New Linearization Method Using Interstage Second Harmonic Enhancement

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***Abstract*—Efficient use of the frequency spectrum necessitates the use of modulation formats such as $\pi/4$-DQPSK, which requires linear amplification to minimize spectral regrowth. A new linearization technique is presented that allows a more efficient operation of these linear amplifiers by combining both the advantage of the transparent nature of feed-forward linearization with the efficiency of feedback linearization. The method of convolution is used to analyze the amplifier characteristics and to determine how linearization can be achieved. This method is verified experimentally and proves that by careful use of the second harmonic component, a new method of linearization has been realized.**

***Index Terms*—Amplifiers, linearization, spectral regrowth.**

I. Introduction

IN DIGITAL wireless communication systems, the final stage power amplifier is one of the key components in terms of cost and power consumption. Many modern digital wireless communication systems such as North America Digital Cellular (NADC) and Personal Handy-Phone System (PHS) adopt some form of quadrature phase-shift keying (QPSK) formats, which requires linear amplification if spectral regrowth is to be avoided. The main concern of spectral regrowth is its spillover to adjacent channels causing interference and, therefore, degradation in overall system performance.

The origin of spectral regrowth can be traced back to the AM/AM and AM/PM distortion present in linear power amplifiers when operating under large signals. Work has recently been done on the spectral regrowth problem using low-frequency transformation, the Volterra method, and the harmonic balance method [1]–[5]. The control of the second harmonic in improving efficiency [6], and the use of the second harmonic in feedback [7] to reduce intermodulation distortion has been reported. No work, however, has been reported on linearization techniques [8] in reducing spectral regrowth using interstage second harmonic enhancement.

For amplifiers with memoryless and weak nonlinearity, the method using power series can be used for characterization [9]. The method of convolution and Fourier transform is used to analyze the spectral regrowth phenomenon, and based on this analysis a new linearization method that uses interstage second harmonic enhancement is presented. According to theoretical predictions, by using interstage second harmonic enhancement, the spectral regrowth of a narrow bandwidth signal can be reduced significantly, especially for systems with dominant third order nonlinearity.

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II. Power Series Analysis of Spectral Regrowth

A linear amplifier operating under large signals, which is memoryless and has weak nonlinearity, will have an output $y(t)$ for an input $x(t)$ given by

$$y(t) = g_1 x(t) + g_2 x(t)^2 + g_3 x(t)^3 + \cdots.$$

The coefficients g_i are constants and describe the transfer characteristic of the amplifier. In the frequency domain its Fourier Transform is given by

$$\begin{aligned} Y(j\omega) = {} & g_1 X(j\omega) + g_2 X(j\omega) \otimes X(j\omega) \\ & + g_3 X(j\omega) \otimes X(j\omega) \otimes X(j\omega) + \cdots. \end{aligned} \tag{1}$$

In digital wireless communication systems, the spectrum of a digitally modulated signal can be viewed as a carrier supplemented with a baseband spectrum $B(j\omega)$ given by

$$X(j\omega) = B(j\omega) \otimes \tfrac{1}{2}\,\delta(\omega \pm \omega_0). \tag{2}$$

The higher order terms in (1) can thus be represented by

$$\begin{aligned} & g_2 X(j\omega) \otimes X(j\omega) \\ & \quad = g_2 B(j\omega) \otimes B(j\omega) \otimes \tfrac{1}{4}[\delta(\omega \pm 2\omega_0) + 2\delta(\omega)] \end{aligned} \tag{3}$$

$$\begin{aligned} & g_3 X(j\omega) \otimes X(j\omega) \otimes X(j\omega) \\ & \quad = g_3 B(j\omega) \otimes B(j\omega) \otimes B(j\omega) \otimes \tfrac{1}{8}\,[\delta(\omega \pm 3\omega_0) \\ & \qquad + 3\delta(\omega \pm \omega_0)]. \end{aligned} \tag{4}$$

From (4), we find that the cubic term produces both the third harmonic and the fundamental signal. It can be seen that the self convolution of $B(j\omega)$ shown in (4) results in spectral regrowth.

III. Linearization Method

Since the cubic term is the main source of spectral regrowth, the second harmonic can be utilized to combat this distortion. A two-stage power amplifier is proposed which makes use of the interstage second harmonic component for linearization purposes. The fundamental output of the first amplifier is fed directly to the second amplifier while the second harmonic is amplified and phase shifted by a feed forward circuit before being fed to the input of the second amplifier. The output of the second harmonic amplifier is given by

$$Y_{2nd}(j\omega) = \tfrac{1}{4}\, g_2 \rho e^{-j\varphi}[B(j\omega) \otimes B(j\omega)] \otimes \delta(\omega \pm 2\omega_0) \qquad (5)$$

where ρ is the gain and φ is the phase shift of the second harmonic amplifier.

After algebraic manipulation, the fundamental frequency output of the first amplifier can be found to be

$$\begin{aligned} Y_{1st}(j\omega) = &\tfrac{1}{2}\, g_1 B(j\omega) \otimes \delta(\omega \pm \omega_0) + \tfrac{3}{8}\, g_3 B(j\omega) \\ &\otimes B(j\omega) \otimes B(j\omega) \otimes \delta(\omega \pm \omega_0). \end{aligned} \qquad (6)$$

The input spectra of the second amplifier is, therefore, given by

$$Y^{\mathrm{In}}(j\omega) = Y_{1st}(j\omega) + Y_{2nd}(j\omega). \qquad (7)$$

Similar to (3), the output of the second amplifier $Z(j\omega)$ can then be written as

$$\begin{aligned} Z(j\omega) = &h_1 Y^{\mathrm{In}}(j\omega) + h_2 Y^{\mathrm{In}}(j\omega) \otimes Y^{\mathrm{In}}(j\omega) \\ &+ h_3 Y^{\mathrm{In}}(j\omega) \otimes Y^{\mathrm{In}}(j\omega) \otimes Y^{\mathrm{In}}(j\omega) + \cdots. \end{aligned}$$

Substituting (5)–(7) into this expression we can obtain the output of the second amplifier. Considering the fundamental frequency component only, the output of the second amplifier is given by

$$Z_{\mathrm{out}}(j\omega) = B_{\mathrm{out}}(j\omega) \otimes \tfrac{1}{2}\, \delta(\omega \pm \omega_0)$$

where

$$\begin{aligned} B_{\mathrm{out}}(j\omega) \approx &h_1 g_1 B(j\omega) + \left[\tfrac{3}{4}\, h_1 g_3 + \tfrac{1}{2}\, \rho e^{-j\varphi} h_2 g_1 g_2 \right. \\ &\left. + \tfrac{3}{4}\, h_3 g_1^3\right] [B(j\omega) \otimes B(j\omega) \otimes B(j\omega)]. \end{aligned} \qquad (8)$$

The physical meanings of the four terms in (8) are the following.

1) $h_1 g_1 B(j\omega)$ is the linearly amplified signal through the first and the second amplifier; this is ideal what is required linear amplification requirements.
2) $(3/4) h_3 g_1^3 [B(j\omega) \otimes B(j\omega) \otimes B(j\omega)]$ is the linearly amplified signal of the first amplifier, distorted by the cubic term of the second amplifier.
3) $(3/4) h_1 g_3 [B(j\omega) \otimes B(j\omega) \otimes B(j\omega)]$ is the signal distortion caused by the cubic term of the first amplifier and subsequently linearly amplified by the second amplifier.
4) $(1/2) \rho e^{-j\varphi} h_2 g_1 g_2 B(j\omega) \otimes B(j\omega) \otimes B(j\omega)$ is the mixing product of the amplified and phase shifted second harmonic signal with the linearly amplified fundamental signal in the second amplifier.

According to (8), by choosing the appropriate ρ and φ, $[(3/4) h_1 g_3 + (1/2) \rho e^{-j\varphi} h_2 g_1 g_2 + (3/4) h_3 g_1^3]$ can be made zero thus reducing the spectral regrowth.

IV. Experimental Verification

The experimental setup is shown in Fig. 1 and shows two amplifiers using the minicircuits ERA-1SM monolithic amplifier in the main path and an adjustable harmonic amplifier and phase shifter in the second harmonic path. The -1 dBgcp of the second-stage amplifier was 8 dBm, and the -1 dBgcp of

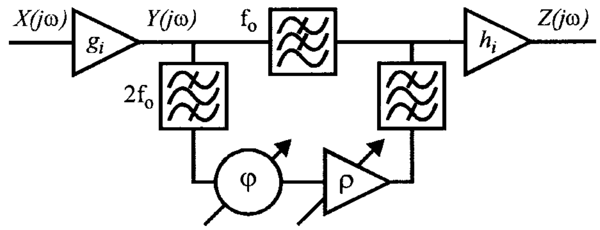

Fig. 1. Diagram of experimental setup.

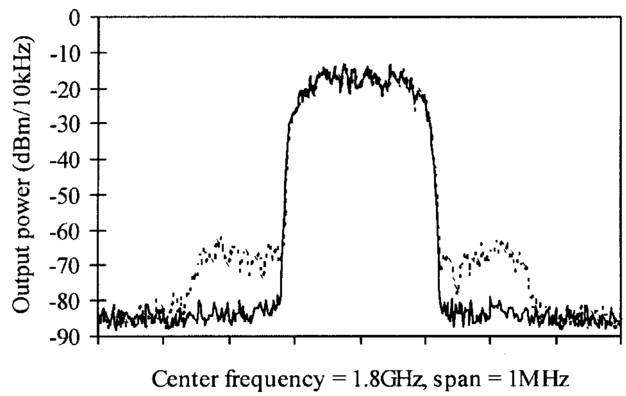

Fig. 2. Spectral regrowth (—) with and without (- - -) interstage second harmonic amplifier linearizing circuit for amplifier operating in the weakly nonlinear region.

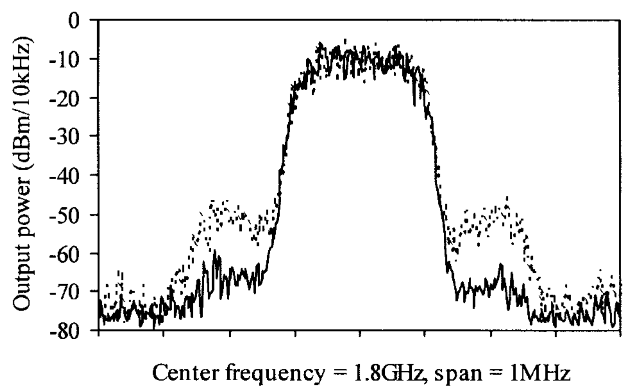

Fig. 3. Spectral regrowth (—) with and without (- - -) interstage second harmonic amplifier linearizing circuit for amplifier operating in the strongly nonlinear region.

the fundamental and second harmonic signal referenced to the input of the second stage was -1 and -2.5 dBm, respectively. A $(\pi/4)$-DQPSK modulated signal at 1.8 GHz was used to drive the input and the output is compared with and without the second harmonic path shown in Fig. 2. We can see that the spectral regrowth was eliminated completely when the second harmonic path was introduced. This was achieved by carefully adjusting the gain and the phase shift of the second harmonic path. Fig. 3 shows the output signal with a higher input signal when the amplifier was operating in the strongly nonlinear region. By careful adjustment of the gain and the phase shift of the second harmonic path, the most predominant spectral regrowth generated by the cubic term was reduced by 15 dB. In order to reduce the spectral regrowth, the power required for the second harmonic was 7 dB below that of the fundamental.

Some work was also performed to see how sensitive this linearization method was to changes in amplitude and phase of the second harmonic path. A change in phase of $\pm 10^\circ$ gave an increase of 6 dB, while a change of ± 2 dB gave an increase of 8 dB in the spectral regrowth.

V. Discussion and Conclusion

Amplifiers that are memoryless and with weak nonlinearity has been modeled using the power series. Fourier transform was used to study spectral regrowth and according to our analysis, the mechanism of spectral regrowth is the self intermodulation of the signal. The regenerated spectral width is proportional to the primitive bandwidth of the input digitally modulated signal and its amplitude is dependent on the strength of the amplifier nonlinearity. A linearization technique is proposed that uses interstage second harmonic enhancement. The theory predicts that the spectral regrowth of digitally modulated signals can be reduced by the using the second harmonic signal generated by the first amplifier to feed the second amplifier. Experimental results proved that this method is practical and works well for weakly nonlinear amplifiers by adjusting the amplitude and phase of the second harmonic signal. Unlike feedback linearization, this method has no stability problems, similar to that found in feedforward linearization making the method easy to implement. Higher order terms not considered in the calculations would explain the incomplete cancellation of the spectral regrowth in the stronger nonlinear region of operation.

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