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Efficiency improvement in microwave power amplifiers by using Complex Gain Predistortion technique

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Abstract: Power Amplifiers (PAs) are important parts of the transmitters. They amplify the signals that are going to be transmitted. With increasing the input power of the PA, it creates the nonlinearity at the output. The nonlinearity causes out of band distortion and in band distortion. To overcome these effects the power amplifier should be backed off but it will reduce the efficiency of the PA. To increase the efficiency, the Complex Gain Memory Predistortion (CGP) is added to the system. Experimental results with the Mini Circuit power amplifier show an improvement of 7% in Power Added Efficiency (PAE) when the CGP method is applied.

Keywords: predistortion, efficiency, power amplifier, CGP

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

One of the most important aspects in the future radio communication services is the use of spectrally efficient modulation schemes to increase the system capacity. Modulation schemes such as QPSK, MQAM with an appropriate pulse shaping are spectrally efficient, but this type of modulation presents variations in amplitude and phase due to filtering. This could cause amplitude and phase distortion after nonlinear power amplification resulting Inter Symbol Interference (ISI), adjacent channel interference and reduction of efficiency. This means that the power amplifier needs to be backed off far from its saturation point, which results in very low efficiencies, typically less than 10% [1], more than 90% of the dc power is lost and turns into heat. This will significantly reduce the efficiency and this means that linearization technique should be applied in the system. A number of linearization techniques have been reported in recent years [2, 3, 5, 6]. In [7] author proposed a method for compensating nonlinear distortion in TWTA amplifiers. One technique that can potentially compensate for power amplifier (PA) nonlinearities in such an environment is the adaptive digital predistortion technique. The concept is based on inserting a non-linear function (the inverse function of the amplifier) between the input signal and the amplifier to produce a linear output. The Complex Gain Predistortion (CGP) requires being adaptive because of variation in power amplifier nonlinearity with time, temperature and different operating channels and so on.

In this paper the novel complex gain predistoriton technique is applied for linearizing the power amplifier and the experimental results with the new setup improves the overall efficiency of the system and also increase the Adjacent Channel Leakage Ratio (ACLR) of the output spectrum. In [4] also authors used the experimental setup with Agilent equipments for testing their power amplifier. Here the results are compared with the memory polynomial technique that is proposed in [2] and show an improvement in power added efficiency (PAE).

2 Complex gain predistortion technique

The efficiency of an amplifier is a measure of how effectively DC power is converted to RF power. But, by just considering the dc power converted into RF power, the measure do not have to consider the power that is already exist in RF power and injected into the power amplifier, so then the PAE is defined as [1]:

$$PAE = \frac{P_{out} - P_{in}}{P_{DC}}\% \tag{1}$$

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Where P_{out} and P_{in} are output and input power in watt respectively and P_{dc} is the dc power in watt. By adding the predistoriton not only linearity of the power amplifier improves but also the efficiency of the PA. The predistoriton technique that is used here includes memory effects of the PA which has significant impact in increasing the nonlinearity of the PA. Then this technique can compensate those effects.

The equivalent discrete baseband PA model considering memory effects and bandpass nonlinearity can be represented with a memory polynomial model which is a special case of Volterra series. This model can be expressed as below [2]:

$$y(n) = \sum_{\substack{k=1 \\ Odd}}^{K} \sum_{q=0}^{Q} a_{kq} v(n-q) \left|v(n-q)\right|^{2(k-1)} \tag{2}$$

where is the discrete input complex signal of power amplifier after predistortion block and is the discrete output complex envelope signal. K is the order of nonlinearity and Q is the memory length. In (2) also can be represented as below:

$$v(n) = x(n)F[|x(n)|^2] \tag{3}$$

Where X(n) is the discrete input complex and $F[|x(n)|^2]$ is the complex gain of the predistortion block. Equation (2) can be simplified,

$$y(n) = \sum_{q=0}^{Q} v(n-q) \sum_{\substack{k=1 \\ Odd}}^{K} a_{kq} \left|v(n-q)\right|^{2(k-1)} \tag{4}$$

Where the function $G_q(|\mathrm{v(n-q)}|^2)$ can be represented as:

$$G_q[|v(n-q)|^2] = \sum_{\substack{k=1 \\ Odd}}^{K} a_{kq} \left|v(n-q)\right|^{2(k-1)} \tag{5}$$

Then (4) can be expressed as below:

$$\begin{aligned} y(n) &= \sum_{q=0}^{Q} v(n-q) G_q[|v(n-q)|^2] = v(n)G_0[|v(n)|^2] + \\ & v(n-1)G_1[|v(n-1)|^2] + \ldots \end{aligned} \tag{6}$$

This equation demonstrates that the memory contents of the power amplifier are not only appeared in the coefficients a_{kq} of the (2), but it also can be shown as the complex function, which means that the memory effects are appeared in the function $G_q[|v(n)|^2]$. From (3) for finding the function $F[|x(n)|^2]$, first it is assumed that Q=0 or the power amplifier is memoryless thus from (6) it can be conculded,

$$y(n) = v(n)G_0[|v(n)|^2] \tag{7}$$

Ideally the power amplifier should satisfy the below condition for having the linear output,

$$y(n) = Gx(n) \tag{8}$$

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Where G is the linear gain of power amplifier. Replacing (6) in (8) then:

$$y(n) = \sum_{q=0}^{Q} v(n-q) G_q[|v(n)|^2] = Gx(n) \tag{9}$$

With assuming Q=0 and replacing the V(n) in (7) and with considering that the quadrature modulator is a perfect unity gain device the optimum predistorter characteristic, denoted by $F[|x(n)|^2]$, would satisfy:

$$x(n)F[|x(n)|^2]G_0[\left|x(n)F[|x(n)|^2]\right|^2] = Gx(n) \tag{10}$$

Then the optimum value of the predistortion complex gain is calculated from below iterative equation:

$$F_{i+1}[|x(n)|^2] = F_i[|x(n)|^2] - \frac{F_i[|x(n)|^2]}{v(n)G_0[|v(n)|^2]} V_{error}(n) \tag{11}$$

Where

$$V_{error}(n) = y(n) - Gx(n) \tag{12}$$

Now assume that the power amplifier includes one memory or Q=1 then after some simplification, equation below is generated:

$$F(|x(n)|^2) = \frac{G}{G_0[|v(n)|^2]} - \frac{v(n-1)G_1[|v(n-1)|^2]}{x(n)G_0[|v(n)|^2]} \tag{13}$$

The second fraction of (13) indicates the memory effects of the power amplifier. If Q increases then the elements in (13) also increase. The iterative solution for (13) is:

$$\begin{aligned} F_{i+1}(|x(n)|^2) = F_i[|x(n)|^2] - \frac{F_i[|x(n)|^2]}{v(n)G_0[|v(n)|^2]} V_{error}(n) + \\ \frac{F_i[|x(n)|^2] v(n-1)G_1[|v(n-1)|^2]}{v(n)G_0(|v(n)|^2)} - \frac{v(n-1)G_1[|v(n-1)|^2]}{x(n)G_0[|v(n)|^2]} \end{aligned} \tag{14}$$

This equation can be simplified as below:

$$\begin{aligned} F_{i+1}(|x(n)|^2) = F_i[|x(n)|^2] - \frac{F_i[|x(n)|^2]}{v(n)G_0[|v(n)|^2]} V_{error}(n) + \\ \frac{v(n-1)G_1[|v(n-1)|^2]}{G_0[|v(n)|^2]} \left(\frac{F_i[|x(n)|^2]}{v(n)} - \frac{1}{x(n)} \right) \end{aligned} \tag{15}$$

According to Eq. 15, the last part becomes zero and therefore it will be canceled. Then Eq. 15 can be represented as below:

$$F_{i+1}(|x(n)|^2) = F_i[|x(n)|^2] - \frac{F_i[|x(n)|^2]}{v(n)G_0[|v(n)|^2]} (V_{error}(n)) \tag{16}$$

If we combine Eq. (6) and Eq. (12) and replace it in Eq. (16), then:

$$\begin{aligned} F_{i+1}(|x(n)|^2) = F_i[|x(n)|^2] - \\ \frac{F_i[|x(n)|^2]}{v(n)G_0[|v(n)|^2]} (v(n)G_0[|v(n)|^2] + v(n-1)G_1[|v(n-1)|^2] + \ldots - Gx(n)) \end{aligned} \tag{17}$$

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As it is shown in Eq. (17), it is clear that the power amplifier model is with memory effects and this is appeared in the difference of power amplifier output and normalized input in the parentheses of Eq. (17). It is concluded that the Predistortion function $F_{i+1}(|x(n)|^2)$ in Eq. (17) includes the memory effects which later will be presented by simulation results the effect of this compensation. The main difference between Eq. (11) and Eq. (17) is in the function $V_{error}(n)$, where in Eq. (11) $V_{error}(n)$ does not have memory effect but in Eq. (17) it includes memory effect. This formula can be extended to more memory and is still valid. Memory polynomial method was very complicated and it couldn't calculate all the coefficients in the Volterra series and only could compensate for 2 or 3 memory length but this method proves that it can compensate all the memory contents of the power amplifier. Fig. 1 shows the block diagram of the CGP technique that is proposed here:

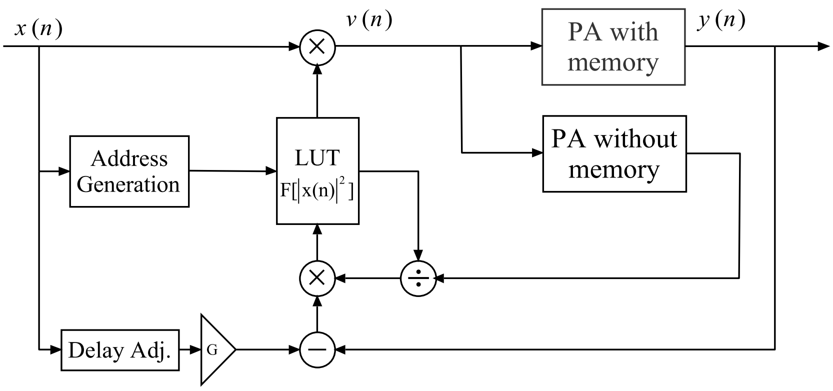

Fig. 1. The CGP block diagram with memory compensation

The general predistortion function can be expressed as below. This equation later will be applied in experimental testing.

$$F_{i+1}(|x(n)|^2) = F_i[|x(n)|^2] - \alpha \frac{F_i[|x(n)|^2]}{v(n)G_0[|v(n)|^2]}(v(n)G_0[|v(n)|^2] + v(n-1)G_1[|v(n-1)|^2] + \ldots - x(n)) \quad (18)$$

The parameter α is a constant between 0 and 1. This parameter indicates the convergence rate and stability and its value should be allocated with considering the linearity requirements.

3 Experimental results

Here the experimental results of testing the Mini Circuit power amplifier using Agilent equipments are presented. The VSA software and Matlab are used for this experiment. The VSA software is used for capturing the samples from the Agilent equipment. The PA is wideband from 2 GHz to 8 GHz with 30 dB gain. Here the PA is working at 2.4 GHz. The PA is designed based on Eq. (2) which is the PA model with memory effects. Table I shows the coefficients that are extracted from this PA which is assumed that the

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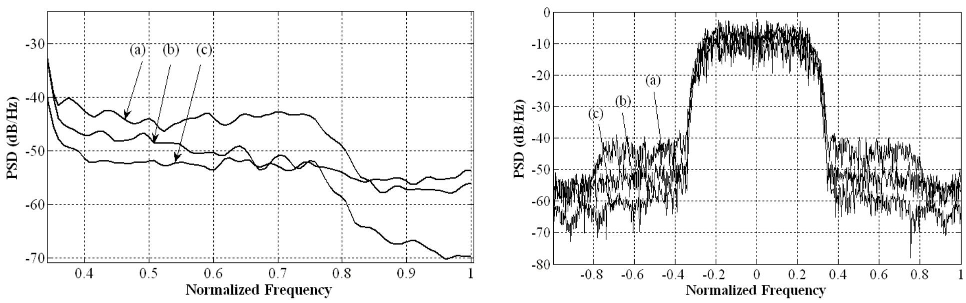
Table I. Comparison of Memory Polynomial and CGP techniques

Predistortion technique	Power amplifier coefficients	ACLR(dBc) Left	Right
Memory Polynomial	a_{10}=0.9800-0.300i; a_{11}=0.06+0.03i; a_{12}=0.02+0.08i; a_{13}=-0.01+0.02i; a_{30}=-0.3+0.42i; a_{31}=-0.02+0.05i; a_{32}=-0.01-0.08i; a_{33}=0.02-0.01i;	-45.1	-40.2
CGP	a_{10}=0.9800-0.300i; a_{11}=0.06+0.03i; a_{12}=0.02+0.08i; a_{13}=-0.01+0.02i; a_{30}=-0.3+0.42i; a_{31}=-0.02+0.05i; a_{32}=-0.01-0.08i; a_{33}=0.02-0.01i;	-53.1	-49.6

nonlinearity order and memory length are K=3 and Q=3 respectively. The input signal which is QPSK with sample rate of 1 Mbps and the root rate cosine filter with alfa that is equal to 0.35, is generated from Matlab and is passed to Agilent vector signal generator which is upconvert the signal and passes it to the power amplifier. The Matlab and VSA software are running in PC to control the whole process. The VSA software in PC will capture the data of the PA. The captured data can then import to Matlab for further analysis. Synchronization should be done to get a complete coordination among the signal sent and the signal imported into Matlab. The whole testing is done offline, meaning that the signal that is received and the transmit signal are not analyzed in realtime. Finally the CGP technique is applied to the PA to measure the amount of reduction.

In Fig. 2 the Power Spectral Density (PSD) of the experimental results is compared with the simulation. Fig. 2 (2) Right side, (a) is the PSD of the power amplifier without predistortion and it can be seen the ACLR is around −35 dB. After applying CGP, the experimental result is shown in Figure 2 (b) in which we have the ACLR around −45 dB. The simulation result also is added and is shown in Fig. 2 (c) and the ACLR is now almost



(1) (2)

Fig. 2. Comparison of PSD for ZVE-8G power amplifier (1): (a) without CGP (b) With memory polynomial method with Q=2 (c) With CGP technique after 5 iterations.(2): (a) Without CGP (b) Experimental PSD with CGP and after 5 iterations (c) Simulation PSD with CGP after 5 iterations

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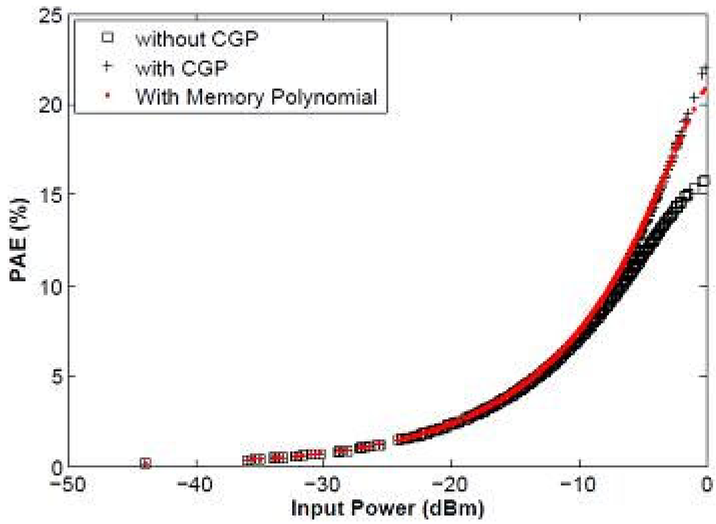

Fig. 3. PAE of the ZVE-8G power amplifier with and without CGP and with memory polynomial method

−50 dB.

It is obvious that there is a difference between experimental and simulation results and the reason is the effects of DAC, mixer and upconversion are not considered in the simulations and those effects along with effects of power amplifier memory effects which here it is modeled for memory length of 2, can cause this difference. In Fig. 2 (1) Left side, the comparison of power spectral density between memory polynomial technique and CGP technique is shown. There is almost 3 to 5 dB more reduction when the CGP technique is applied as compare to memory polynomial. The figure focuses on the PSD of the left side to distinguish the difference. In Fig. 3, the PAE of this power amplifier is shown. By applying the CGP technique, around 7% improvement in efficiency of the power amplifier is achieved when the input power is 0 dBm. This achievement is without the lost of the linearity. The value is less when the memory polynomial method is applied. As compare to the memory polynomial technique the efficiency and ACLR improvement are more and memory polynomial couldn't compensate the ACLR and efficiency even when the memory length was increased more

4 Conclusion

In this paper the novel predistoriton technique is applied for the power amplifier from Mini Circuit to improve its efficiency. The efficiency improves almost 7% when applying the CGP technique. The comparison with memory polynomial technique also shows 3 to 5 dB improvement in ACLR.

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