Design of RF Pre-Distortion Linearizer for Various Transfer Characteristics of Power Amplifiers

Dong-Hee Jang[1] · Kyoung-Joon Cho[1] · Sang-Hee Kim[1] · Jong-Heon Kim[1] · Shawn P. Stapleton[2]

Abstract

We propose a diode-based RF pre-distorter with various gain and phase characteristics, for non-linearity compensation of RF power amplifiers. This pre-distorter results in the removal of the diode- and configuration-dependent characteristics in the conventional diode-based RF pre-distorters. We have analyzed the operation principle of the proposed pre-distorter. The results show that gain and phase characteristics of the pre-distorter in all four quadrants are achieved. Several power amplifiers and test signals are used for verifying the performance of the proposed diode-based RF pre-distorter.

Key words : Gain Characteristic, Phase Characteristic, Signal Phase Shift, Pre-Distorter, ACPR.

Ⅰ. Introduction

Normally, the gain and phase characteristics of power amplifier are constant at high output back-off. However, these are not constant at low output back-off nearby P1dB due to the non-linearity of power amplifier. Generally, it can be classified as four different AM-AM and AM-PM distortions: a) gain compression and phase lag, b) gain expansion and phase lag, c) gain compression and phase advance, and d) gain expansion and phase advance. In order to correct these AM-AM and AM-PM distortions, a RF pre-distortion linearizer can be used. The RF pre-distorter should then properly match to the inverse of the gain and phase characteristics of the power amplifier.

Many researchers have proposed diode-based RF pre-distorters according to device-and configuration-dependent characteristics. In-line type diode-based RF pre-distorters have been proposed which only provide either gain expansion and phase lag characteristics[1], or gain compression and phase advance characteristics[2]. Reflection type diode-based RF pre-distorters have been also proposed to compensate for power amplifier with gain compression and phase lag characteristics[3]. These diode-based RF pre-distorters cannot achieve the gain and phase characteristics in all quadrants. Separate gain and phase adjustments of a diode-based RF pre-distorter has been investigated[4]. Tuning of the matching circuits and bias points, however, cannot perfectly separate the gain and phase characteristics in this configuration.

In this paper, we propose a diode-based RF pre-distorter. This pre-distorter has a balanced type reflection structure with device- and configuration- independent characteristics and it can provide both gain and phase compensations in all four quadrants. This pre-distorter is verified experimentally and through simulations with several test signals at 880 MHz band. Section II shows the description and analysis of the proposed pre-distorter. Simulated and measured results of the proposed pre-distorter are presented in section III. Conclusion is offered in Section IV.

Ⅱ. Diode-Based RF Pre-Distorter

Fig. 1 shows the schematic diagram of the proposed diode-based RF pre-distorter. This pre-distorter consists of two main sections: linear path in upper path and nonlinear path in lower path. The input signal is first split into two paths by a 90 degrees hybrid coupler: One going to the linear path with phase shifter and the other to the nonlinear path with an IM generator. The important operational feature of the proposed pre-distorter is the phase shift of signals in the upper path. The phase shifter in linear path, which provides the

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[1] Department of Radio Science and Engineering, Kwangwoon University, Seoul, Korea.
[2] School of Engineering Science, Simon Fraser University, Vancouver, BC, Canada.

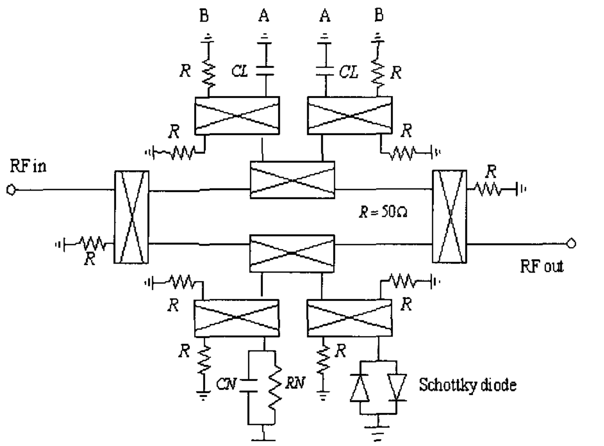


Fig. 1. Schematic diagram of proposed diode-based RF pre-distorter.

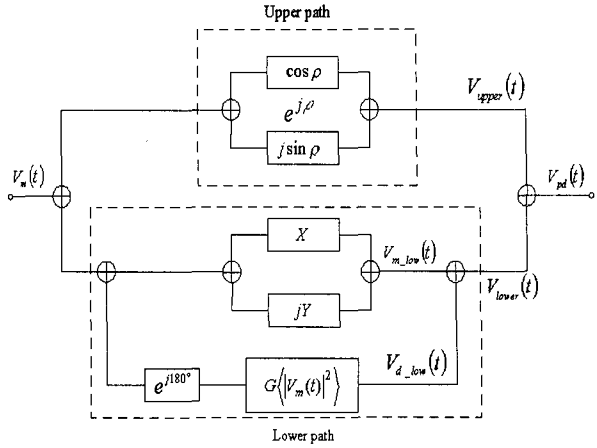


Fig. 2. Equivalent block diagram of the proposed pre-distorter.

signal phase shift of 360 degrees, is realized by placing hybrid couplers, and shunt capacitance and resistance elements. The phase shift is controlled by these capacitances and termination resistances in position A and B of the couplers. Theoretically, the variation of capacitance generates a phase shift of up to 180 degrees and an additional phase shift of 180 degrees can be obtained by changing termination positions of the 90 degrees hybrid couplers. The nonlinear gain and phase characteristics are generated by using Schottky anti-parallel diodes and hybrid couplers with terminating capacitor and resistor. Finally, four types of gain and phase characteristics can be achieved with signal vector combinations in upper and lower paths.

Fig. 2 presents the equivalent block diagram of the pre-distorter shown in Fig. 1, using a complex gain representation. We assume that non-linearity of Schottky diodes depends on the input power and loss of couplers is neglected. The pre-distorter signal is obtained by adding the upper path signal with phase-shifted signal to the lower path signal by passive components and diode's non-linearities. In upper path, the phase shift of ρ is utilized to achieve the desired slope types of gain and phase characteristics. In lower path, CN(capacitor) and RN(resistor) adjust the X and Y, and diodes introduce the non-linearities. The X, Y, and non-linearity determine the desired slope ranges of gain and phase characteristics. The complex gain of the diodes, using a first-order function, can be expressed as reference[5]

$$G\langle|V_m(t)|^2\rangle = (\alpha_1 + j\beta_1) + (\alpha_3 + j\beta_3)\cdot|V_m(t)|^2 \tag{1}$$

where α and β coefficients are complex quantities. The signal after signal phase shifts, ρ, in the upper path can now be written as

$$V_{upper}(t) = (\cos\rho + j\sin\rho)\cdot V_m(t) \tag{2}$$

The signal after the parallel resistor and capacitor can be written as

$$V_{m\_low}(t) = (X + jY)\cdot V_m(t) \tag{3}$$

The signal after passing through the nonlinear devices, with an anti-phase state, is given by

$$V_{d\_low}(t) = e^{j180°}\cdot V_m(t)\cdot G\langle|V_m(t)|^2\rangle = -(\alpha_1 + j\beta_1)\cdot V_m(t) - (\alpha_3 + j\beta_3)\cdot V_m(t)\cdot|V_m(t)|^2 \tag{4}$$

By selection of and in (3) and (4), the output signal in the lower path is

$$V_{lower}(t) = -(\alpha_3 + j\beta_3)\cdot V_m(t)\cdot|V_m(t)|^2 \tag{5}$$

The overall output signal of the pre-distorter model is

$$V_{pd}(t) = (\cos\rho + j\sin\rho)\cdot V_m(t) - (\alpha_3 + j\beta_3)\cdot V_m(t)\cdot|V_m(t)|^2 \tag{6}$$

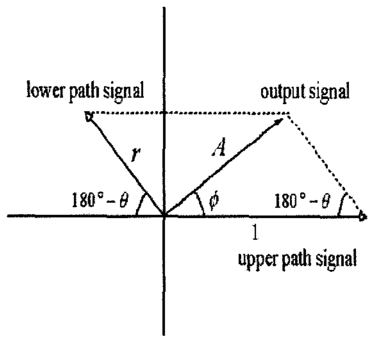
Dividing (6) by the first term of the right side in (6) gives the normalized pre-distorter signal as

$$\overline{V_{pd}(t)} = 1\cdot\angle 0° + |V_m(t)|^2\sqrt{\alpha_3^2 + \beta_3^2}\cdot\angle\left(180° - \rho + \tan^{-1}\frac{\beta_3}{\alpha_3}\right) = 1\cdot\angle 0° + r\cdot\angle\theta° \tag{7}$$

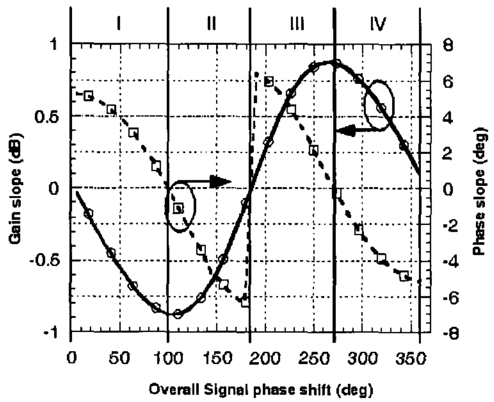
where $\tan^{-1}(\beta_3/\alpha_3)$ is the signal phase shift introduced in lower path. From (7), θ is calculated by an amount of phase shift in upper path with respect to phase shift in lower path generated by nonlinear process, and then is recognized as the phase difference of the signal combined at output of pre-distorter. Therefore, overall signal phase shift can be considered as the phase difference, θ. The term of left side is identified as, $A(r, \theta) \cdot \angle\phi\ (r, \theta)$, as polar vector representation shown Fig. 3(a).

Fig. 3 shows the calculated slope characteristics of gain and phase for the diode-based RF pre-distorter, as a function of overall signal phase shift, at fixed input power. Fig. 3(a) shows the signal vector combinations in upper and lower paths of the proposed pre-distorter.

For analysis, we assume that the upper path signal is the reference signal. The gain of the signal is 1 and the phase is 0°. The gain of the lower path signal is r and the phase is $\theta°$. The slope characteristics of gain and phase of the pre-distorter as a function of overall signal phase shift at fixed input power is calculated.



(a) Vector diagram of proposed pre-distorter



(b) Slope characteristics for r = 0.1

Fig. 3. Calculated slope characteristics of gain and phase at fixed input power.

Using the cosine rule, the gain and phase characteristics can be calculated as

$$A(r,\theta)_{dB} = 20\log\left(\sqrt{1+r^2-2\cdot r\cdot\cos(180°-\theta)}\right) \tag{8}$$

$$\phi(r,\theta) = \cos^{-1}\left(\frac{1-r\cdot\cos(180°-\theta)}{\sqrt{1+r^2-2\cdot r\cdot\cos(180°-\theta)}}\right) \tag{9}$$

The gain and phase slope at particular point can be calculated with the partial derivatives due to the two variables. Therefore, slope characteristics of gain and phase, respectively, can be written as

$$\frac{\partial A(r,\theta)}{\partial\theta} = \frac{\partial}{\partial\theta}\left(20\log\left(\sqrt{1+r^2-2\cdot r\cdot\cos(180°-\theta)}\right)\right) \tag{10}$$

$$\frac{\partial\phi(r,\theta)}{\partial\theta} = \frac{\partial}{\partial\theta}\left(\cos^{-1}\left(\frac{1-r\cdot\cos(180°-\theta)}{\sqrt{1+r^2-2\cdot r\cdot\cos(180°-\theta)}}\right)\right) \tag{11}$$

Using (10) and (11), the gain and phase slope characteristics are calculated and the results are shown as a function of overall signal phase shift. For the calculation, gain of the lower path nonlinear signal was fixed as 0.1.

From Fig. 3(b), it is clearly visible that four types of gain and phase characteristics are achieved at fixed input power: a) region I with negative gain slope and positive phase slope has a characteristic of gain compression and phase advance, b) region II with negative gain slope and negative phase slope has a characteristic of gain compression and phase lag, c) region III with positive gain slope and positive phase slope for gain expansion and phase advance, and d) region IV with positive gain slope and negative phase slope for gain expansion and phase lag, respectively.

From (7), the overall signal phase shift is expressed as

$$\theta = 180° - \rho + \tan^{-1}\frac{\beta_3}{\alpha_3} \tag{12}$$

where $\tan^{-1}(\beta_3/\alpha_3)$ is generated by diode biasing, diode configuration, input power, and passive components in lower path. The phase shift introduced in lower path is not varied until these conditions are changed. The overall signal phase shift (θ) to obtain the desired types of gain and phase characteristics is adjusted with phase shift (ρ) by termination positions (R) and capacitor values (CL) in upper path, at fixed phase shift in lower path. Therefore, the phase shift in upper path should be adjusted to obtain the desired types of gain and phase characteristics, provided that the phase shift in lower path is changed.

Ⅲ. Simulated and Measured Results

The proposed pre-distorter was simulated using Agilent Technologies' ADS version 2002 and fabricated on a Teflon substrate with 2.52 dielectric constant and 0.54 mm thickness. We used 3 dB hybrid coupler by Anaren and Schotty diode by Motorola. Fig. 4 shows the photograph of fabricated diode-based RF pre-distorter

Fig. 5 shows the simulated and measured gain and phase characteristics of the pre-distorter, as a function of input power. Fig 5(a) presents the simulated and measured gain compression and phase lag characteristics of the pre-distorter under termination arrangement of capacitor/resistor/resistor/capacitor(CRRC) at hybrid couplers in upper path. The capacitance of 11 pF was chosen. This gain and phase characteristics are appropriate for power amplifiers with gain expansion

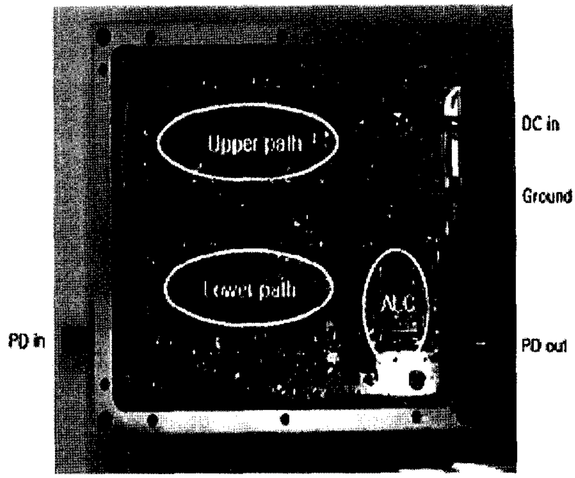


Fig. 4. Photograph of fabricated diode-based RF pre-distorter.

and phase advance characteristics at high output back-off, such as deep Class AB and Class B amplifiers. Fig. 5(b) shows the simulated and measured gain expan-

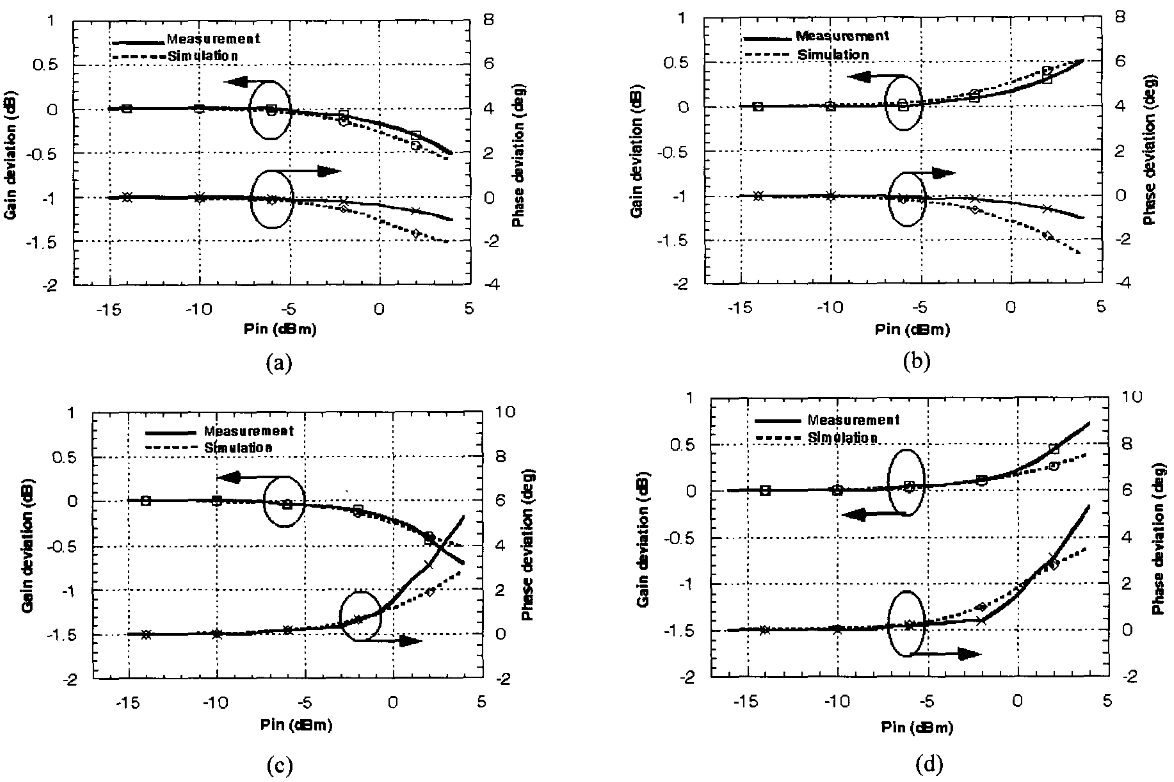


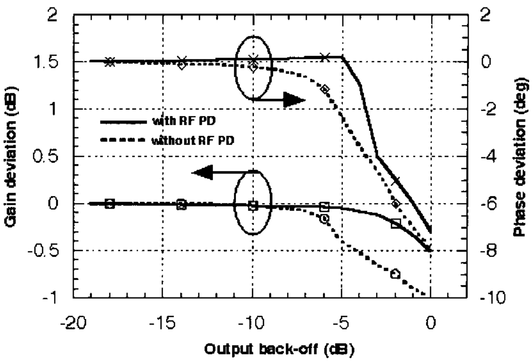
Fig. 5. Simulated and measured performances of the diode-based RF pre-distorter.
(a) Gain compression and phase lag characteristics(11 pF and CRRC), (b) Gain expansion and phase lag characteristics(11 pF and RCCR), (c) Gain compression and phase advance characteristics(2 pF and RCCR), (d) Gain expansion and phase advance characteristics(2 pF and CRRC).

sion and phase lag characteristics under test condition of 11 pF capacitance and RCCR arrangement. This gain and phase characteristics are suitable to power amplifiers with gain compression and phase expansion characteristics at low output back-off or near P1dB. Fig. 5(c) and Fig. 5(d) present the simulated and measured gain and phase characteristics under test conditions of 2 pF capacitance and RCCR arrangement, and 2 pF capacitance and CRRC arrangement, respectively. The characteristics in Fig. 5(c) are used to compensate for power amplifiers with gain expansion and phase lag characteristics at high output back-off, such as deep Class AB and Class B. The characteristics in Fig. 5(d) are adopted for power amplifiers with gain compression and phase lag characteristics at low output back-off or near P1 dB. Deviations between the simulated and measured results are generated because of circuit parasitics. However, it is clearly visible that the slopes of the measured gain and phase characteristics are similar to that of the simulated gain and phase characteristics.

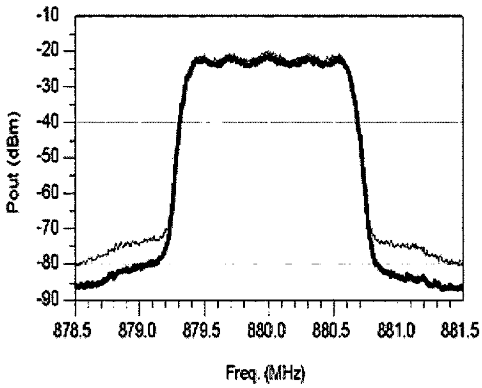
This pre-distorter was demonstrated experimentally with a 1-tone test signal, and an IS-95 CDMA(880 MHz) 1-channel signal with a peak to average ratio of 9.5 dB at CCDF of 0.01 %. Linearization is focused on the PAR of CDMA signal in order to obtain sufficient linearity. The pre-distorter was applied to two amplifiers with distinct gain and phase characteristics.

For experiments, the pre-distorter was applied to ERA-4SM amplifier with 14 dB gain and 17 dBm P1 dB by Mini Circuit. The amplifier has gain compression and phase lag characteristics, as shown in Fig. 6. After linearization, the improvement in AM/AM and AM/PM distortions cancellation of the power amplifier is easily observed. Fig. 6(b) shows measured results of ERA-4SM by single CDMA carrier. Before linearization, the output power of amplifier was 8 dBm at the output back-off of 9 dB and ACP was −52.5 dBc. After linearization, the output power was almost same but ACP was −58.5 dBc and then ACP improvement of 6 dB was obtained. Fig. 6(c) shows ACP improvement over a range of output back-off from −20 dB to −3 dB.

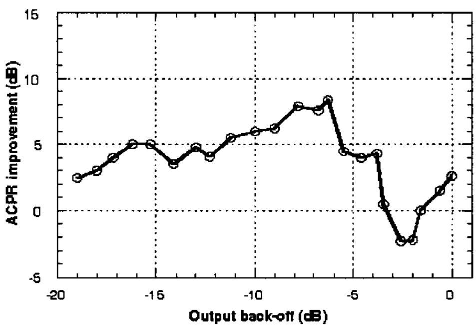
In Fig. 7, the pre-distorter was applied to AH1 amplifier with 13.5 dB gain and 21 dBm P1dB by Watkin-Johns. The amplifier has gain compression and phase advance characteristics. The AM/AM and AM/PM distortions of this amplifier shown in dashed lines were increased rapidly at the low output back-off after 10 dB. By using the pre-distorter, the amplifier's gain



(a) 1-tone test signal



(b) Output CDMA spectra with and without PD at output back-off of 9 dB



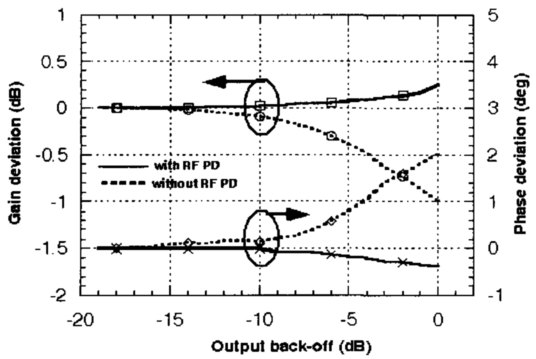
(c) ACPR improvement for IS-95A CDMA test signal

Fig. 6. Measured linearization results for amplifier with gain compression and phase lag characteristics (offset frequency of 885 kHz).

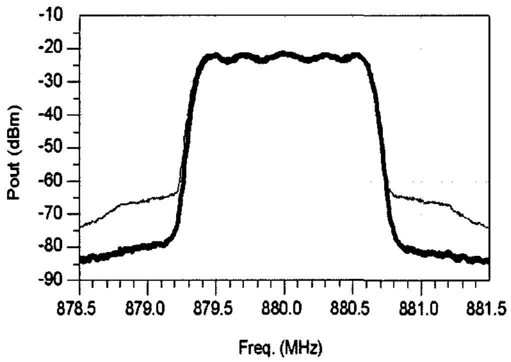
and phase characteristics became almost constant and then distortions of the amplifier could be improved.

Fig. 7(b) shows the output CDMA spectra with and without the diode-based RF pre-distorter at back-off of 14 dB. Fig. 7(c) demonstrates the linearization of an IS-95A CDMA 1-FA test signal. ACP improvement of 10.5 dB at an output back-off of 10 dB was observed.

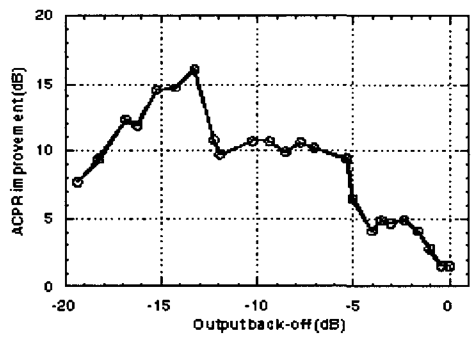
In Fig. 8 we measured IMD cancellation of ampli-



(a) 1-tone test signal



(b) Output CDMA spectra with and without PD at output back-off of 14 dB



(c) ACPR improvement for IS-95A CDMA test signal

Fig. 7. Measured linearization results for amplifier with gain compression phase advance characteristics (offset frequency of 885 kHz).

fiers with different AM/AM and AM/PM distortions for variation of two-tone spacing. The solid line represents the IMD characteristics of ERA-4SM amplifier at 6 dB output back-off before and after linearization, respectively. The dashed line represents the IMD characteristics of AH1 amplifier at 9 dB output back- off, before and after linearization, respectively. For maximum IMD cancellation, the optimum structure parameters of the pre-distorter were fixed for two-tone spacing

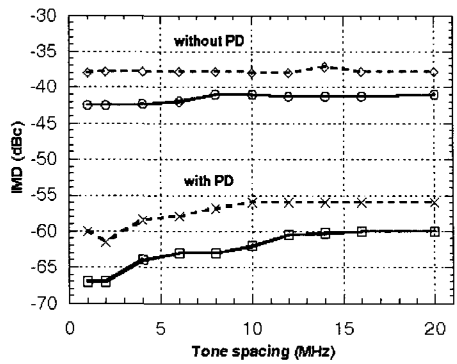


Fig. 8. Measured frequency dependence of linearizer. Solid-line: for gain compression and phase lag (OBO 6 dB), dashed-line: for gain compression and phase advance(OBO 9 dB).

of 2 MHz. After that, we measured IMD cancellation for variation of two-tone spacing from the 1 MHz to 20 MHz band. The IMD cancellation performance degrades with the increasing tow-tone spacing.

Ⅳ. Conclusion

A diode-based RF pre-distortion linearizer for various transfer characteristics of power amplifiers has been designed. The simulated and measured results show that this pre-distorter is suitable to remove the diode- and configuration-dependent characteristics in the conventional diode-based RF pre-distorters. Further work on the application of this pre-distorter to high power amplifiers should be investigated.

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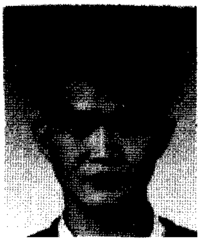
Dong-Hee Jang

received the B.S. and M.S. degrees in radio science and engineering from Kwangwoon University, Seoul, in 2000 and 2002, respectively. He is currently working toward the Ph.D. degree in radio science and engineering at Kwangwoon University. His current interests include power amplifier linearization and high efficiency power amplifier techniques.

Kyoung-Joon Cho

received the B.S. degree in information and communication engineering from An-Yang University in 1998 and received the M.S degree in radio science and engineering from Kwangwoon University in 2000, respectively. He is currently working toward the Ph.D. degree in radio science and engineering at Kwangwoon University, Seoul. His current research interests include efficiency enhancement and linearization technique for high power amplifiers.

Sang-Hee Kim



received the B.S. degree in electronic communication engineering from Kwandong University, and the M.S. degree in radio science and engineering from Kwangwoon University, Seoul, in 1999 and 2001, respectively. He is currently working toward the Ph.D. degree in radio science and engineering at Kwangwoon University. His current interests include efficiency enhancement and linearization techniques for high power amplifiers.

Jong-Heon Kim

received the B.S. degrees in electronic communication engineering from Kwangwoon Univ. in 1984, the M.S. degree in electronic engineering from Ruhr Univ. Bochum, Germany, in 1990, and the Ph. D. degree in electronic engineering from Dortmund Univ., Germany, in 1994. Since March 1995, he is a professor in the Dept. of Radio Science and Engineering at Kwangwoon Univ., Seoul, Korea. He is currently a research associate at Simon Fraser University, Canada, working in DSP techniques for power amplifiers for wireless industry. His current interests include digital linearization of power amplifier and transmitter, smart power amplifier and integrated RF/DSP design.

Shawn P. Stapleton

received the M.Sc. and Ph.D. degree in engineering, both from Carleton University, Ottawa, Canada, in 1984 and 1987, respectively. Since the fall of 1988, he has been a professor in electrical engineering at Simon Fraser University. His current interests include power amplifier linearization, high efficiency power amplifier techniques, mobile communications, integrated RF/DSP techniques, satellite communications, adaptive array antennas, and RF/Microwave circuits and systems.