FFT WINDOWS FOR INTERMODULATION ANALYSIS OF MICROWAVE CIRCUITS FROM TRANSIENT SIMULATION

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ABSTRACT

The use of time-domain window functions is investigated for intermodulation analysis of two-tone transient simulations. Window selection is dependent on wether fast Fourier transform (FFT) dynamic range is noise limited by interpolation noise or by window roll-off characteristics. Two tone transient and harmonic balance simulations of a MESFET amplifier show excellent agreement over a wide dynamic range.

INTRODUCTION

Time domain transient simulators such as SPICE and its many derivatives are popular simulators for analog and digital integrated circuit design. Transient simulators are capable of accurately simulating high order intermodulation products of RF and microwave integrated circuits where high Q circuits and distributive elements are not prevalent. Harmonic balance techniques are generally more efficient at solving two-tone intermodulation; however, many commercial transient simulators do not include harmonic balance analysis. Typically, SPICE post processors provide a FFT algorithm to analyze simulation spectrum, but usually there is little information available about signal processing techniques for achieving good FFT dynamic range and frequency resolution. Moreover, time-domain results are often interpolated to generate uniform time step data from adaptive time step results or to generate 2^N data points to take advantage of computation efficient FFT algorithms without regard or warning as to the impact on the resulting spectrum.

This paper presents a method for analyzing the intermodulation products of two-tone transient simulations using the fast Fourier transform and time domain window weighting functions. Use of a window weighting function enhances FFT dynamic range for a small loss in frequency resolution. Several window functions are compared for dynamic range improvements over using no window function. Window selection for noise limited and window limited dynamic range is discussed. Finally, two tone transient simulations of a MESFET amplifier are compared with two tone harmonic balance results.

TIME DOMAIN WINDOW FUNCTIONS

Spectral leakage is a phenomena associated with applying the FFT to signals that are not periodic within a finite sample set. Interpolated results, simulator inaccuracies, and transient response are sources of spectral leakage when analyzing transient simulation results. Spectral leakage represent signal energy which is not commensurate with any one frequency bin of the FFT; as a result, part of the signal is distributed randomly, or leaked, over the spectrum. Spectral leakage increases FFT noise floor thus degrades dynamic range.

Use of time domain window weighting functions greatly reduces the detrimental effects of spectral leakage. Window functions are characterized by their frequency domain characteristics. The most important properties for intermodulation analysis are peak side-lobe level, side-lobe roll-off, and main lobe bandwidth. Good window functions for intermodulation analysis exhibit low peak side-lobe level, steep side-lobe roll-off, and minimal bandwidth. Peak side-lobe levels and roll-off indicate the ability of a widow to resolve small signals in the presences of a large signal while the bandwidth indicates the loss in frequency resolution. A listing of the frequency properties of five windows is given in table 1 [1]. Many window functions exists; however, these four are commonly available in several FFT post processors.

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WINDOW	GAIN	PEAK SIDE-LOBE LEVEL dB	SIDE-LOBE ROLL-OFF dB/OCT	3 dB BW (BINS)
RECTANGLE	1.0	-13	-6	0.89
HAMMING	0.54	-43	-6	1.30
HANNING α=2	0.50	-32	-18	1.44
HANNING α=4	0.38	-47	-30	1.86
BLACKMAN	0.42	-58	-18	1.68

Table 1: Window function frequency domain characteristics.

NOISE LIMITED DYNAMIC RANGE

Transient simulators implement adaptive time-step algorithms to reduce simulation time when signals are not changing rapidly. The final results are interpolated to a uniform time step from the adaptive results. Typically, linear or second order interpolation is used to generate uniform time steps from adaptive time step data. In addition, the data may also be interpolated to 2^N data points to take advantage of the computational efficiency of FFT algorithms.

Interpolation generates spectral noise and nonlinear distortion which limits FFT dynamic range. Dynamic range of noise limited data is improved with the use of time-domain window weighting functions. Window functions only suppress spectral leakage allowing dynamic range to be improved down to the noise floor generated by interpolation. Peak side-lobe level and bandwidth are more important than side-lobe roll-off when selecting a window function for noise limited results. Frequency resolution is slightly improved since tones can be moved closer together without generating additional interference. Comparisons of noise limited window responses are shown in figures 1a and 1b. The Hanning α=2 window provides the best trade off between dynamic range and frequency resolution.

WINDOW LIMITED DYNAMIC RANGE

Best dynamic range is achieved when simulation results occur at uniform time steps corresponding to an integer division of the beat frequency period. A few time-domain simulators find solutions at a fixed simulation time step; although, simulation run times are longer than when using adaptive time steps. In this case, dynamic range is limited by simulator accuracy and circuit transient response since interpolation is not needed.

Unfortunately, the transient response generates enough spectral leakage that window functions are required to enhance dynamic range; although, the data is not noise floor limited as in the case of interpolated results. In this case, FFT dynamic range is limited by window side-lobe roll off rate and peak side-lobe level. Here the trade-off between frequency resolution and dynamic range is more pronounced. Dynamic range is improved by increasing the number of frequency bins between the input tones by either lengthening simulation time or increasing tone frequency spacing. Comparisons of window limited dynamic range are shown in figures 2a and 2b. Note that the dynamic range is increased by 100 dB over the noise limited case when using the Hanning α =4 window.

EXAMPLE

A single stage GaAs MESFET common source amplifier was chosen to demonstrate the dynamic range capability of two-tone transient simulations. The TOM-2 [3] MESFET model was used from a commercial transient simulator library [4]. The same model was implemented in a commercial harmonic balance simulator as a symbolically defined device for comparison. Input tones were selected a 820 MHz and 850 MHz and swept in power from -50 to 10 dBm in 1 dB steps. The Hanning α=2 window was selected because of its excellent amplitude and frequency resolution characteristics for noise limited results. Transient simulation time step was set to 20ps and simulation time length to 200ns yielding a sampling frequency of 25 GHz and FFT resolution of 5 MHz/bin. A plot of fundamental, third order intermodulation, and fifth order intermodulation simulation results for transient and harmonic balance are shown in figure 3. Transient simulation has an IMR dynamic range around 100 dB at -35 dBm input power and becomes noisy at lower input power levels. The fifth order dynamic range is greater than 80 dB at -10 dBm input power. Third order IM transient results show excellent agreement with harmonic balance simulations for input powers between -35 and 0 dBm. Transient results begin to differ at saturation power levels due to the transient response at high drive levels. Transient results over estimate compressed output power and third order distortion for input levels

Another transient simulation was performed to overcome the transient response by lengthening the duration from 200ns to 2µs without changing the tone spacing. Results of this simulation are show in figure 4. The lengthened transient simulation converges to the steady state harmonic balance solution. The fundamental, third, and fifth order intermodulation products are in good agreement with harmonic balance results. These results emphasize that harmonic balance techniques are more efficient for obtaining steady state results when devices are operating near or above saturated output power levels.

CONCLUSION

This paper presented a method for analyzing the intermodulation products of two-tone transient simulations using the fast Fourier transform and time domain window weighting functions. Several window functions were compared for dynamic range improvements over using no window function. Hanning α=2 and α=4 windows provide the best trade off between amplitude and frequency resolution for noise limited and window limited simulation results respectively. Two-tone transient simulations of a GaAs MESFET amplifier were shown to have excellent agreement with two tone harmonic balance results for input power levels below device saturation. Short duration transient simulations over estimate saturated output power and intermodulation distortion levels. Lengthening simulation time improves transient results when operating near or above output saturation.

REFERENCES

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[3] D. H. Smith, “TOM-2: An Improved Model for GaAs MESFETs,” copies available from TriQuint Semiconductor.

[4] PSpice trademark of MicroSim Corporation version 6.3.

[5] Microwave Design System trademark of HP-ESSOF version 7.0.

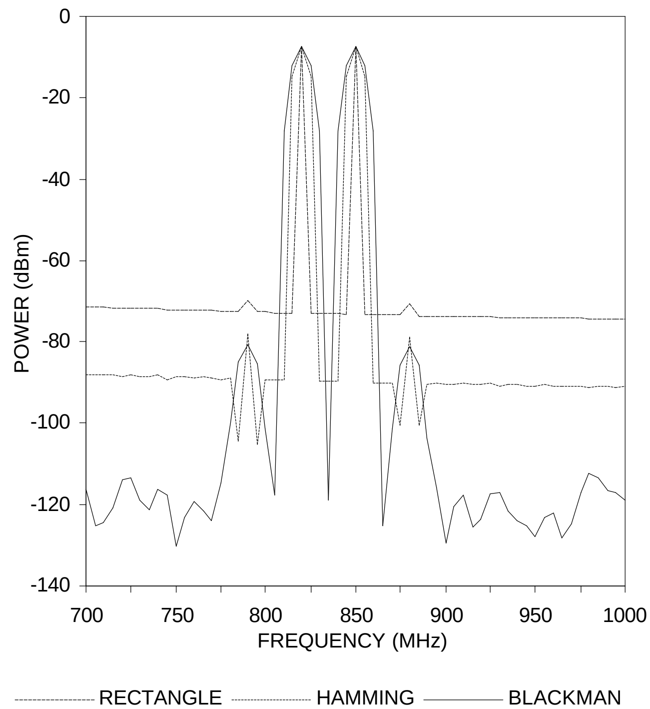

Figure 1a: Noise limited dynamic range comparison.

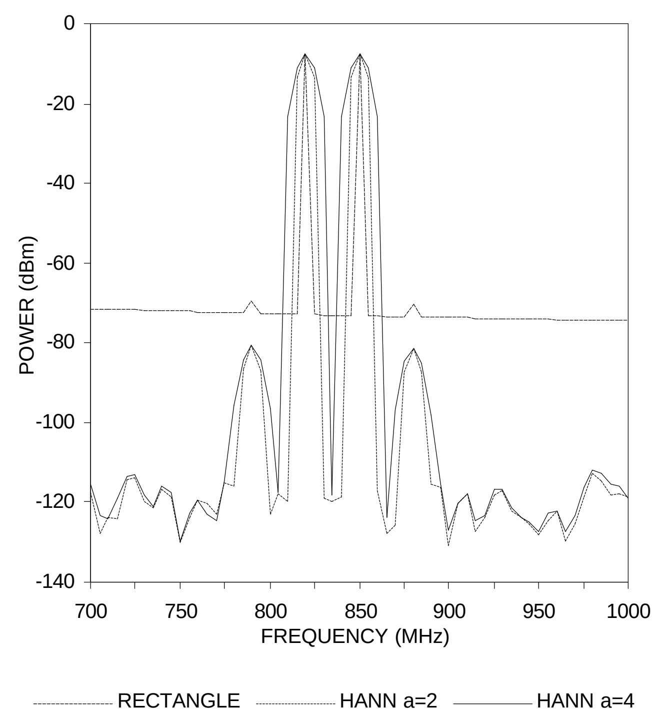

Figure 1b: Noise limited dynamic range comparison.

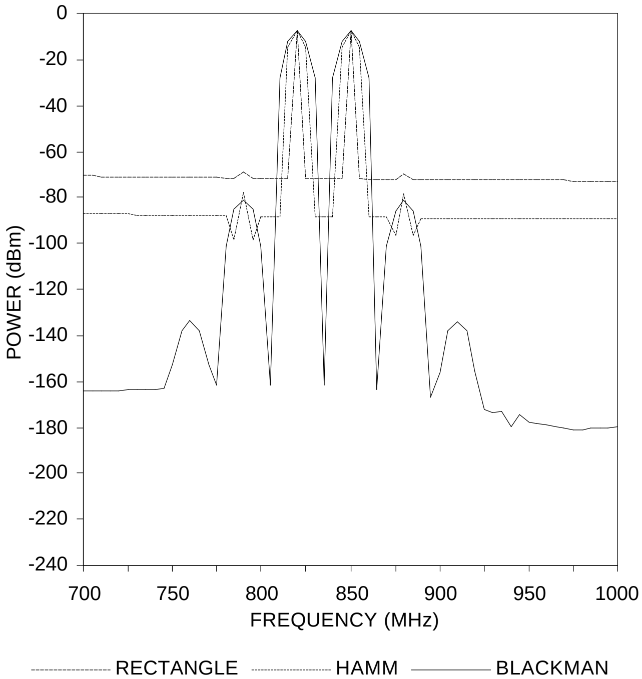

Figure 2a: Window limited dynamic range comparison.

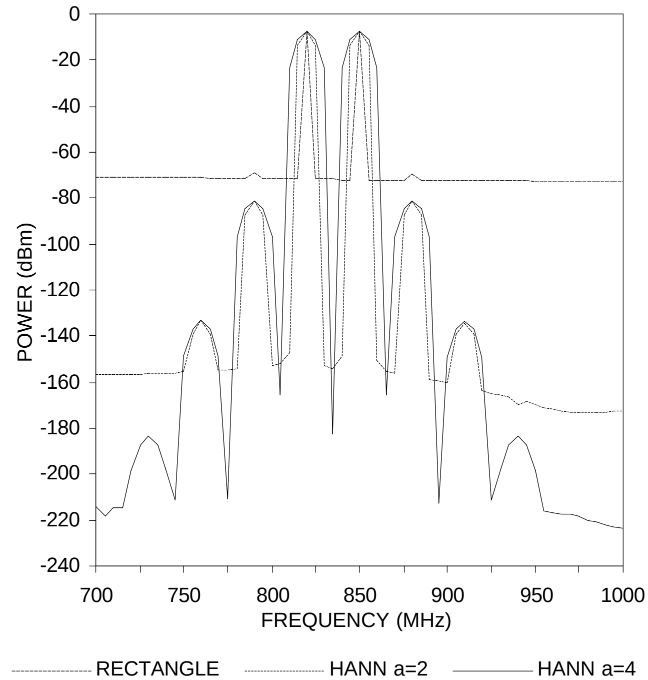

Figure 2b: Window limited dynamic range comparison.

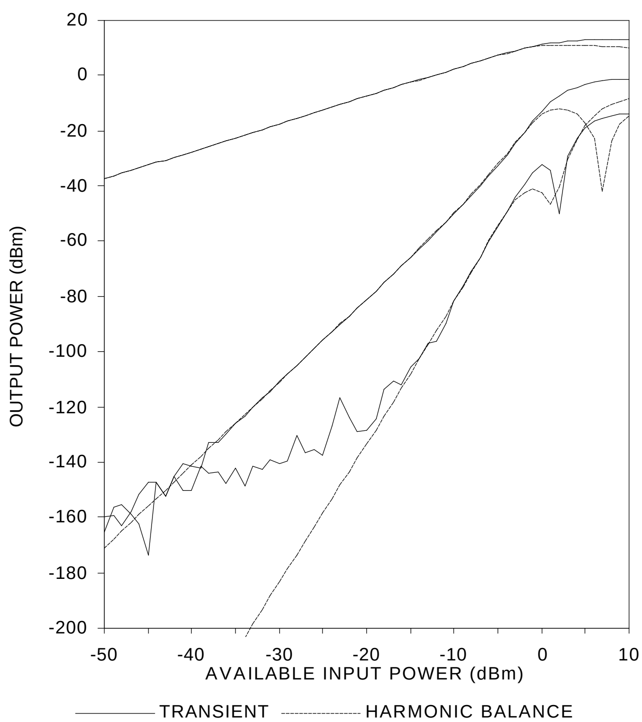

Figure 3: Power sweep results of 3rd and 5th order intermod using noise limited Hanning α=2 window with 5MHz/bin resolution.

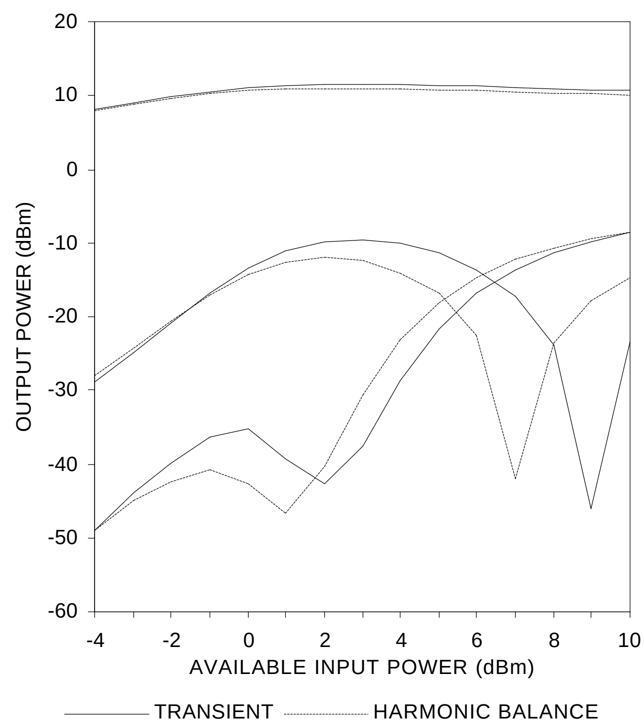

Figure 4: Power sweep results of 3rd and 5th order intermodulation with simulation time increased to $2\mu s$.