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DIGITAL PERDISTORTION TECHNIQUE FOR COMPENSATING MEMORY EFFECTS OF POWER AMPLIFIERS IN WIDEBAND APPLICATIONS

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The application of digital predistortion in base band signal is an extended method of amplifier linearization to reduce the Adjacent Channel Interference (ACI) in those systems in which a varying envelope modulation scheme like OFDM and MQAM is used. Digital baseband predistortion is a highly cost-effective way to linearize Power amplifiers (PAs), but most existing architectures assume that the PA has a memoryless nonlinearity. For wider bandwidth applications such as wideband code-division multiple access (WCDMA), wideband orthogonal frequency-division multiplexing (W-OFDM) and worldwide interoperability for microwave access (WiMAX), PA memory effects can no longer be ignored. In this paper a novel technique for compensating such effects is proposed. This technique is a combination of two techniques, memory polynomial predistortion and the gain based predistorter method. This method is compared with the other technique, memory polynomial method and validated using a Mini-Circuit power amplifier and QPSK signal with 1 MHz bandwidth. Simulations and results show improvement in ACLR reduction and EVM with applying this method.

Keywords: digital predistortion, memory effects, ACLR, power amplifier, WCDMA

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 so on. A number of linearization techniques have been reported in recent years [1-5], [8], [13-14]. 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 digital predistortion (DPD) requires to be adaptive because of variation in power amplifier nonlinearity with time, temperature and different operating channels and so on. Another limitation of predistortion is the dependence of amplifier's transfer characteristic's on the frequency content of the signal or defined as changes of the amplitude and phase in distortion components due to past signal values, that is called memory effects. The memory effects compensation is an important issue of the DPD algorithm in addition to correction of power amplifier (PA) nonlinearity especially when the signal bandwidth increases. Many studies are involved in this technique but many of them suffer from limitations in bandwidth, precision or stability [5], [8], [13].

In this paper a new technique which is the combination of two techniques, the gain based predistorter [5] and memory polynomial model [4] is presented. Both previous techniques have demonstrated acceptable results but both have disadvantages. In memory polynomial predistortion the complexity of extracting the coefficients of predistortion function decrease the capability of linearization and so it needs to apply other method like [6] for implementing it. In complex gain predistortion method the memory effects that cause dynamic AM-AM and AM-PM are not considered. So here the main objective is not only to demonstrate the capability of this new method to overcome for such disadvantages, but also to show that with applying this technique all the memory contents of power amplifier that is modeled with memory polynomial is compensated. for validating this technique several simulations are applied. The adaptation is based on linear convergence method in the simulations. For simplicity, the effects of the quadrature modulator and demodulator and A/D and D/A is not considered. The LUT size is 10 bit and addressing the LUT is based on the input power. Simulations are compared with the memory polynomial technique and two power amplifiers. It will be shown that with applying this method all the memory contents of the power amplifier especially the one that cause dynamic AM-AM and AM-PM are compensated.

For obtaining these results the Mini-Circuit power amplifier ZVE-8G is used for this experiment. The power

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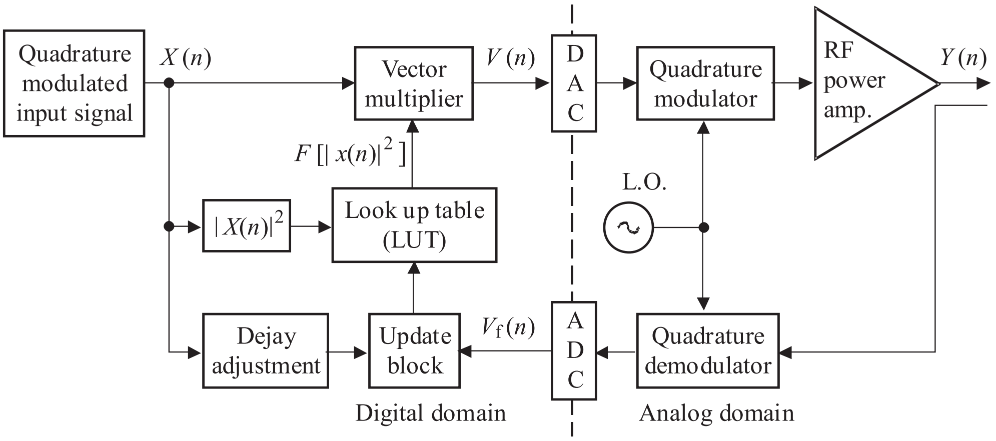

Fig. 1. Adaptive digital predistortion block

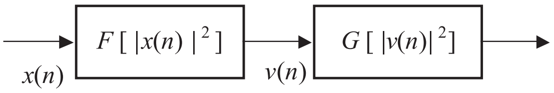

Fig. 2. Cascade of predistortion and power amplifier

amplifier is wideband from 2 GHz to 8 GHz with 30 dB gain. Here the PA is working at 2.4 GHz. The input signal is QPSK with 1MHz bandwidth. The experimental results will be shown to confirm this technique.

2 PREDISTORTION TECHNIQUE

Figure 1 shows a block diagram of the adaptive digital predistortion [5]. A fully adaptive digital predistortion system requires the addition of a predistortion circuit consisting of a digital predistorter and look up table (LUT) to the transmission path in addition to a feedback path consisting of a demodulator, analog to digital converter (ADC) and adaptation circuit for updating the LUT.

The block diagram assumes that all components of the system except the predistorter and high power amplifier (HPA) have a linear response and hence can be ignored in the analysis. In this paper also these effects are ignored. The predistorter is equivalent to a nonlinear circuit with gain expansion response that is inverse of the power amplifier gain compression AM-AM (Amplitude dependent gain) and a phase rotation that is the negative of the Power Amplifier phase rotation AM-PM (Amplitude Dependent Phase Shift).

In this figure $x(n) = I + jQ$ is the quadrature modulated input signal and $V_f(n)$ is the quadrature demodulated feedback signal. These signals are sampled synchronously, and their values are used to generate a predistortion vector function $F\left[|x(n)|^2\right]$ which is stored in polar or rectangular form in a look-up table (LUT). The input signal $x(n)$ is predistorted according to $F\left[|x(n)|^2\right]$, so that the predistorted signal $V(n)$ produced the linearized output from the RF amplifier. Here the LUT is 10bit and the absolute of input signal is used for addressing it.

The main objective of this paper is to study the electrical memory effects that cause dynamic AM-AM and AM-PM [11]. The previous studies [3–7, 10–16] were all restricted to calculation of the coefficients of the power amplifier. This way needs a lot of computation and therefore takes a lot of processor time and also never can be implemented when the number of coefficients increases. The technique that is proposed here doesn't have that drawback. It even claims that can compensate the dynamic memory effects in wideband applications. This method will be discussed in details in next section. One of the other important things in studying the predistortion method is that the predistortion attempts to add 3rd and 5th order intermodulation products to the input signals that cancels out the 3rd and 5th order intermodulation products added by the PA, thus the bandwidth of the predistorted signal must be three times greater than the bandwidth of the input signals to be able to represent up to 5th order intermodulation products. In the real world the predistorted signals are fed into a DAC and then low pass filtered at the Nyquist rate (half the input sample rate), the predistorted signal must have a sample rate of at least six times that of the original input signals. Thus in simulations the input signals are interpolated by a factor of six before being fed into the predistorter. In the next section the new technique of predistortion is discussed.

3 COMPLEX GAIN PREDISTORTION

Figure 2 shows the predistortion function $F\left[|x(n)|^2\right]$ that cascades with power amplifier that has shown with $G\left[|v(n)|^2\right]$ function. $F\left[|x(n)|^2\right]$ and $G\left[|v(n)|^2\right]$ are complex gain functions of predistortion and power amplifier. As proposed in [4] 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 presented as below

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

where $v(n)$ is the discrete input complex signal of power amplifier after predistortion block and $y(n)$ is the discrete output complex envelope signal. K is the order of nonlinearity and Q is the memory length.

This model considers only odd-order nonlinear terms due to bandpass nonlinear characteristics that cause intermodulation distortion. In (1) $v(n)$ also can be represented as below:

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

where $x(n)$ is the discrete input complex and $F\left[|x(n)|^2\right]$ is the complex gain of the predistortion block. Equation (1) can be simplified as below

$$y(n) = \sum_{q=0}^{Q} v(n-q) \sum_{\substack{k=1 \\ \text{Odd}}} a_{kq} |v(n-q)|^{2(k-1)}\,, \tag{3}$$

Where the function $G_q\left[|v(n-q)|^2\right]$ can be represented as:

$$G_q\left[|v(n-q)|^2\right] = \sum_{\substack{k=1 \\ \text{Odd}}} A_{kq} |v(n-q)|^{2(k-1)}\,. \tag{4}$$

Then (3) is as below

$$\begin{aligned} y(n) &= \sum_{q=0}^{Q} v(n-q) G_q\left[|v(n-q)|^2\right] \\ &= v(n) G_0\left[|v(n)|^2\right] + v(n-1) G_1\left[|v(n-1)|^2\right] + \dots \end{aligned} \tag{5}$$

This equation demonstrates that the memory contents of the power amplifier are not only appeared in the coefficients a_{kn} of the (1), but it also can be shown as the complex function, which means that the memory effects are appeared in the function $G_q\left[|v(n)|^2\right]$. Previous efforts only tried to extract the a_{kn} to compensate for such memory effects but here it will be shown that without having the coefficients also the memory effects can be compensated and even the compensation is better and includes all the memory [9].

From (2) for finding the function $F\left[|x(n)|^2\right]$, first it is assumed that $Q = 0$ or the power amplifier is memoryless thus from (5) it can be conculded

$$y(n) = v(n) G_0\left[|v(n)|^2\right]\,. \tag{6}$$

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

$$y(n) = Gx(n)\,. \tag{7}$$

Where G is the linear gain of power amplifier.

Replacing (5) in (7) then

$$y(n) = \sum_{q=0}^{Q} v(n-q) G_q\left[|v(n)|^2\right] = Gx(n)\,. \tag{8}$$

With assuming $Q = 0$ and replacing the $v(n)$ in (6) and with considering that the quadrature modulator is a perfect unity gain device the optimum predistorter characteristic, denoted by $F\left[|x(n)|^2\right]$, would satisfy

$$x(n) F\left[|x(n)|^2\right] G_0\left[\left| x(n) F\left[|x(n)|^2\right] \right|^2\right] = Gx(n)\,. \tag{9}$$

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

$$F_{i+1}\left[|x(n)|^2\right] = F_i\left[|x(n)|^2\right] - \frac{F_i\left[|x(n)|^2\right]}{v(n) G_0\left[|v(n)|^2\right]} V_{\text{error}}(n) \tag{10}$$

where

$$V_{\text{error}}(n) = y(n) - Gx(n)\,. \tag{11}$$

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

$$F\left(|x(n)|^2\right) = \frac{G}{G_0\left[|v(n)|^2\right]} - \frac{v(n-1) G_1\left[|v(n-1)|^2\right]}{x(n) G_0\left[|v(n)|^2\right]}\,. \tag{12}$$

The second fraction of (12) indicates the memory effects of the power amplifier. If Q increases then the elements in (12) also will increase.

The iterative solution for (12) is:

$$\begin{aligned} F_{i+1}\left(|x(n)|^2\right) &= F_i\left(|x(n)|^2\right) - \frac{F_{i+1}\left(|x(n)|^2\right)}{v(n) G_0\left[|v(n)|^2\right]} V_{\text{error}}(n) \\ &\quad + \frac{F_i\left[|x(n)|^2\right] v(n-1) G_1\left[|v(n-1)|^2\right]}{v(n) G_0\left[|v(n)|^2\right]} \\ &\quad - \frac{v(n-1) G_1\left[|v(n-1)|^2\right]}{x(n) G_0\left[|v(n)|^2\right]}\,, \end{aligned} \tag{13}$$

This equation can be simplified as below:

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

$$F_{i+1}\left[|x(n)|^2\right] = F_i\left[|x(n)|^2\right] - \frac{F_i\left[|x(n)|^2\right]}{v(n) G_0\left[|v(n)|^2\right]} V_{\text{error}}(n)\,.$$

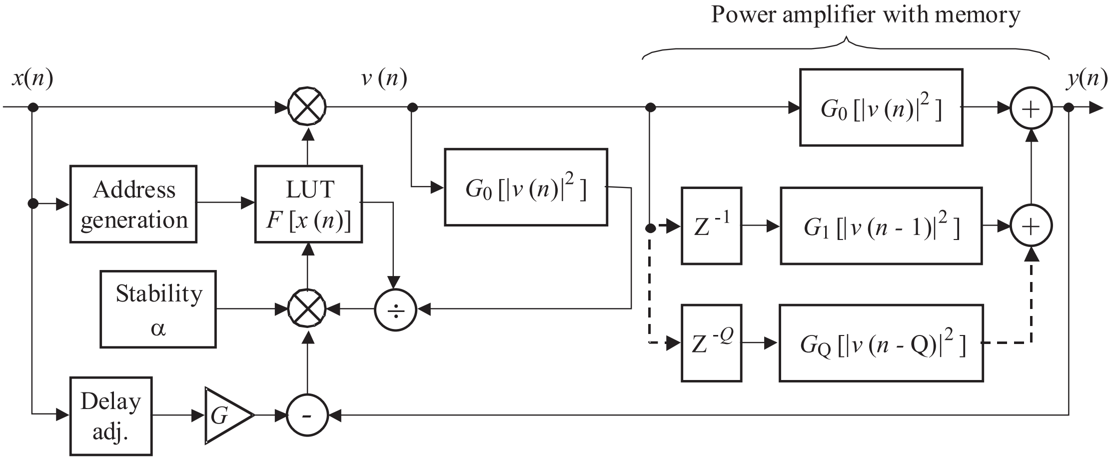

Fig. 3. Predistortion block with memory

The function $F\left[|x(n)|^2\right]$ in (14) is similar to (10) when the power amplifier has no memory. This formula can be extended to more memory and is still valid.

Simulations and results will prove the validity of this equation later. 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.

The important parameter in (14) is the gain factor which is the only difference between (10) and (13) and it is the $F\left[|x(n)|^2\right]$ over $v(n)G_0\left[|v(n)|^2\right]$. In the case of having memory, $G_0\left[|v(n)|^2\right]$ can not be found and also (6) can not be assumed except the case of memoryless power amplifier. As it is shown in [5, 8] the gain factor can be a constant number between zero and one and it indicates the stability and convergence rate. If the gain factor sets to the larger value then the convergence is faster but the probability of convergence is low. For controlling and making the convergence slower and reach to the highest linearity especially at saturation point, (13) can be written as below

$$F_{i+1}\left[|x(n)|^2\right] = F_i\left[|x(n)|^2\right] - \alpha\frac{F_i\left[|x(n)|^2\right]}{v(n)G_0\left[|v(n)|^2\right]}V_{\mathrm{error}}(n)\,. \qquad (15)$$

In [5] 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. In [5] the condition for convergence of (15) is shown. For calculating the function $F\left[|x(n)|^2\right]$ in (15) first the error vector should be calculated and then the gain factor which involves the division and then these values multiply together. $F\left[|x(n)|^2\right]$ is initially one then after some iteration the optimum value will be found. Finding the appropriate gain factor is possible as described below.

The parameter $v(n)G_0\left[|v(n)|^2\right]$ in the gain factor is the power amplifier output without memory and it can be modeled with the block diagram in Fig. 3. for finding the $v(n)G_0\left[|v(n)|^2\right]$ parameter, it is possible to initially calculate the coefficients of the power amplifier without memory and save it in LUT and then calculate the gain factor.

With doing this a lot of processor time and hardware resources will be compensated. It is important that if the feedback in Fig. 3 comes from the output of the amplifier with memory which is $y(n)$ rather than that the one which is shown in this figure this method will not linearized the power amplifier and (15) will not convergence. The value of α in (15) should be considered accurately to have a convergence in the loop. The only drawback that is still remained, is calculating the inverse of $v(n)G_0\left[|v(n)|\right]$ which after finding it and multiplied with error vector and predistortion function $F\left[|x(n)|^2\right]$ the LUT contents could be updated. So in implementation the main concern is the division part. One solution for this is to convert the division to multiply and this could be done with Newton Raphson method but it leaves for future work.

In (15) with two or three iterations convergence is achieved and it will be shown that as compared with memory polynomial method the efficiency improves more and it is less complex. The only time consuming part for implementing this method is the calculation of the gain factor which requires the division of the complex gain of predistortion block to the $G_0\left[|v(n)|^2\right]$. The predistorter is assumed to be implemented as a lookup table (LUT) of complex gain values [5] that here the size is 10bit, and is indexed by the squared magnitude, as shown in Fig. 3. It is also possible to index by magnitude, or any other monotonic function of magnitude, depending on the regions of amplifier characteristic that need the greatest accuracy of representation. However, these considerations do not enter the analysis of the present paper. Also to help evaluate the performance of the DPD a figure for in-band distortion as well as out of band distortion which is measured with adjacent-channel-leakage-ratio (ACLR) is calculated. This involves calculating the error vector magnitude (EVM) in transmitter, which is given by the following equation

$$\mathrm{EVM} = \frac{\mathrm{rms}\big(|V_{\mathrm{error}}(n)|\big)}{\mathrm{rms}\big(|x(n)|\big)} \tag{16}$$

where $V_{\mathrm{error}}(n)$ is from (11) and $x(n)$ is the input signal.

4 SIMULATIONS AND RESULTS

In order to validate the proposed method several simulations are done. Matlab is applied for simulations. The power amplifier is ZVE-8G from Mini-Circuit suitable for CDMA applications. The input signal which is generated from Matlab is passed to agilent signal generator which will be upconvert the signal and pass it to the power amplifier. The power amplifier is wideband from 2 GHz to 8 GHz with 30 dB gain. Here the PA is working at 2.4 GHz. The input signal is QPSK with sample rate of 1 Mbps and the root rate cosine filter with alfa equal to 0.35. The output signal of PA is connected to the attenuator for bring down the output power below the input power of the equipment. For receiving part of the measurement, the 89600S VXI equipment from agilent is used which the main task is to downconvert the signal to IF frequency. The VSA software in PC will capture the data of the PA. The captured data can then import to Matlab for further analysis. Synchronization is used in order to achieve a complete coordination among the signal sent and the signal taken into Matlab.

These samples are used to model the power amplifier based on (1) which is the memory polynomial method. The extracted coefficients that include the memory effects are shown in table I. it is assumed that $Q = 2$ and $K = 3$. In Figure 4 the AM-AM and AM-PM characteristics of this power amplifier are shown. It can be seen the scattering of samples in this figure that is because of the memory effects. It can be shown that when the memory effects are more these samples will be scattered more, and then the digital predistortion technique should be designed based on it. It is clear in Fig. 4 (up) that the AM-AM characteristic is not linear when the input amplitude is increased. And also in Fig. 4 (down) the curve bends too. This is because of the nonlinear characteristics of power amplifier. All the input and output samples in the simulations are normalized.

For modeling the memory effects of the power amplifiers authors in [10] proposed a method for modeling the power amplifiers with memory. This method that is based on the spars delay taps is actually able to take into account all the memory effects of power amplifier. The memory effect modeling ratio (MEMR) was used to show the amount of memory that this method can model. The power amplifier from mini circuit has MEMR = 0.62 and the one in [10] has MEMR = 1 and these coefficients are shown in Tab. 1. previous researches could present the comparison of the power amplifier with MEMR that is less than one. Here the presented method is successfully tested with these two types of PA models. In all the simulations the input back off is 3 dB. In simulations, it is avoided to reach to 1 dB compression point which increases the complexity of this method and also the effects of analog imperfections are not considered.

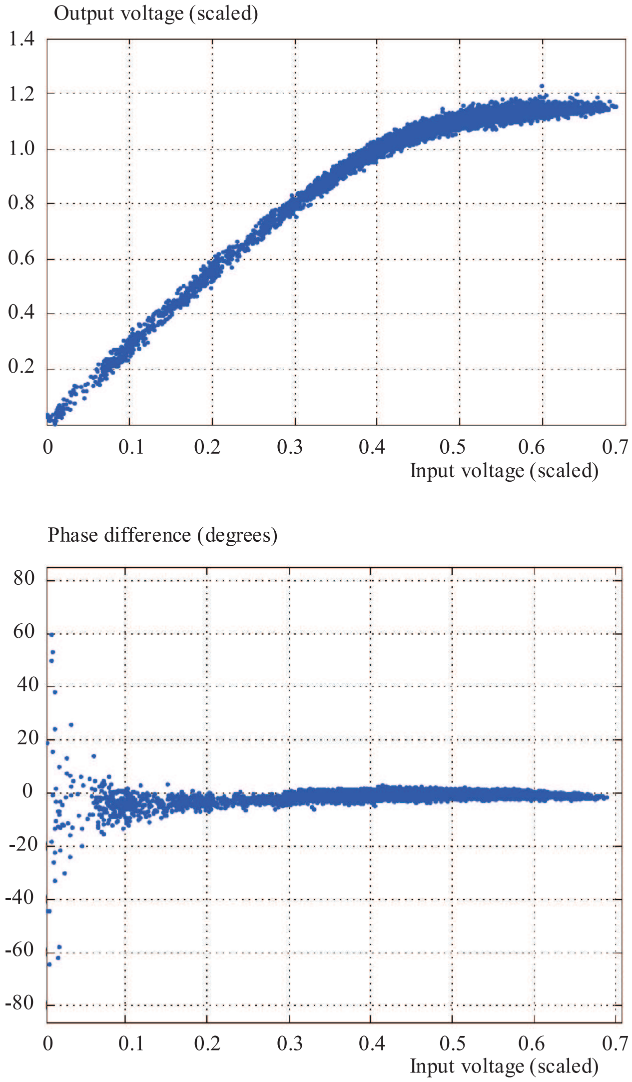

Fig. 4. AM-AM and AM-PM characteristics of the ZVE-8G PA: Input power versus output power (up), Input power versus phase difference (down)

In Tab. 1 the proposed method is compared with the memory polynomial method for two different power amplifiers with different memory contents for QPSK signal. The comparison is with ACLR and EVM.

In Figure 5 the output spectrum of the ZVE-8G power amplifier is shown. The input power is 0 dBm to drive the power amplifier into nonlinearity area and near saturation point. The amount of nonlinearity can be seen in Fig. 5 after applying the new predistortion technique the result of Fig. 6 will be reached. The ACPR reduction is around

Table 1. Comparison of the two predistortion techniques for different power amplifiers with QPSK signal

Predistortion technique	Power amplifier coefficients	MEMR	ACLR(dBc) Left	Right	EVM (%)
Memory Polynomial	$a_{10} = 0.9800 - 0.300i$; $a_{11} = 0.06 + 0.03i$; $a_{12} = 0.02 + 0.08i$; $a_{13} = -0.01 + 0.02i$; $a_{30} = -0.3 + 0.42i$; $a_{31} = -0.02 + 0.05i$; $a_{32} = -0.01 - 0.08i$; $a_{33} = 0.02 - 0.01i$;	1	-39.1	-40.2	2.55
	$a_{10} = 1.524 - 0.211i$; $a_{11} = 0.349 + 0.32i$; $a_{12} = -0.797 - 0.0247i$; $a_{30} = -0.0355 + 0.72i$; $a_{31} = -0.010 - 0.012i$; $a_{32} = -0.0065 + 0.0042i$; $a_{50} = -0.019 - 0.004i$; $a_{51} = 0.009 - 0.019i$; $a_{52} = -0.0069 + 0.013i$;	0.62	-41.2	-42.5	2.25
Complex Gain	$a_{10} = 0.9800 - 0.300i$; $a_{11} = 0.06 + 0.03i$; $a_{12} = 0.02 + 0.08i$; $a_{13} = -0.01 + 0.02i$; $a_{30} = -0.3 + 0.42i$; $a_{31} = -0.02 + 0.05i$; $a_{32} = -0.01 - 0.08i$; $a_{33} = 0.02 - 0.01i$;	1	-42.1	-40.6	1.95
	$a_{10} = 1.524 - 0.211i$; $a_{11} = 0.349 + 0.32i$; $a_{12} = -0.797 - 0.0247i$; $a_{30} = -0.0355 + 0.72i$; $a_{31} = -0.010 - 0.012i$; $a_{32} = -0.0065 + 0.0042i$; $aa_{50} = -0.019 - 0.004i$; $a_{51} = 0.009 - 0.019i$; $a_{52} = -0.0069 + 0.013i$;	0.62	-45.1	-48.3	1.73

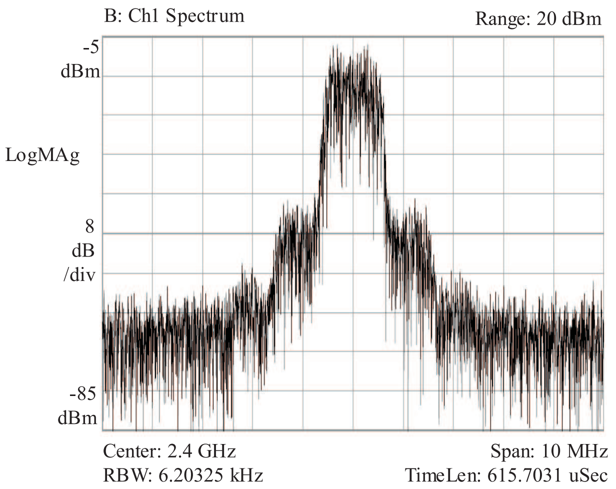

Fig. 5. Output Spectrum of ZVE-8G PA before predistortion

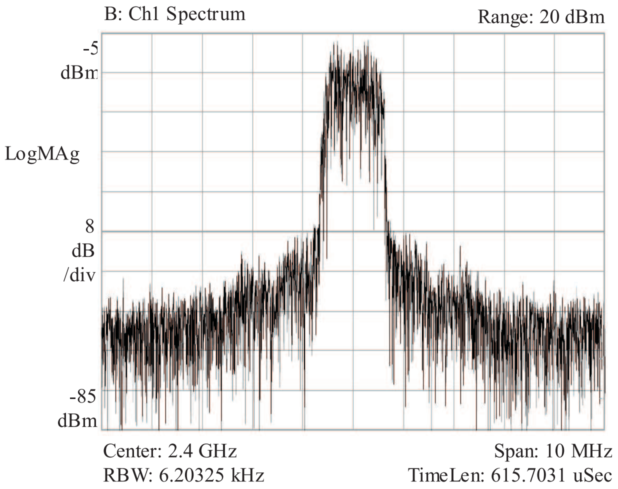

Fig. 6. Output Spectrum of ZVE-8G PA after applying predistortion

8 dB. This result is after 3 iterations and if we use more iteration the amount of reduction will be more.

5 CONCLUSIONS

In this paper the new digital predistortion technique is introduced. This technique is the combination of two techniques, complex gain predistortion and memory polynomial predistortion. By applying this technique all the memory contents of the power amplifier is suppressed. Simulations and results are examined with mini circuit power amplifier with 30 dB gain that is working in 2.4 GHz and the power amplifier with MEMR=1. the QPSK signal with 1 MHz bandwidth is used for input signal. The results show the improvement of 8 dB in ACLR and improvement of 3 % in EVM. The future research should be more on the implementation of this technique using FPGA and DSP and measure the effects of analog imperfection that cause reduction in efficiency in practical implementation and add that effects in the simulations.

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