A Research on the Magnitude/Phase Asymmetry Measurement Technique of the RF Power Amplifier Based on the Predistortive Tone Cancellation Technique

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Abstract

This paper proposes a novel memory effect measurement technique in RF power amplifiers(PAs) using a two-tone intermodulation distortion(IMD) signal with a very simple and intuitive algorithm. Based on the proposed predistortive tone cancellation technique, the proposed measurement method is capable of measuring the relative phase and magnitude of the third-order and fifth-order IMDs, as well as the fundamental signal. The measured relative phase between the higher and lower IMD signal for specific tone spacing can be interpreted as the group delay(GD) information of the IMD signal concerned. From the group delay analysis, we can conclude that an adaptive control of GD as well as the magnitude and phase is a key function in increasing the linearization bandwidth and the dynamic range in a predistortion(PD) technique.

Key words : Intermodulation Distortion, Linearization, Memory Effect, Predistortion.

I . Introduction

To provide multimedia services such as video, music, photo, and other real-time location based applications in addition to the traditional voice and text message, digital modulation techniques which employ complex coding schemes with broader channel bandwidth are utilized to maximize the spectral efficiency in the limited sources of frequency band. These digital modulation schemes increase the peak to average ratio of the RF signal, and as a result the signal envelope is seriously changed over time[1].

For energy efficient operation, the PA is usually operated in a saturation region. Due to a nonlinear transfer function of the high power semiconductor devices and their intrinsic parasitic elements, the PA experiences amplitude and phase distortions in terms of AM-AM and AM-PM, and unwanted IMD signals are generated. Due to its extremely high output power, and therefore the increasing possibility of interference with other mobile units or other communication channels, stringent linearity requirements are specified for the base-station PA[2].

PD techniques have been recognized as a simple and promising solution along with the development of digital signal processing technology, and are still receiving considerable attentions in the form of digital PD. However, due to the memory effect of the PA, which is defined as the modulation bandwidth limitations that are amplitude or phase deviations of intermodulation(IM) responses, the PD technique exhibits some degree of performance degradation. It is important to emphasize that distortion itself is not a memory effect - any non-constant distortion behavior at different tone spacings can be regarded as memory effect[3]~[5]. There is one important point of view missing in the previous study: phase asymmetry, which is induced by the memory effect, eventually leads to the GD variation of the IMD signal. In other words, if we characterize the GD variation according to the tone spacing and output power, then we can minimize the performance degradation of the PD technique.

A number of techniques regarding the measurement of asymmetric IMD signals have been reported[6]~[10]. Some techniques measured relative phases using a frequency mixing operation, or the mixing operation along with direct comparison using a phase detector. The indirect tone cancellation technique has also been used.

In this paper, we propose a novel and simple phase asymmetry measurement technique based on the tone cancellation technique using a two-tone IMD signal. Some advantages of the proposed structure are as follow: (1) no complicated RF circuit is required for measurement setup. Utilizing commercial test instruments, the most complex circuit in the configuration is the variable attenuator and phase shifter, which can be easily designed and fabricated; (2) the measurement mode can

Manuscript received May 20, 2010 ; revised June 15, 2010. (ID No. 20100520-010J)
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be easily changed by the combination of the four single-pole double-through(SPDT) switch operation; (3) the magnitude as well as the phase asymmetry can be measured at the same time with great precision, depending on the resolution of the vector network analyzer(VNA); (4) a calibration is very easily achieved by sending data to the memory and data/memory operation in the VNA; (5) since the main architecture and the operational mechanism are same as the PD structure, the measured result can be directly used for the PD linearizer.

Ⅱ. Group Delay Characterization Based on the Predistortive Tone Cancellation Technique

Fig. 1 shows the IMD magnitude and phase measurement setup proposed in this paper. The test setup consists of three electronic signal generators(ESGs), a spectrum analyzer, and a network analyzer with four SPDT switches and two variable attenuators and phase shifters. In the IMD_3 signal measurement mode, ESG_1 generates a fundamental two-tone signal, in which the tone spacing is Δf, and ESG_2 generates the IMD_3 equivalent input signal, which is similar to the PD signal. The tone spacing of the IMD_3 equivalent signal is $3\Delta f$.

The fundamental signal experiences an arbitrary amount of group delay τ_A, and is added to the third order PD signal before it is applied to the device under test(DUT), a high power amplifier(HPA). The value of τ_A has no effect on the result, because the measurement is performed by a single sideband(IMD) tone cancellation technique. The DUT consists of a commercial broadband amplifier ZVE-8G+ of Mini-Circuits as a driver amplifier, and a gallium nitride high electron mobility(GaN HEMT) device of NPTB00025 of Nitronex as a high power device, where the center frequency is 2.11~2.17 GHz for the wideband code division multiple access(WCDMA) downlink base-station. A 20 W peak envelope power(PEP) is achieved with a total gain of 50 dB, including the driver amplifier.

The phase and the magnitude of the PD signal equivalent to an IMD_3 signal generated at ESG_2 is adjusted by control voltages of V_{A3} and $V_{\Phi 3}$, so that one of the IMD_3 sidebands is perfectly cancelled at HPA output measured by a spectrum analyzer. Simultaneously, the magnitude and the phase responses of the variable attenuator and phase shifter are measured by the VNA through the SW_3 and SW_4. The measured results are stored as memory traces. According to the same procedure, V_{A3} and $V_{\Phi 3}$ are adjusted, so the opposite IMD_3 is cancelled out. By taking the memory trace previously stored in the VNA as the reference, the difference between the stored magnitude and phase response, and the freshly measured response is indirectly interpreted as the relative magnitude and phase.

If we control SW_1 to be connected to 1 position(ESG_1), the relative phase and magnitude of the fundamental signal can be measured. The measurement setup capable of measuring the memory effects regarding IMD_5 signal can also be set, as illustrated in Fig. 2. In the case of the IMD_5 measurement, SW_2, SW_3, SW_4 are connected to 0 positions. Since the measured result is directly represented by degree and dB scale, we can reduce the errors that may be generated during the measurement, such as reading error between the voltage and the translated magnitude and phase, and possible voltage drift over time etc.

Table 1 summarizes the three measurement modes of the proposed setup with respect to the combination of the SPDT switches.

Supposing that the fundamental tone spacing is Δf

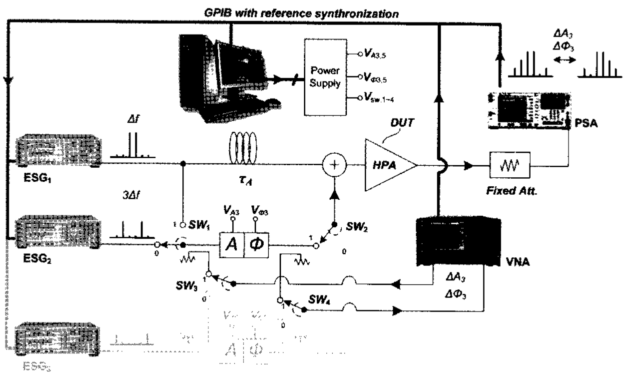

Fig. 1. Configuration of the proposed memory effect measurement setup, adjusted for the IMD_3 signal measurement mode.

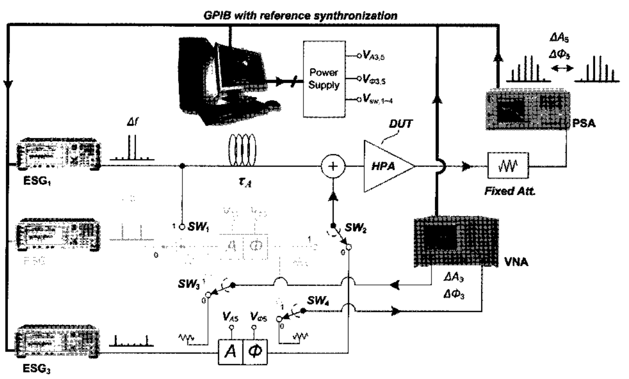

Fig. 2. Configuration of the proposed memory effect measurement setup, adjusted for the IMD_5 signal measurement mode.

Table 1. Three measurement modes according to switch states.

Switch state				Measurement mode
SW_1	SW_1	SW_1	SW_1	
1	1	1	1	Fundamental
0	1	1	1	IM_3
0	0	0	0	IM_5

and the group delay of the IMD_3 and IMD_5 signal are defined as τ_{IM3} and τ_{IM5}, then the GD response of the IMD_3 and IMD_5 signals can be calculated as follows:

$$\tau_{IM3} = -\frac{d\Phi_{IM3}}{d\omega} = -\frac{\Delta\Phi_{IM3}\times(\pi/180)}{2\pi f_{IM3H} - 2\pi f_{IM3L}}, = -\frac{\Delta\Phi_{IM3}}{360\times(3\times\Delta f)} \tag{1}$$

$$\tau_{IM5} = -\frac{\Delta\Phi_{IM5}}{360\times(5\times\Delta f)}, \tag{2}$$

where, respectively, Φ_{IM3} and Φ_{IM5} is the measured relative phase in degrees, and f_{IM3H} and f_{IM3L} are higher and lower IMD_3 frequencies.

Ⅲ. Experimental Results

Although the proposed setup is capable of measuring relative phase as well as magnitude asymmetry between the higher and lower IMD signals, our interest lies in the group delay variation according to the tone spacing Δf and output power dynamic range as a consequence of the memory effect regarding the phase asymmetry.

Fig. 3 shows the response for a 2.14 GHz WCDMA base station PA using the GaN device as a power stage. At tone spacings smaller than 5 MHz along with the high output power region, the relative phase between higher and lower IMD_3 seems close to a small value. However, the phase differences at low output power become larger as the tone spacing increases, which is a consequence of a significant memory effect.

Now, the GDs at different tone spacing and output power are calculated using (1), the result of which is illustrated in Fig. 4. Some interesting properties of the PD technique can be found from Fig. 4. First, the GD of the IMD_3 signal varies according to the output power, which implies that the cancellation bandwidth is limited over output dynamic range in case the GD matching between the linear path(ESG_1 path in Fig. 1) and the IMD_3 path (ESG_2 path in Fig. 1) is fixed to one value. Therefore, the GD in the IMD_3 path should be properly adjusted with respect to the output power level in order to maintain a broad cancellation bandwidth. Second, the GD of the IMD_3 signal also changes with respect to the tone spacing, which implies that the GD matching should be optimized according to the signal bandwidth used in the linear transmitter system.

Fig. 5 shows the measured phase asymmetry according to the tone spacing and average output power in the class-B bias condition(V_{gs}=−1.9 V). In the high output power region, the relative phase between higher and lower IMD_5 seems small. However, the phase difference at low output power becomes larger as the tone

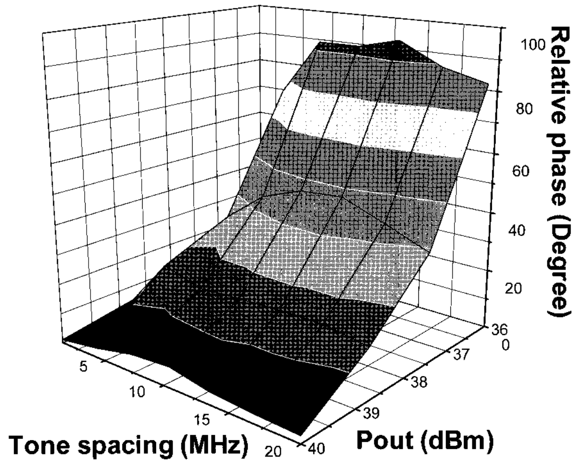

Fig. 3. IMD_3 phase asymmetry according to tone spacing and average output power at V_{gs}=−1.2 V and V_{ds} =27.5 V.

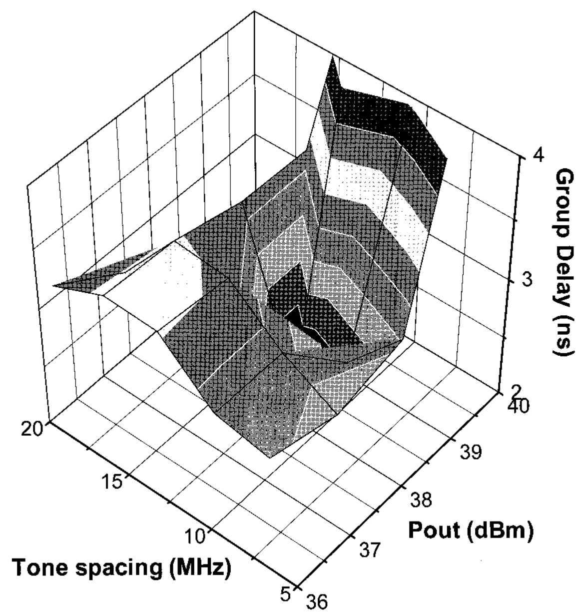

Fig. 4. Calculated group delay of IMD_3 signal using the measured results according to tone spacing and average output power at V_{gs}=−1.2 V and V_{ds}=27.5 V.

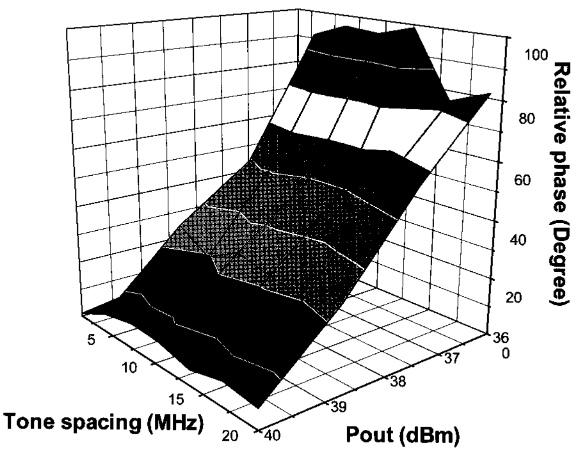

Fig. 5. IMD_5 phase asymmetry according to tone spacing and average output power at $V_{gs}=-1.9$ V and V_{ds} =27.5 V.

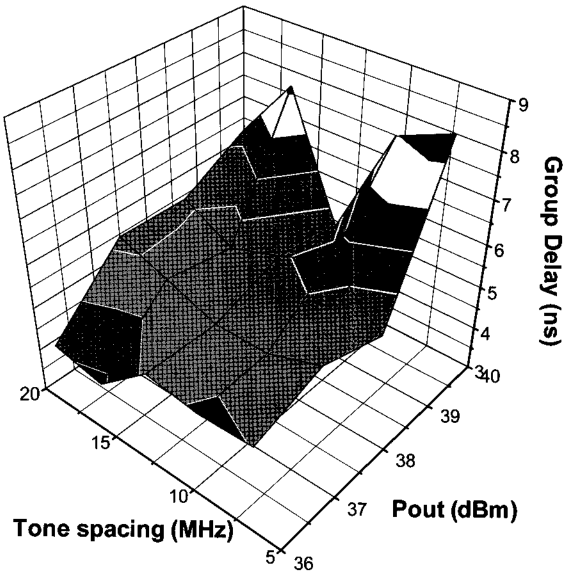

Fig. 6. Calculated group delay of IMD_5 signal using the measured results according to tone spacing and average output power at $V_{gs}=-1.9$ V and V_{ds}=27.5 V.

spacing increases, which is a consequence of a significant memory effect.

According to the similar procedure, the GDs at different tone spacing and output power are calculated using (2), the result of which is illustrated in Fig. 6. A similar tendency is observed in the IMD_5 measurement. Therefore, the GD in the IMD_5 path also should be properly adjusted with respect to the output power level in order to maintain wide cancellation bandwidth.

As a conclusion, we are expected to control the GDs of the 3rd order path and the 5th order path separately with respect to the output power variation to compensate for the memory effect over wide output dynamic range in an individual order predistortion power amplifier.

Ⅳ. Conclusion

This paper proposes the novel memory effect measurement technique in RF power amplifiers using a two-tone intermodulation distortion signal with a very simple and intuitive algorithm. Based on the predistortive tone cancellation technique, the proposed measurement method is capable of measuring relative phase and magnitude of the 3rd and 5th intermodulation distortion, as well as the fundamental signal. The measured relative phase between the higher and lower intermodulation distortion signal for the specific tone spacing can be interpreted as the group delay information of the intermodulation distortion signal concerned. From the group delay analysis, we can conclude that the adaptive control of magnitude and phase, as well as group delay is expected to be a key function in increasing the linearization bandwidth and the dynamic range of the predistortion technique.

Until now, the consequences of the memory effect were only focused on the magnitude/phase asymmetry, the importance of group delay matching in a predistortion technique being out of sight. Care should be taken in determining the optimum group delays in each linear and nonlinear path in a predistortion method. Since this result is just a portion of a great theme to be researched, a lot more detailed experimental study and theoretical analysis still remains to be done.

References

[1] S. C. Cripps, *Advanced Techniques in RF Power Amplifier Design*, Norwood, MA, Artech House, 2002.

[2] P. B. Kennington, *High-Linearity RF Amplifier Design*, Artech House, 1999.

[3] J. Vuolevi, T. Rahkonen, *Distortion in RF Power Amplifiers*, Artech House, 2003.

[4] T. Nojima, T. Konno, "Cuber predistortion linearizer for relay equipment in 800 MHz band land mobile telephone system", *IEEE Trans. Veh. Technol.*, vol. VT-34, no. 4, pp. 169-177, Nov. 1985.

[5] J. Cha, J. Yi, J. Kim, and B. Kim, "Optimum design of a predistortion RF power amplifier for multicarrier WCDMA applications", *IEEE Trans. Microwave Theory Tech.*, vol. 52, no. 2, pp. 655-663, Feb. 2004.

[6] J. S. Kenney, P. Fedorenko, "Identification of RF power amplifier memory effect origins using third-order intermodulation distortion amplitude and phase asymmetry", in *IEEE Int. Microwave Symp. Dig.*, pp. 1121-

1124, Jun. 2006.

[7] P. Fedorenko, J. S. Kenney, "Analysis and suppression of memory effects in envelope elimination and restoration(EER) power amplifiers", in *IEEE Int. Microwave Symp. Dig.*, pp. 1453-14656, Jun. 2007.

[8] N. B. Carvalho, J. C. Pedro, "A comprehensive explanation of distortion sideband asymmetries", *IEEE Trans. Microwave Theory Tech.*, vol. 50, no. 9, pp. 2090-2101, Sep. 2002.

[9] J. H. K. Vuolevi, T. Rahkonen, and J. P. A. Manninen, "Measurement technique for characterizing memory effects in RF power amplifiers", *IEEE Trans. Microwave Theory Tech.*, vol. 49, no. 8, pp. 1383-1389, Aug. 2001.

[10] S. Y. Lee, Y. S. Lee, and Y. H. Jeong, "A novel phase measurement technique for IM3 components in RF power amplifiers", *IEEE Trans. Microwave Theory Tech.*, vol. 54, no. 1, pp. 451-457, Jan. 2006.

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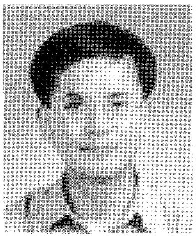

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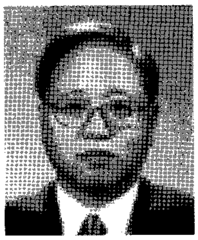

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