An Adaptive Predistortion RF Power Amplifier With a Spectrum Monitor for Multicarrier WCDMA Applications

Seung-Yup Lee, Yong-Sub Lee, Seung-Ho Hong, Hyun-Sik Choi, and Yoon-Ha Jeong, *Senior Member, IEEE*

***Abstract*—This paper presents an adaptive predistortion RF power amplifier for repeater systems with a spectrum monitor. For adaptive control of cancellation, we implement a spectrum monitor that improves the adjacent channel leakage ratio (ACLR) characteristics of the power amplifier by analyzing the output spectrums of RF power amplifiers directly and simultaneously. For experimental validation, we also implement a class-AB RF power amplifier that adopts a predistortion linearizer with the spectrum monitor and measure the characteristics for the wide-band code division multiple access (WCDMA) band. With an optimum gate bias voltage of the power amplifier, ACLRs of 22 and 20.5 dB are improved for the cases of one- and four-carrier WCDMA applications, respectively. The predistortion power amplifier with the spectrum monitor delivers a P_{out} of 37.5 dBm with an ACLR of −45 dBc for four-carrier WCDMA applications. Furthermore, excellent ACLR characteristics are consistently maintained with the minimization algorithm by adaptively controlling the vector modulator in the predistorter under various environments that include varying input power levels, temperatures, and operating frequencies.**

***Index Terms*—Adaptive, adjacent channel leakage ratio (ACLR), linearity, power amplifier, predistorter (PD), spectrum, wide-band code division multiple access (WCDMA).**

I. INTRODUCTION

DIVERSE techniques for linearity improvement of RF power amplifiers have been investigated and developed endlessly in modern wireless communication systems such as global system for mobile (GSM), IS-95 series, CDMA2000, wide-band code division multiple access (WCDMA), etc. [1]. Among the linearization techniques, feedforward approaches provide high linearity, but result in complex and expensive solutions and, thus, are mostly used in base-station systems [2]–[4]. Feedback methods have fatal problems of instability and bandwidth limitations [5]–[7]. Development of digital predistortion (DPD) techniques is being actively pursued due to their high intermodulation distortion (IMD) suppression, but is complicated and typically implemented at the baseband level. Therefore, these techniques are not suitable for repeater systems, such as feedforward systems [8]–[11]. In contrast, analog predistortion techniques have the advantages of simple structure, low cost, and proper linearization [12]–[15]. Compared with DPD techniques, they are suited to repeater systems because they can amplify RF signals directly between handsets and base stations with the above-mentioned advantages. However, conventional predistortion power amplifiers also have problems such as memory effects and variations in linearity depending on the environment. Therefore, adaptive control methods are in great demand for improving the performance of predistortion RF power amplifiers.

In this paper, for adaptive control, we propose a spectrum monitor (we refer to the semispectrum analyzer implemented as the spectrum monitor to distinguish it from general spectrum analyzers) that is applied to an analog predistortion RF power amplifier. It directly analyzes the spectrum components of output power from RF power amplifiers. Its structure is not much different from those of general spectrum analyzers and can be adopted by other linearization applications. In the implemented adaptive predistorter (PD), the spectrum monitor impresses the proper control voltages of an attenuator and a phase shifter in the PD while analyzing the output spectrums. Down-link WCDMA signals are focused rather than continuous waves (CWs) or two-tone signals. For experimental validation, we linearize a 2.11∼2.17-GHz-band class-AB RF power amplifier with 30-W peak envelope power (PEP). Adjacent channel leakage ratios (ACLRs) of −59.5 dBc (improved value of 22 dB) and −52.14 dBc (improved value of 20.5 dB) are obtained for one- and four-carrier WCDMA applications, respectively. As an ACLR of −45 dBc is put as a reference of the linearity in WCDMA applications, the predistortion power amplifier delivers a P_{out} of 37.5 dBm for four-carrier WCDMA applications. Furthermore, excellent cancellation of nonlinearity is maintained with the spectrum monitor under all environments formed by varying input power levels, temperatures, and WCDMA channels.

II. OPERATION OF PREDISTORTION POWER AMPLIFIER WITH SPECTRUM MONITOR

We propose a predistortion RF power amplifier based on a spectrum monitor. Fig. 1 shows the block diagram of the proposed system. In conventional analog predistortion techniques that do not use a spectrum monitor, the spurious signal out of the main power amplifiers are cancelled with distorted signals in the PD by controlling two parameters of a variable attenuator and variable phase shifter (a vector modulator). However, the magnitude and phase of the vector modulator in the PD is

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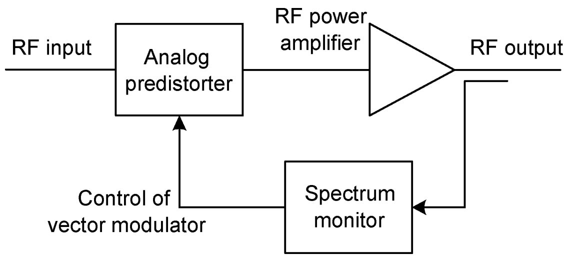

Fig. 1. Block diagram of the proposed adaptive predistortion RF power amplifier.

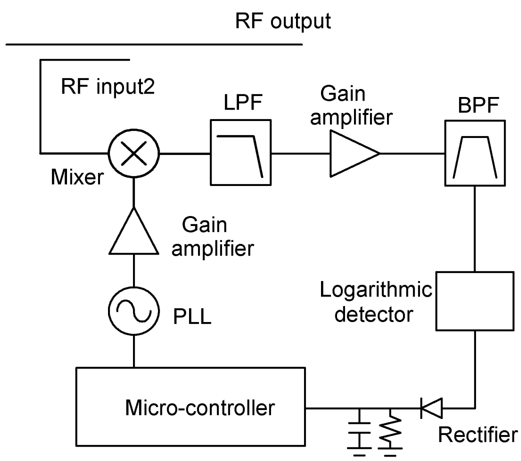

Fig. 2. Block diagram of the spectrum monitor.

fixed so the performance of the power amplifier is limited in the presence of environmental changes. In the proposed adaptive predistortion technique, the spectrum monitor analyzes the output spectrum components and maximizes the linearity of the predistortion power amplifier by controlling the vector modulator adaptively in the PD whenever the environment is changed. This method is similar to what engineers do to control the vector modulator while measuring the spectrums of output power on spectrum analyzers.

The spectrum monitor is composed of a phase-locked loop (PLL), mixer, power detection unit, and microcontroller, as shown in Fig. 2. Its operation resembles that of a general spectrum analyzer. Stable local oscillation (LO) signals are generated in the PLL, and the RF signals are down-converted to IF signals by the LO signal in the mixer. The shape of down-converted IF signals is the same as that of RF signals, but only the frequency band is changed now, as shown in Fig. 3. The IF signals become a CW signal after passing through narrow bandpass filters (BPFs). A specific frequency component can be determined by detecting the CW signal in a logarithmic detector. If the frequency of the LO signal is swept gradually by the PLL, that of the IF signals is also swept. The magnitudes of the IF signals through the narrow windows of BPFs are detected gradually; thus, finally, the spectrums of the RF signals can be determined with the information of the frequency of the PLL (x-axis) and the magnitudes of the detected CW signals (y-axis).

Fig. 4 shows the flowchart of the microcontroller in the spectrum monitor, which is optimized for WCDMA applications. The microcontroller detects changes in spectrum components

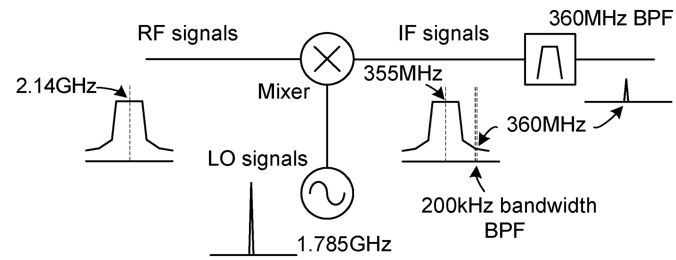

Fig. 3. Frequencies and shapes of RF, IF, and LO signals.

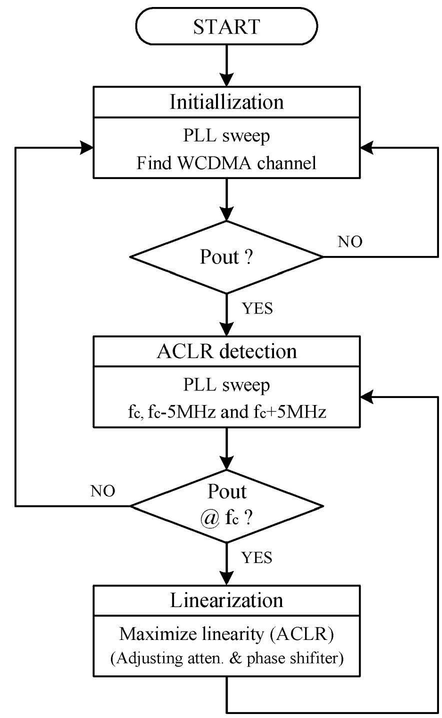

Fig. 4. Flowchart for maximizing ACLR characteristics.

continuously and minimizes spurious power with a minimization algorithm [16]. In WCDMA applications, it is not necessary for all spectrum components with a 70-MHz bandwidth to be detected to improve linearity. To improve the speed of minimization, 12 WCDMA channels are detected first and then spurious power (especially 5-MHz-offset components) of the activated channels are detected. The LO frequency is swept to search activated and deactivated channels frequently during minimization. It is the 5-MHz-offset frequency components that are necessary for ACLR improvement, and this frequency is swept easily by the PLL.

In the adaptive analog predistortion technique, there are two control parameters in the attenuator and phase shifter. The power detection and control of the vector modulator are achieved continuously by the microcontroller. Denoting the spurious power density that is detected first with the first control voltage of the attenuator (V_{ATTEN1}) as P_{ACLR1}, and the spurious power density that is detected second after applying the changed control voltage of the attenuator (V_{ATTEN2}) as P_{ACLR2}, the minimization process for the ACLR is as follows:

$$\Delta V_{\mathrm{ATTEN}} = \frac{P_{\mathrm{ACLR2}} - P_{\mathrm{ACLR1}}}{V_{\mathrm{ATTEN2}} - V_{\mathrm{ATTEN1}}} \tag{1}$$

TABLE I
FOUR CASES OF APPLIED CONTROL VOLTAGES USED IN THE MINIMIZATION ALGORITHM

	Conditions	Renewed voltage
Case 1	$P_{ACLR2} > P_{ACLR1}$ $V_{ATTEN2} > V_{ATTEN1}$	Decrease
Case 2	$P_{ACLR2} > P_{ACLR1}$ $V_{ATTEN2} < V_{ATTEN1}$	Increase
Case 3	$P_{ACLR2} < P_{ACLR1}$ $V_{ATTEN2} > V_{ATTEN1}$	Increase
Case 4	$P_{ACLR2} < P_{ACLR1}$ $V_{ATTEN2} < V_{ATTEN1}$	Decrease

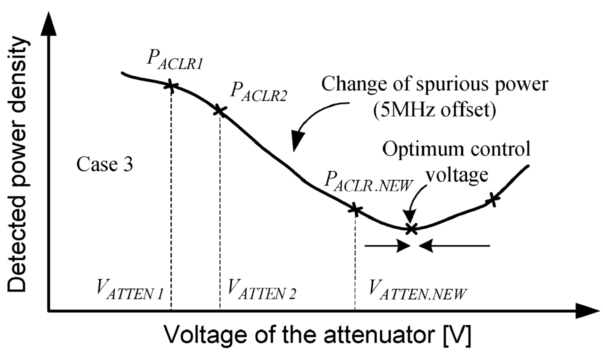

Fig. 5. Concept of minimization algorithm.

$$V_{\text{ATTEN.NEW}} = V_{\text{ATTEN2}} - \Delta V_{\text{ATTEN}} \tag{2}$$

where $V_{\text{ATTEN.NEW}}$ is the new control voltage to be applied to the attenuator. The two directions of the new control voltage of the attenuator around possible four cases are arranged in Table I.

As shown in (1) and (2), if ΔV_{ATTEN} has a negative value (Cases 2 and 3 in Table I), $V_{\text{ATTEN.NEW}}$ moves in a positive direction. Fig. 5 describes the concept of the minimization algorithm and especially shows Case 3. Conversely, if ΔV_{ATTEN} has a positive value (Cases 1 and 4), $V_{\text{ATTEN.NEW}}$ moves in a negative direction. The minimum value of the spurious power is obtained while this process is repeated continuously in the algorithm, and this value is continuously maintained. The control of the phase shifter operates in the same way as that of the attenuator. The simultaneous control of the attenuator and the phase shifter is difficult because it is not known which parameter contributes the improvement of the ACLR characteristics in a particular situation and, thus, these two components are controlled in an alternating manner.

III. Experimental Results of Predistortion Power Amplifier With Spectrum Monitor

Here, we present the implementation and experimental results of the spectrum monitor and the adaptive predistortion RF power amplifier. The spectrum monitor analyzes the output spectrums directly. It automatically improves the linearity and maintains the maximum ACLR characteristics of the predistortion power amplifier.

A. Implementation of the Spectrum Monitor

Fig. 6 shows the entire block diagram of the implemented adaptive predistortion RF power amplifier with the spectrum monitor. In the spectrum monitor, the frequency range of the PLL is chosen as 1.75~1.81 GHz because that of the down-link WCDMA applications is 2.11~2.17 GHz and the center frequency of the BPFs is 360 MHz. The frequency of the PLL is initialized and swept by a microcontroller, i.e., Microchip's PIC16F877. The RF input signals to a mixer should be small enough to escape the mixer's nonlinear region.

A power detection module consists of a low-pass filter (LPF), gain amplifiers, BPFs, logarithmic detector, and rectifier. The down-converted IF signals are filtered out by the LPF ahead to eliminate higher order harmonics. To obtain accurate specific frequency components, BPFs with narrow bandwidth are required. The bandwidth of the surface acoustic wave (SAW) filters used in the spectrum monitor is 200 kHz. The performances of one- and two-stage BPFs are compared in Fig. 7. The two-stage filter has excellent bandpass capability, and is suitable for separating and analyzing specific frequency components. The magnitudes of the separated frequency components are detected in the logarithmic detector and measured in a 10-bit analog-to-digital converter (ADC) in the microcontroller. The rectifier with Schottky diode is placed between the logarithm detector and the microcontroller to prevent detected voltages from rippling. The BPFs and the rectifier in the spectrum monitor are similar to the resolution bandwidth (RBW) and video bandwidth (VBW) in spectrum analyzers, respectively. The gain amplifiers should be placed in a few places in advance to prevent an increase of noise levels.

Fig. 8 shows the low-cost and small-sized spectrum monitor that is implemented. The spectrum monitor operates at a supply voltage of 5 V and consumes 180 mA of current, excluding a liquid crystal display (LCD). It has an input port for RF signals, an output connector for the LCD to read the detected values, and two output ports to control the predistortion linearizer. A 3-dBm down-link WCDMA signal (Agilent's E4433B) is measured by the spectrum monitor and a spectrum analyzer, and the spectrums are almost the same, as shown in Fig. 9. The sequence of the minimization algorithm in the spectrum monitor is detection, calculation of the new voltage, and control of the vector modulator. The loop time of the sequence in the implemented spectrum monitor is approximately 80 ms. The control of the attenuator and phase shifter is performed ten times in the microcontroller in an alternating manner.

B. Experimental Results of Adaptive Predistortion Power Amplifier

The spectrum monitor with the minimization algorithm is adopted into a predistortion RF power amplifier. The algorithm always maintains the minimum spurious power level by adjusting the vector modulator in the PD regardless of the environments (i.e., given various input power levels, temperatures, and WCDMA channels). A driver amplifier has a gain of 30 dB and a 1-dB compression point ($P_{1\ \text{dB}}$) of 36 dBm. The power amplifier is designed and implemented using MRF21030 LD-MOSFET from Motorola with 30-W PEP at a V_{DD} of 28 V.

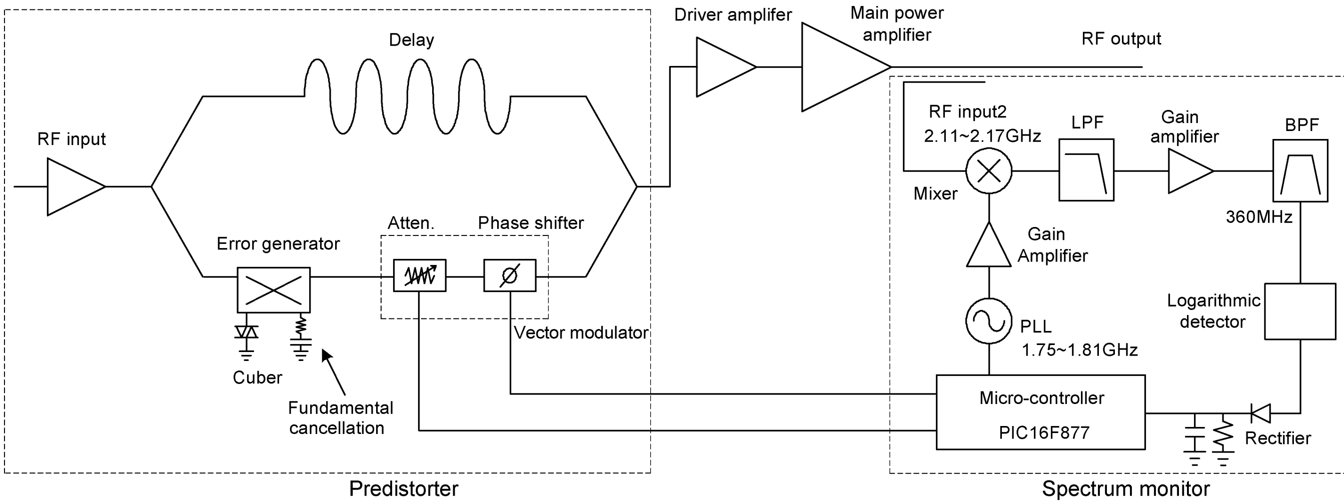

Fig. 6. Overall block diagram of an adaptive predistortion power amplifier with the spectrum monitor.

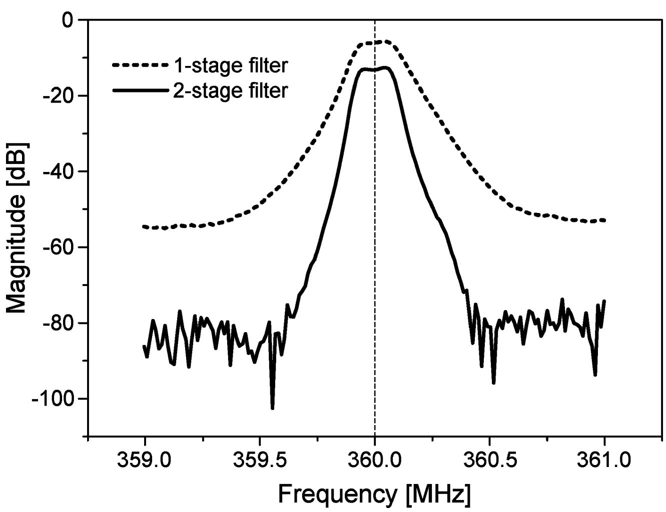

Fig. 7. Characteristics of the BPFs.

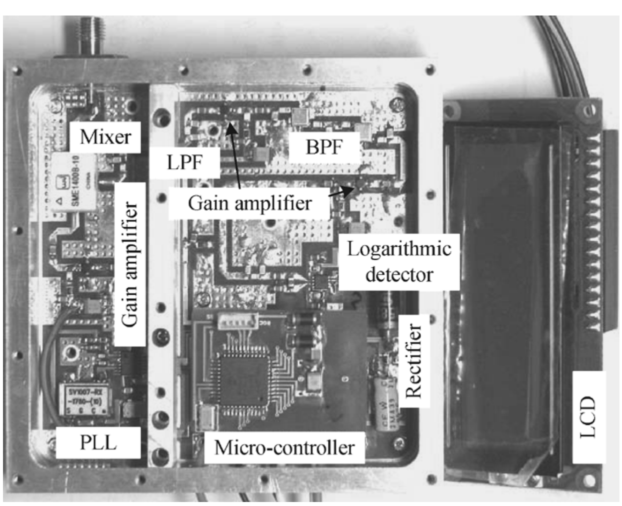

Fig. 8. Implemented spectrum monitor.

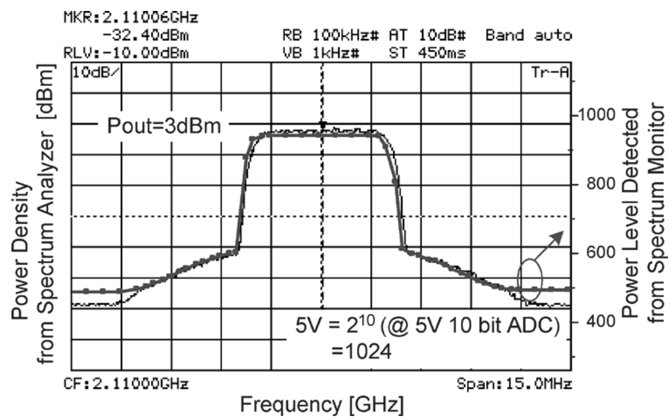

Fig. 9. Comparison of the spectrums of the implemented spectrum monitor and a spectrum analyzer at a $P_{\rm out}$ of 3 dBm.

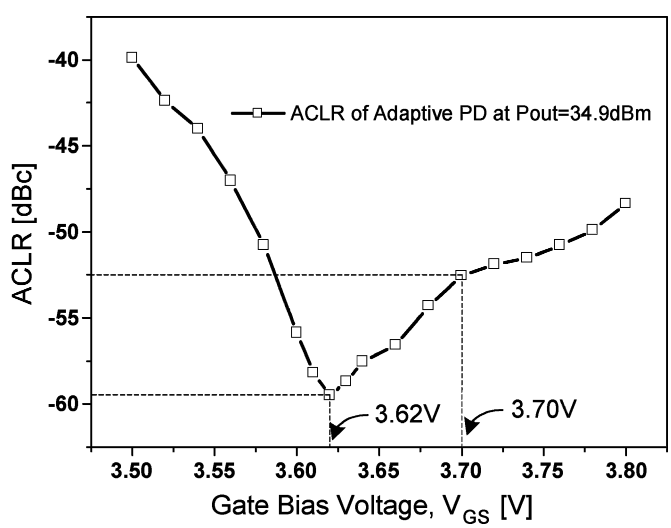

Fig. 10. Changes of ACLR with the gate-bias voltage in the power amplifier.

In the predistortion systems, the ACLR characteristics changes with not only the magnitudes and phases of the predistorted signals, but also the gate-bias voltage of the main power amplifier, as shown in Fig. 10. The best cancellation of nonlinearity in the predistortion power amplifier occurs at a $V_{\rm GS}$ of 3.62 V (quiescent current, $I_Q = 142$ mA), which the gate-bias voltage is fixed. Under this condition, the power amplifier has a $P_{1\ {\rm dB}}$ of 43.2 dBm and a gain of 11.5 dB. For the proper comparison of the ACLR characteristics, we also measured the power

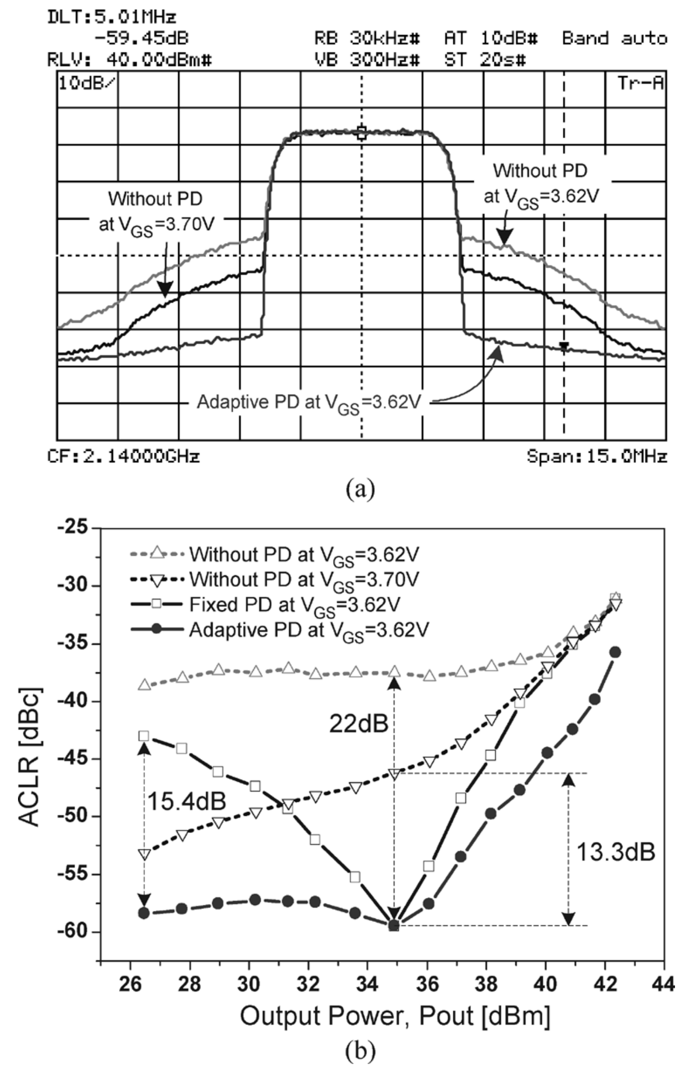

Fig. 11. ACLR characteristics for a one-carrier WCDMA signal. (a) Measured spectrum densities at a $P_{\rm out}$ of 34.9 dBm. (b) Comparison of the ACLR characteristics of the power amplifier with and without a PD.

amplifier without the PD at a $V_{\rm GS}$ of 3.7 V $(I_Q = 250\ \mathrm{mA})$, which provides a moderate ACLR performance according to the datasheets. For reference, Agilent's E4438C is used in the measurement of one- and four-carrier WCDMA applications.

Fig. 11(a) shows the power spectrum densities measured under various conditions at an average output power ($P_{\rm out}$) of 34.9 dBm for a one-channel WCDMA application. The ACLR of the power amplifier with the PD reaches -59.5 dBc at a $V_{\rm GS}$ of 3.62 V. The ACLRs of 13.3 and 22 dB are improved and compared with the ACLR of the power amplifier without the PD at $V_{\rm GS}$ of 3.7 V and 3.62 V, respectively. The ACLR characteristics of the predistortion power amplifier with the spectrum monitor and the other conditions above are compared in Fig. 11(b), while input power levels are swept. In the case when the conventional PD is optimized for high output power, there is a problem in that the ACLR characteristics become worse than that of the power amplifier without the PD (@ $V_{\rm GS} = 3.7$ V) at low-output power levels because the optimum magnitude and phase are varied along the levels of the output power. Therefore, adaptive control of the linearizer is necessary. The implemented spectrum monitor searches and maintains excellent ACLR characteristics. From the viewpoint of power-added efficiency (PAE), since the gate bias voltage becomes small (3.62 V), the PAE is also improved as much as 1.9% compared with that of the power amplifier at a $V_{\rm GS}$ of 3.7 V.

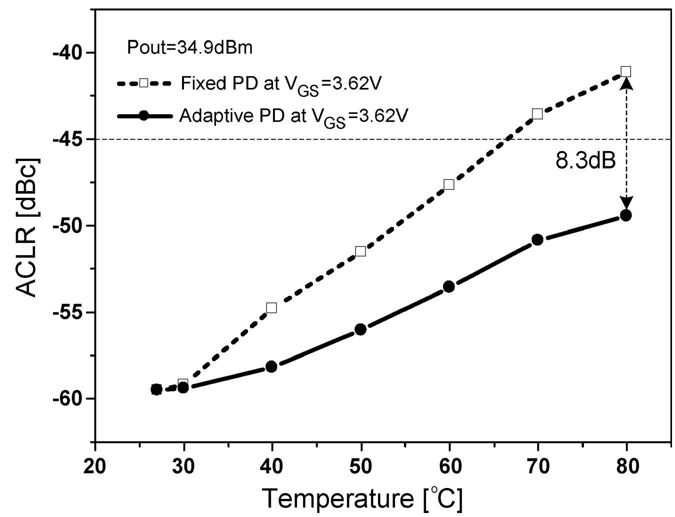

Fig. 12. ACLR characteristics of the adaptive predistortion power amplifier as a function of temperature for one-carrier WCDMA signals.

Furthermore, an increase in temperature causes an increase in the current of LDMOSFETs, and it eventually changes the optimum cancellation points of third-order intermodulation (IM3) power. The adaptive predistortion power amplifier with the spectrum monitor is excellent with an even variation in temperature, as shown in Fig. 12. The conventional predistortion power amplifier at a fixed control voltage in the vector modulator cannot follow the optimum cancellation of the spurious power; however, the adaptive power amplifier, which adopts the minimization algorithm, shows an improvement up to 9.2 dB at 80 °C.

There is another problem with conventional fixed PDs. As shown in Fig. 13, the optimum magnitudes and phases of IM3L and IM3H are also changed according to the center frequencies of the activated channels when a two-tone signal is applied because the output power levels are varied and the magnitudes and phases of the intermodulation terms vary with different frequencies. This results in negative effects on ACLR characteristics for WCDMA applications, as shown in Fig. 14, i.e., when the control voltages of the attenuator and the phase shifter are fixed in the PD for a specific channel, the ACLR characteristic can become worse in the other channels. However, the adaptive RF power amplifier with the spectrum monitor maintains maximum ACLR characteristics. Compared with the ACLR of the conventional PD that is fixed at a center channel, that of the adaptive predistortion power amplifier is improved up to 6.8 dB at the outside channels. It shows excellent performance at different input power levels, temperatures, and even WCDMA channels with the aid of the spectrum monitor.

To reduce the memory effects of an LDMOSFET, a 3-mm-wide dc feed line is designed [17]. A four-carrier

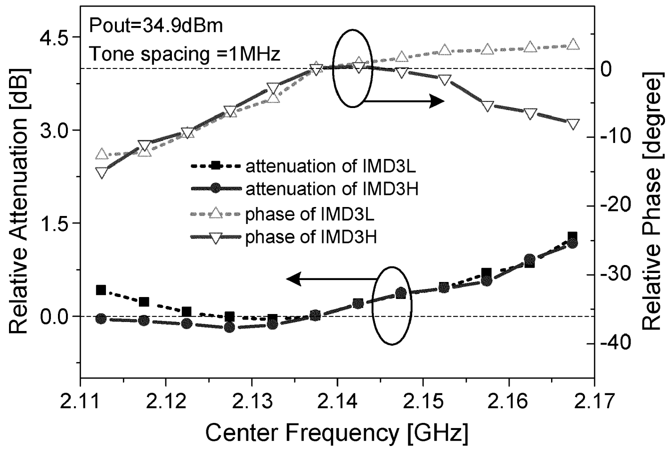

Fig. 13. Measured magnitudes and phases of IM3 power with changes in frequencies.

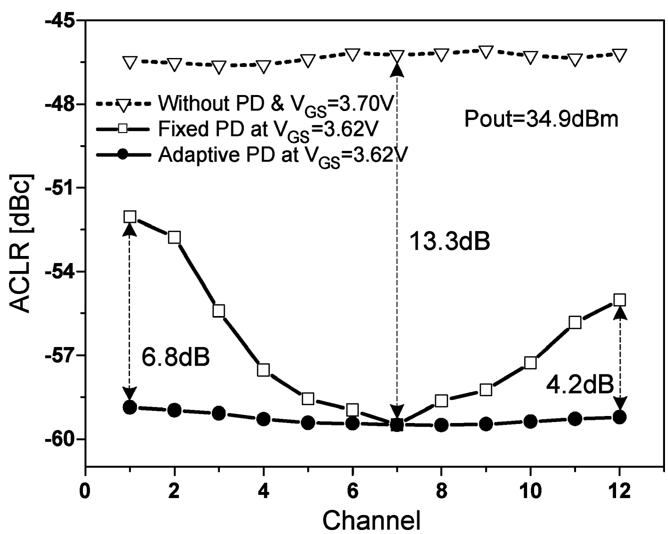

Fig. 14. ACLR characteristics of the adaptive predistortion power amplifier with changes in the channels.

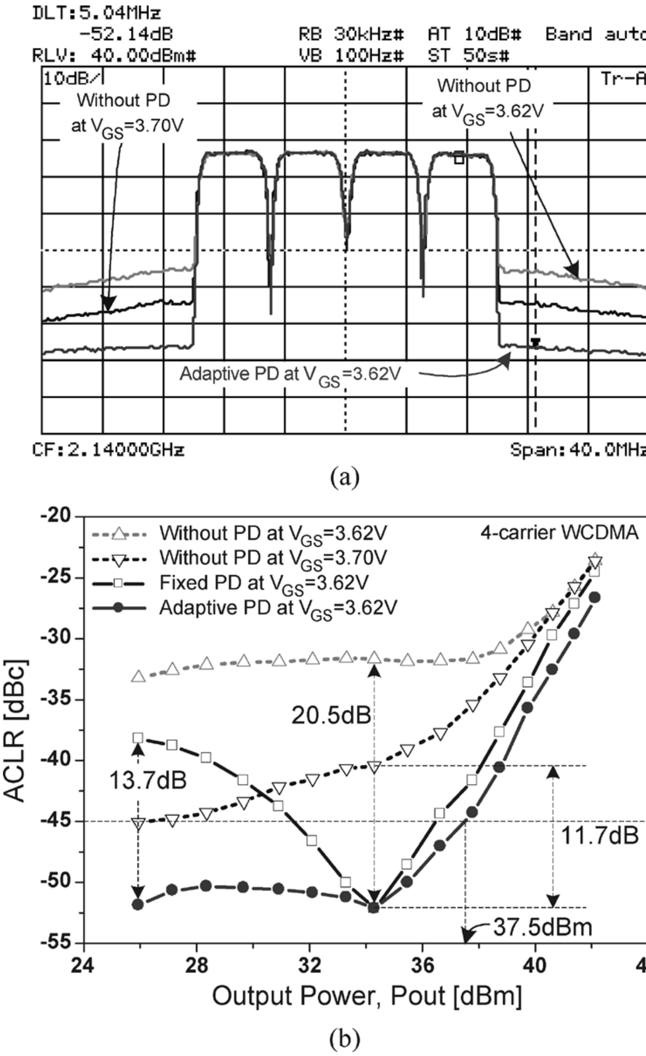

Fig. 15. ACLR characteristics for four-carrier WCDMA signal. (a) Measured spectrum densities at $P_{\rm out}$ of 34.3 dBm. (b) Comparison of the ACLR characteristics of the power amplifier with and without a PD.

WCDMA signal is created by one signal generator. The maximum ACLR of -52.14 dBc is obtained at a $P_{\rm out}$ of 34.3 dBm, as shown in Fig. 15. The ACLR upper and ACLR lower values are measured in symmetric states. The improved ACLR (5-MHz offset) values are 11.7 and 20.5 dB under the conditions of $V_{\rm GS}$ of 3.7 and 3.62 V, respectively. The predistortion power amplifier with the spectrum monitor can deliver a $P_{\rm out}$ of 37.5 dBm with an ACLR of -45 dBc for four-carrier WCDMA applications, whereas the power amplifier without the PD at a $V_{\rm GS}$ of 3.7 V delivers a $P_{\rm out}$ of only 26 dBm. Excellent ACLR characteristics are maintained, due to the spectrum monitor. An ACLR of 13.7 dB is improved and compared with the power amplifier with a conventional PD at a $P_{\rm out}$ of 26 dBm. As shown in Fig. 16, the spectrum monitor minimizes the variation of ACLR characteristics under temperature changes and improves it by up to 9.2 dB at 70 °C. In the case of four-carrier applications, the predistortion power amplifier also shows excellent ACLR characteristics at a $V_{\rm GS}$ of 3.62 V, and this performance is maintained by the spectrum monitor under various environmental conditions.

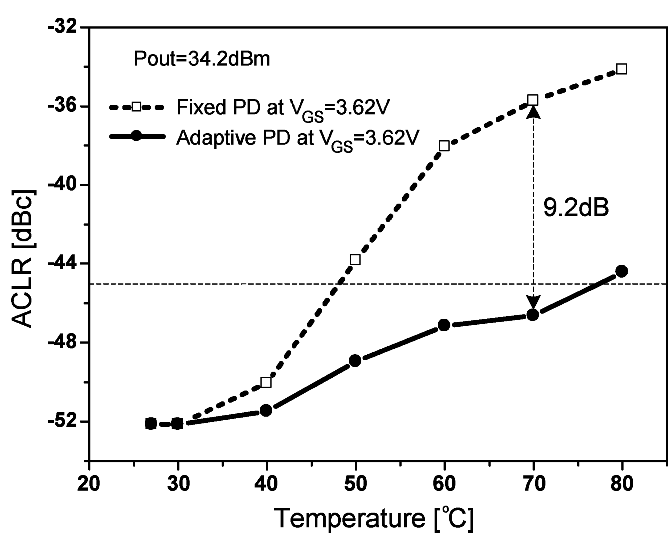

Fig. 16. ACLR characteristics of the adaptive predistortion power amplifier as a function of temperature for four-carrier WCDMA signals.

IV. Conclusion

For the adaptive control of the predistortion RF power amplifier, we have proposed and implemented a low-cost spectrum monitor that can analyze the output spectrums directly. We have also implemented a predistortion RF power amplifier for repeaters in the WCDMA band of 2.11∼2.17 GHz with a 30-W PEP LDMOSFET. The ACLR characteristics of the power amplifier with the PD changes with the gate-bias voltage of the power amplifier, and the optimum gate bias voltage is determined. For one-carrier WCDMA applications, the ACLR reaches -59.5 dBc at a P_{out} of 34.9 dBm, and is improved by up to 22 dB by the spectrum monitor. From the viewpoint of input power levels, the problem of the linearity of the predistortion power amplifier becoming worse while the input power levels are decreased is solved with ACLR improvements of up to 15.4 dB. The variations of the ACLR with temperature in the fixed PD are also solved up to 8.3 dB. Another problem that can occur with changes of WCDMA channels is solved up to 6.8 dB with the spectrum monitor for one-carrier WCDMA applications. Even for four-carrier WCDMA applications, an ACLR of -52.14 dBc is obtained at a P_{out} of 34.3 dBm by improving an ACLR of 20.5 dB. The power amplifier with the spectrum monitor delivers a P_{out} of 37.5 dBm with an ACLR of -45 dBc. Excellent performance is maintained by the spectrum monitor under various temperatures.

The output signals of the power amplifiers need to be analyzed in real time in order to solve the problems faced by conventional predistortion RF power amplifiers. Thus, the use of the spectrum monitor is proposed. The characteristics of the adaptive predistortion RF power amplifier with the spectrum monitor are excellent under various conditions such as varying input power levels, temperatures, and operating frequencies.

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