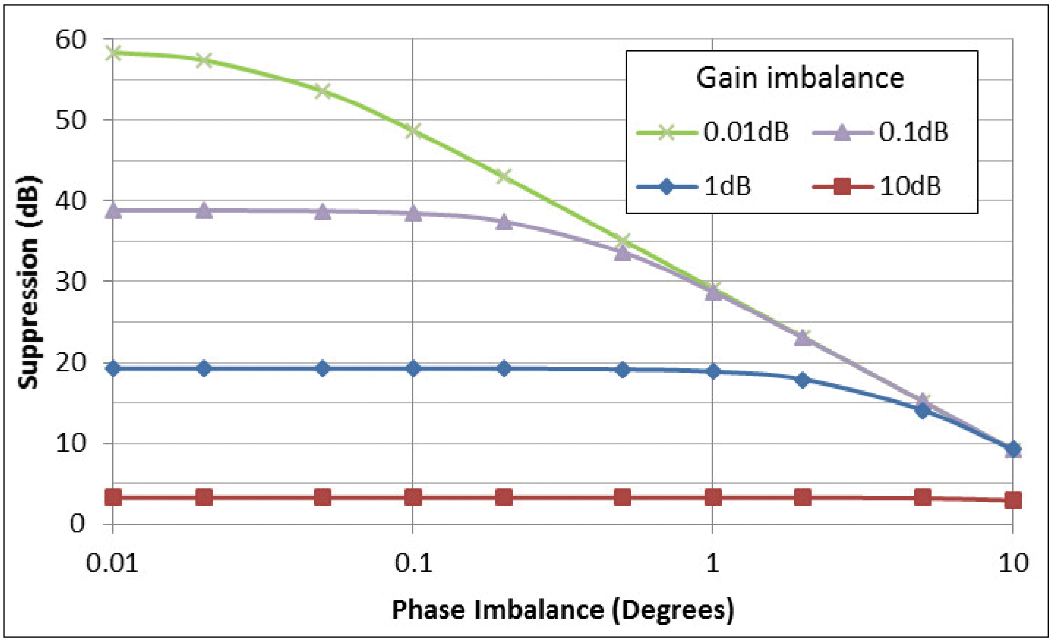

Figure 2 • Dependence of signal suppression on gain and phase imbalance.

Fig. 2 is applicable for 2HD imbalance incurred at the output of the SEAs. Phase imbalance to the FUN at the input of the SEAs will result in a doubling of the 2HD phase imbalance at their outputs because if:

$$x = \cos \delta\theta \tag{5}$$

then:

$$x^2 = (\cos \delta\theta)^2 = \frac{\cos 2\delta\theta + 1}{2} \tag{6}$$

The impact of FUN input gain mismatch on the 2HD will be similarly affected by the x^2 term.

Practical Amplifier Measurements

A test amplifier using two Analog Devices ADL5536s [9] was developed based on Fig. 1 (b). A photograph of it is shown in Fig. 3.

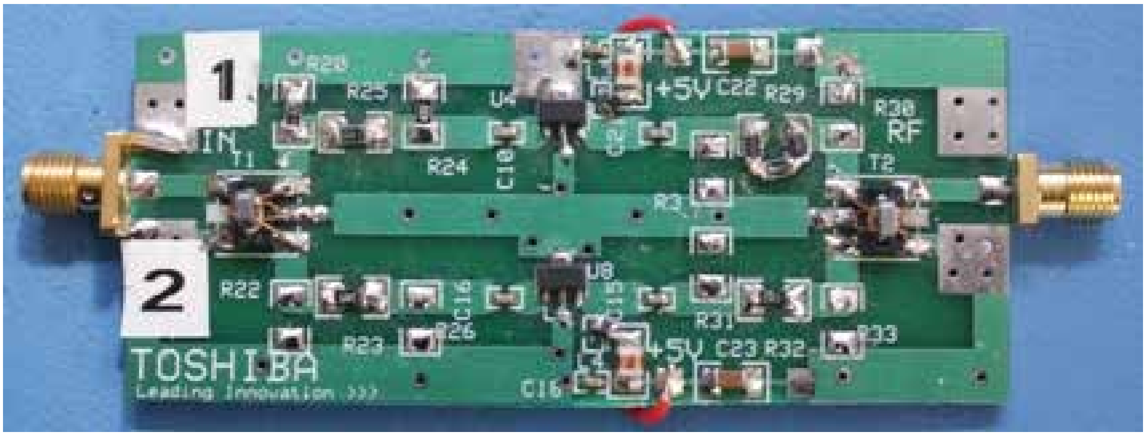

Figure 3 • Photograph of test amplifier.

The ADL5536 has a 1dB compression point (P_{1dB}) of 20 dBm and a second order intercept point (IP2) of 60 dBm. In a push-pull amplifier due to the signal power being amplified by two separate paths the combined P_{1dB} will be 3 dB greater at 23 dBm. This assumes that the two paths are combined perfectly in phase. Any discrepancy in their phase will lead to a slight reduction in the combined amplitude [10].

The ADL5536 has a gain of 20 dB. With an IP2 of 60 dBm at the individual SEAs P_{1dB} of 20 dBm, the 2HD will be -17 dBm, or -37 dBc relative to the FUN [7]. The 2HD at the output of the push-pull amplifier will be susceptible to the 3dB loss due to the combining transformer. Therefore it follows, that without any suppression the 2HD at the P_{1dB} should be -40 dBc. This is a typical value for a broadband transformer coupled push-pull amplifier [2]. The measured P_{1dB} and 2HD suppression of the test amplifier are shown in Fig. 4.

Although the two paths of the amplifier in Fig. 3 appear visually identical, Fig. 4 suggests otherwise. At 100 MHz the P_{1dB} is 23 dBm as it should be, and the 2HD suppressed by an additional 17 dB to -54 dBc. However at 300 MHz the measured P_{1dB} and 2HD suppression are equivalent to that of a single SEA.

This degradation is due to gain and phase imbalance between the paths. By splitting the push-pull amplifier into two paths each can be examined in isolation. Since the imbalance is due to both the SEAs and the transformer, it is necessary to include the transformers in these measurements. For example, to evaluate Path 1, the two X blocks of Path 2 in Fig. 1 are broken, both the transformers and SEA's input and output ports terminated with 50 Ω resistors. The ADL5536 has an $|S_{11}|$ of approximately -19 dB and an $|S_{22}|$ of -15 dB over the band of interest, which is close enough to 50 Ω.

By doing this the FUN and 2HD transfer responses of each path can be measured as shown in Fig. 5 and Fig. 6 respectively at both 150 MHz and 300 MHz, where performance is worse.

At 150 MHz, the gain imbalance between the generated 2HD is approximately 1.5 dB. Assuming zero phase imbalance, then (2) predicts an additional 2HD suppression of 16 dB. At 300 MHz the 2HD has a highly no-linear response, increasing by 6.4 dB/dB at worst. However, the gain imbalance at the P_{1dB} is only 0.2 dB, equivalent to an additional 33dB of suppression, assuming zero phase imbalance.

It will be noted that the level of 2DH generated is considerably greater than that predicted by the IP2. This is likely due to the IP2 being a small signal measurement, not when the ADL5536 is at its P_{1dB}.

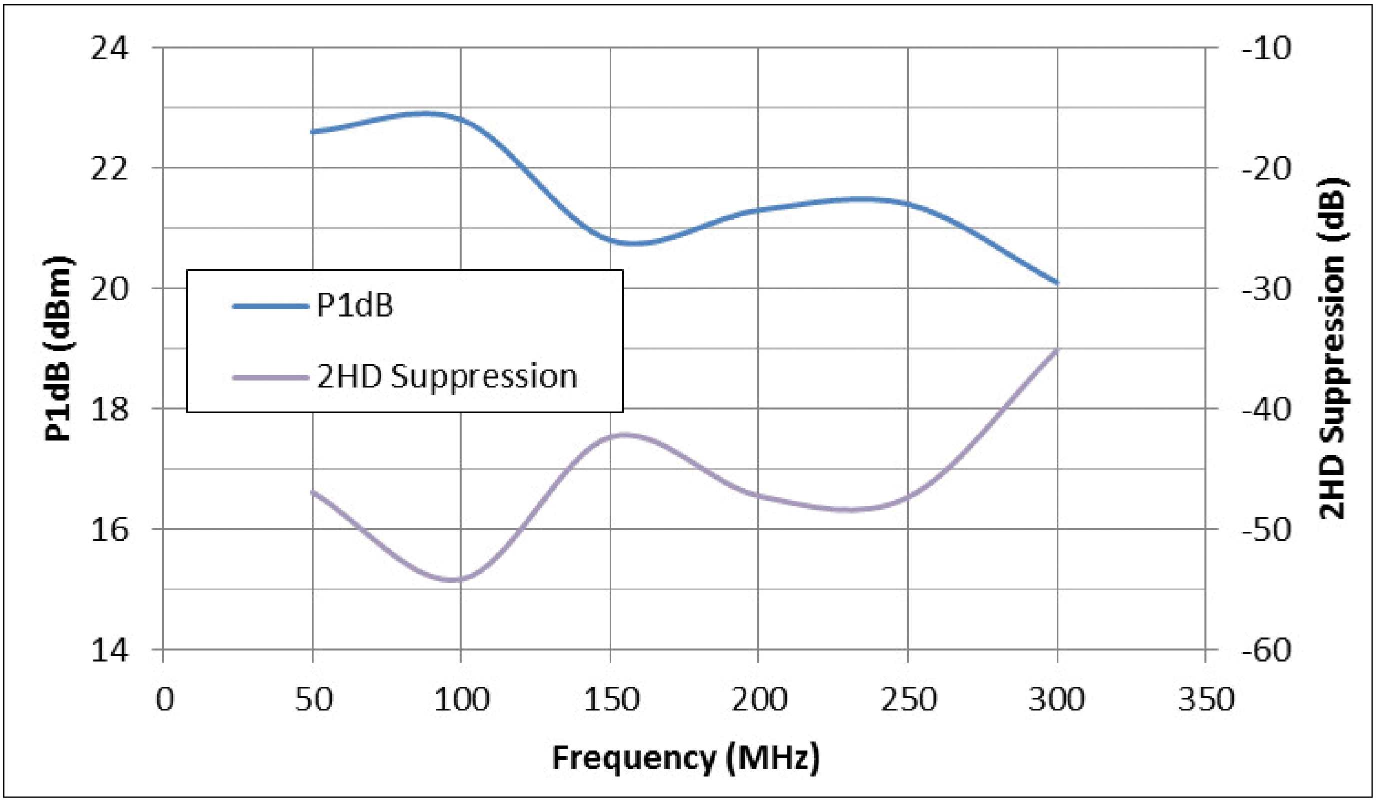

Figure 4 • P_{1dB} and 2HD suppression of test amplifier.

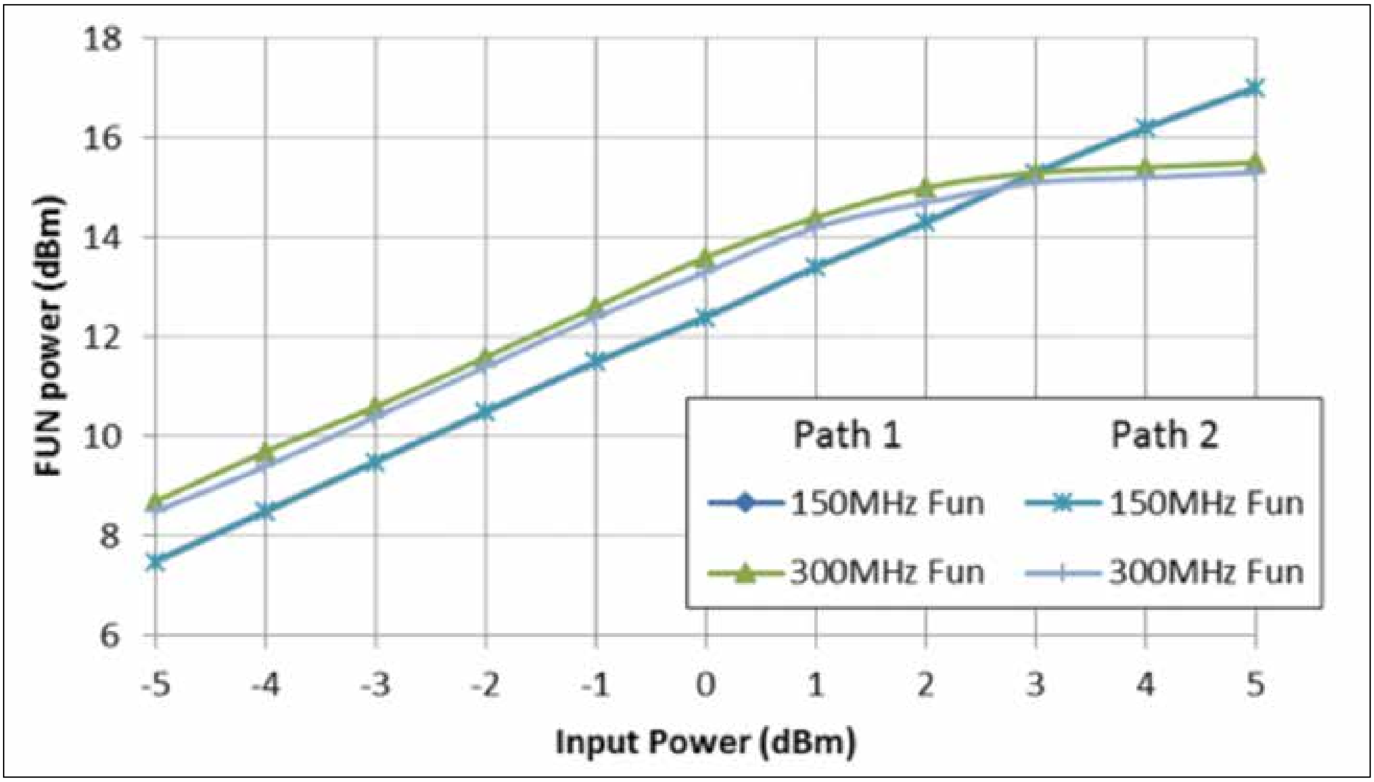

Figure 5 • Power of the fundamental component at 150 MHz and 300 MHz up to the P_{1dB}.

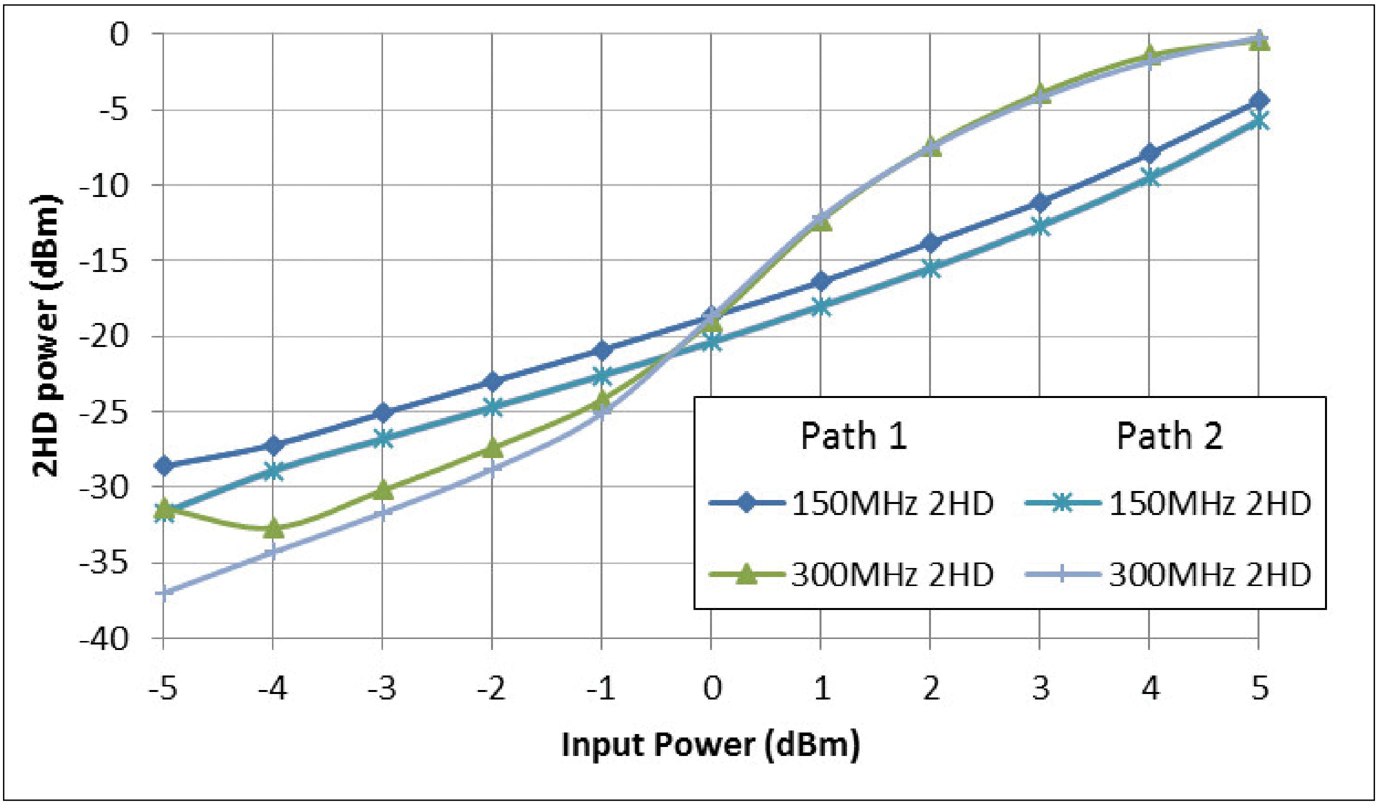

Figure 6 • Power of the second harmonic component at 150 MHz and 300 MHz up to the P_{1dB}.

Modelling the 2HD Suppression

The degree to which gain imbalance in the individual paths affects the generated 2HD distortion can be analyzed by subtracting the individual powers of each path:

$$2HD_{pp} = 20\log_{10}\left(\left|10^{\left(\frac{2HD1}{20}\right)} - 10^{\left(\frac{2HD2}{20}\right)}\right|\right) \tag{4}$$

$2HD_{pp}$ is the 2HD of the push-pull amplifier, $2HD_1$ path 1 and $2HD_2$ path 2. Base on (7) and the results presented in Fig. 4, and Fig. 6 are compared in Table 1 at the P_{1dB}.

2HD	150 MHz	300 MHz
Measured push-pull amplifier	-21.7 dBm	-15.0 dBm
Measured Suppression	-42.4 dBc	-35.1 dBc
Measured Path 1	-4.4 dBm	-0.4 dBm
Measured Path 2	-5.7 dBm	-0.2 dBm
Modelled (7)	-21.5 dBm	-33.1 dBm
Modelled Suppression	-44.4 dBc	-54.5 dBc

Table 1 • Measured versus modelled 2HD.

It is noted that at 150 MHz the model fits the measurements, suggesting that limited 2HD suppression is due to a gain imbalance between the paths. However, at 300 MHz, there exists a 19.4 dB difference between the measured and modelled results, suggesting a phase imbalance is the cause.

If zero gain imbalance is assumed, then the phase imbalance at 300 MHz is 5.2°. Since the phase shift through a delay line is proportional to frequency that at 150 MHz would be 2.6 °. This assumes a first order phase response, i.e.

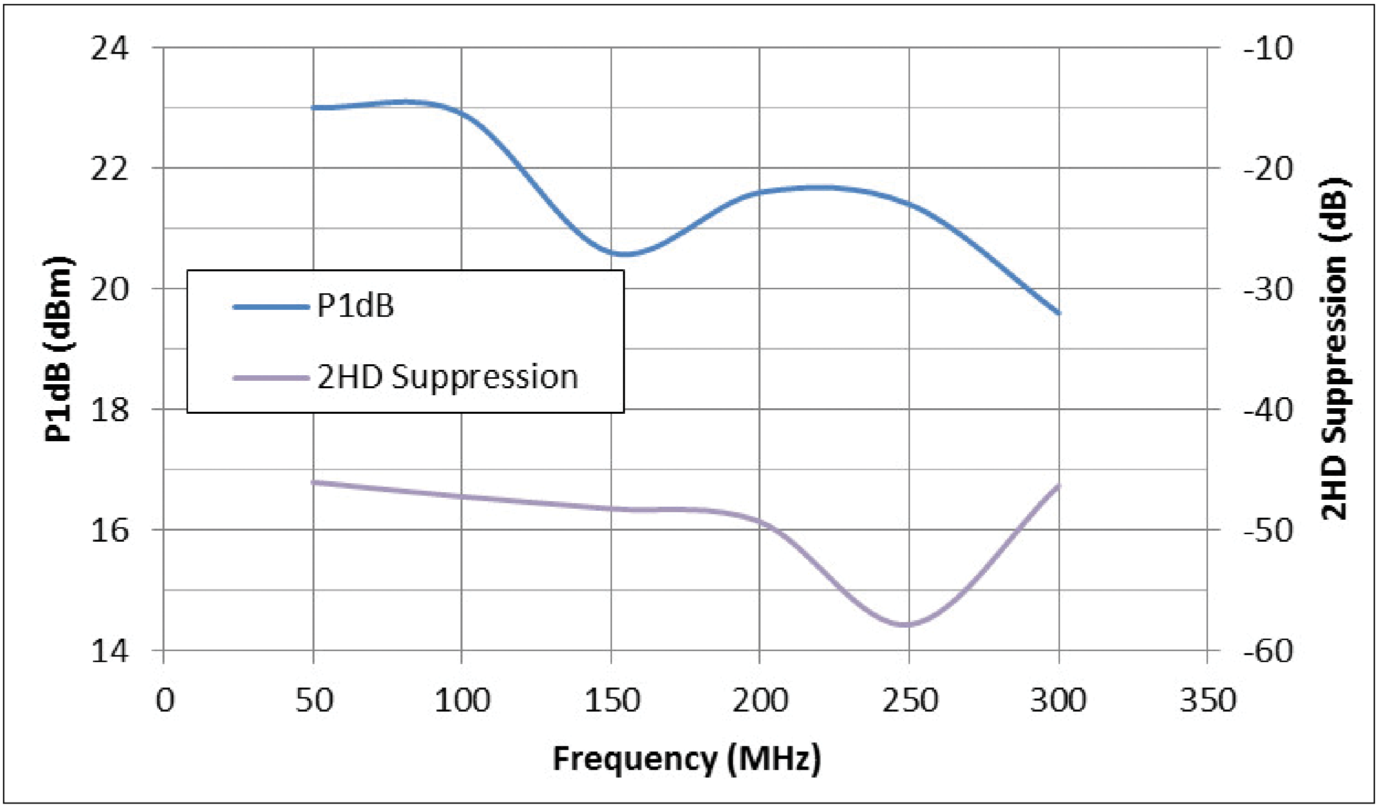

Figure 7 • Broadband compensated second harmonic.

increasing linearly with frequency. However, if the phase imbalance originates from the input of the SEAs it will be second order (6), i.e. phase shift is proportional to frequency^2.

Compensation of Phase and Gain Imbalance

The 2HD of the SEAs at 150MHz increases at a rate of 2.8dB/dB as they approach the P_{1dB}. Therefore $x(t)^2$ in (1) becomes $x(t)^{2.8}$. The 2HD generated in Path 1 is reduced to the level of that of Path 2 with an attenuator at the input. As a compromise a 0.2dB Pi attenuator composed of 1 Ω and 4.3 kΩ resistors was found to work best. The 2HD suppression at 300MHz was improved with a small delay line also in Path 1. The optimum place for this was after the SEA, the phase shift it introduces will therefore be first order. The enhanced 2HD suppression is shown in Fig. 7.

Comparing Fig. 7 to Fig. 4, it is observed, that the 2HD is now suppressed by at least 45dB over all of the band, an improvement of 11.2dB at 300MHz.

Over narrow bandwidths suppression could be enhanced further, but the aim of this work is broadband compensation of 2HD over the whole 50 MHz to 300 MHz band. The measured 2HD with compensation at 150 MHz at the P_{1dB} was -22.2 dBm, resulting in -42.7 dBc suppression and -26.7 dBm at 300 MHz resulting in -46.3 dBc. The 2HD is kept below -45 dBc apart from at 150 MHz due to a dip in FUN power. The reason for this is currently unknown, but likely due to resonances in the board layout. Applying these techniques to other push-pull amplifier like [2] would improve its 2HD suppression.

Other factors not modelled in this paper are the distortion products generated at the input of the SEAs and reflected back into the input transformer [11]. The input generated distortion of one SEA will be amplified by the other. This highly non-linear effect, is hard to model, due to its phasing and combining in the transformer, but could possibly be exploited to improve 2HD suppression in the future.

Conclusion

The second harmonic suppression of a broadband push-pull amplifier is examined here and mechanisms devised to improve it. Although the generation of the distortion is non-linear its suppression is linear. For a test amplifier phase imbalance was compensated for by introducing a small electrical delay into one of paths and gain imbalance with an attenuator. Using these techniques, the suppression was enhanced by up to 11.2 dB over an operating bandwidth of 50 MHz to 300 MHz.

About the Author:

Gavin T. Watkins, MIET, MEuMA, serves as Principal Research Engineer at Toshiba Research Europe Limited, 32 Queen Square, Bristol BS1 4ND, United Kingdom, gavin.watkins@toshiba-trel.com.

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