Received: 26 November 2018
DOI: 10.1002/mop.31765

WILEY

RESEARCH ARTICLE

Efficiency enhancement of cross cancellation power amplifier using negative group delay circuit

Junhyung Joeng | **Girdhari Chaudhary** | **Yongchae Jeong**

Division of Electronics and Information Engineering, IT convergence Research Center, Chonbuk National University, Jeonju, Republic of Korea

Correspondence
Yongchae Jeong, Division of Electronics and Information Engineering, IT convergence Research Center, Chonbuk National University, Jeonju, Republic of Korea.
Email: ycjeong@jbnu.ac.kr

Funding information
Ministry of Education, Science and Technology, Grant/Award Number: 2016R1D1A1A09918818

Abstract
In this article, a cross cancellation power amplifier (CCPA) with negative group delay circuits (NGDCs) for an efficiency enhancement is proposed. The proposed CCPA with NGDCs consists of a balanced power amplifier (BPA), NGDCs, error amplifier, small signal amplifier, and magnitude/phase control circuits. The NGDC can remove delay elements of the conventional CCPA and improve output power and efficiency. The fabricated main BPA provides 44.37 dBm peak power, 71.3% drain efficiency, and 68% PAE at 2.14 GHz. The drain efficiency of the proposed CCPA with NGDCs is improved by 6.7% than the conventional CCPA. Moreover, adjacent channel leakage ratios of CCPA with NGDCs are improved by 12.2, 18.9, 17.7, and 14.2 dB at −10, −5, +5, and +10 MHz offset points with the WCDMA 4-FAs (20 MHz) signal, respectively.

KEYWORDS
cross cancellation, linear power amplifier, linearization, negative group delay circuit

1 | INTRODUCTION

In modern wireless communication systems, the high power amplifier (HPA) is one of the most important circuits, and in particular, for the base station. The HPA in the base station should satisfy several requirements, peak power capability, linearity, and efficiency at the allocated frequency bandwidth (BW). Class E, class F/F^{-1}, and class J HPAs have been introduced for high efficiency performance by controlling drain current and voltage waveforms of the transistor according to harmonic impedance matching around the peak power.[1–4] Theoretically, the harmonic impedances of these HPAs are matched, that is, open, short, or capacitive. However, in practice, only the second and third harmonic impedances are considered for actual circuit design, because the second and third harmonic components provide the most valuable effect on the efficiency performance with the limited circuit size.

Several linearization techniques have been developed to achieve the linearity requirement. Digital predistortion (DPD) techniques are most widely used in commercial communication transmitting systems.[5,6] The DPD technique uses inverse models of the gain and phase characteristics of the HPA. According to the inverse models of the HPA, the DPD circuits predistort input signals of the HPA using the baseband digital signal processing. When the inversely distorted signal is applied to the modeled HPA, the linear output signal can be obtained.

Feedforward power amplifier (FFPA) and cross cancellation power amplifier (CCPA) use analog linearization techniques and are suitable on base station systems. The FFPA has broad linearization BW and best linearization performance due to self-distortion signal cancellation.[7] Billsberry and Beach8 introduced the fundamental concept of CCPA, and many research results have been presented.[9,10] Choi et al.[10] described the efficiency merit of the CCPA being relatively higher than the FFPA. However, the insertion loss of delay elements for the group delay (GD) matching in the conventional CCPA degrades efficiency and output power. Nevertheless, the delay elements in CCPA are essential for broadband operation.

This article presents the CCPA with negative group delay circuits (NGDCs) for efficiency enhancement. The NGDCs are utilized for the GD matching on each loop and can remove the delay elements at the input and output paths of the HPA in the balanced power amplifier (BPA). As a result, it can enhance the overall power and efficiency of the proposed CCPA.

 © 2019 Wiley Periodicals, Inc.

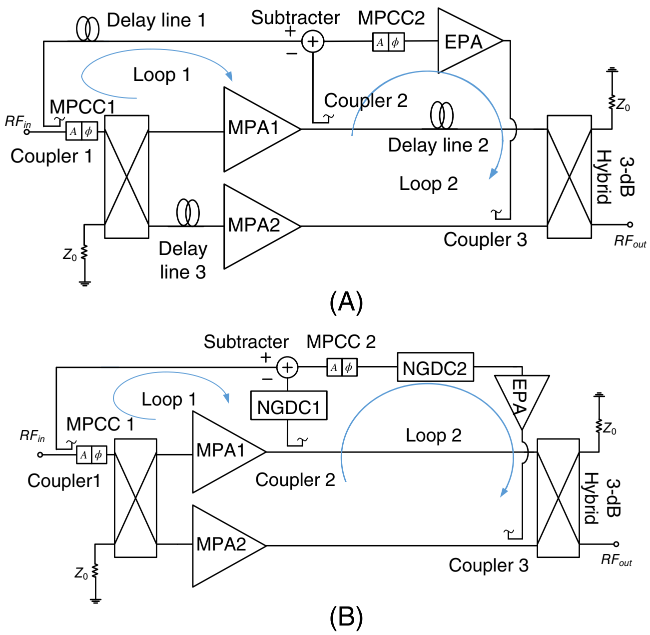

FIGURE 1 Simplified block diagrams of A, conventional cross cancellation power amplifier and B, proposed cross cancellation power amplifier with negative group delay circuits [Color figure can be viewed at wileyonlinelibrary.com]

2 | DESIGN EQUATION

Figure 1A shows the simplified block diagram of the conventional CCPA. The CCPA based on a BPA consists of two main power amplifiers (MPAs), which have the same electrical characteristics, bias condition, and input/output matching networks with the same transistors. The BPA structure is generally used for higher output power application by power combination of two MPAs. Input signal cancellation at a subtracter extracts the distortion signals during nonlinear amplification of MPA1 in loop 1. The error power amplifier (EPA) amplifies distortion signals and injects them at the output of MPA2 through coupler 3. To remove all distortion signals of MPA1 and MPA2, the injected distortion signals are controlled two times magnitude and out-of-phase with the distortion signals of MPA2 using magnitude and phase control circuit 2 (MPCC 2). Finally, the linear amplified RF signals appear at the RF output port. Delay lines (DLs) must be used for broadband signal cancellation by the GD matching.

In the conventional CCPA, the insertion losses of DLs 2 and 3 reduce the output power of MPAs; in particular, DL 2 affects more than DL 3, because DL 2 reduces the amplified output signal power of MPA1. Even though the insertion losses of DLs 2 and 3 are small, they cannot be neglected, because only 0.5 dB insertion loss reduces MPA output power by as much as 10%.[10] As a result, the conventional CCPA has drawbacks such as reduced efficiency and output power due to the insertion losses of the DLs at the MPA. In addition, the different locations of DLs 2 and 3 prohibit perfectly balanced amplification of MPA1 and MPA2.

To overcome these drawbacks, the CCPA with NGDCs is proposed. Figure 1B shows the simplified block diagram of the proposed CCPA. The proposed structure consists of BPA, two NGDCs, two MPCCs, three couplers, subtracter, and EPA. Compared with the conventional CCPA, the proposed CCPA involves two NGDCs, while removing all DLs. In loop 1, the NGDC 1 utilizes to match the GD between RFin port-coupler 1-subtracter path and RFin port-coupler 2-subtracter path for input signals cancellation. In loop 2, NGDC 1 and NGDC 2 compensate the GD of distortion signals in the coupler 2-subtracter-MPCC 2-EPA-coupler 3 path. Finally, coupler 3 injects the amplified distortion signals by the EPA at the output of MPA 2. The output power difference between the conventional and the proposed CCPAs is expressed as

$$P_{\text{conventional\_CCPA}} = P_{\text{CCPA\_NGDC}} - \text{IL}_{\text{delay\_line2}}, \tag{1}$$

where $P_{\text{conventional\_CCPA}}$, $P_{\text{CCPA\_NGDC}}$, and $\text{IL}_{\text{delay\_line2}}$ are the output power of the conventional CCPA, the output power of the CCPA with NGDC, and the insertion loss of DL 2, respectively.

3 | SIMULATION AND MEASUREMENT RESULTS

To validate the mathematical analysis, the CCPA with NGDCs was designed for a wideband code division multiple access (WCDMA) downlink band operating at 2.14 GHz (f_0). Figure 2 shows the load-pull simulation results of the Cree Inc. GaN HEMT CGH40010F. Selected bias conditions were V_{DD} = 28 V, V_{GS} = −2.75 V, and I_{DQ} = 200 mA. Optimum efficiency load impedance and second harmonic impedance are 15.5 + j16.7 Ω and 2 + j250 Ω with 75.8% power added efficiency (PAE) and 40.3 dBm output

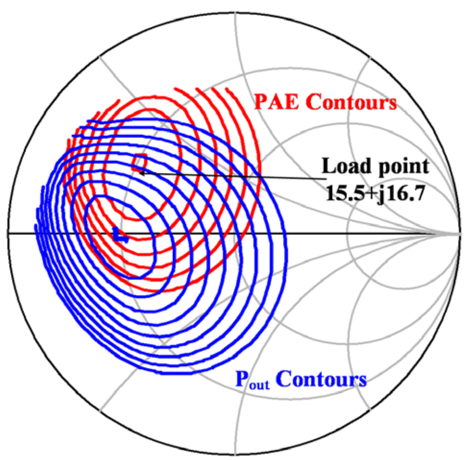

FIGURE 2 Load pull and simulation results of a single CGH40010F with bias conditions of V_{DD} = 28 V, V_{GS} = −2.75 V, and I_{DQ} = 200 mA [Color figure can be viewed at wileyonlinelibrary.com]

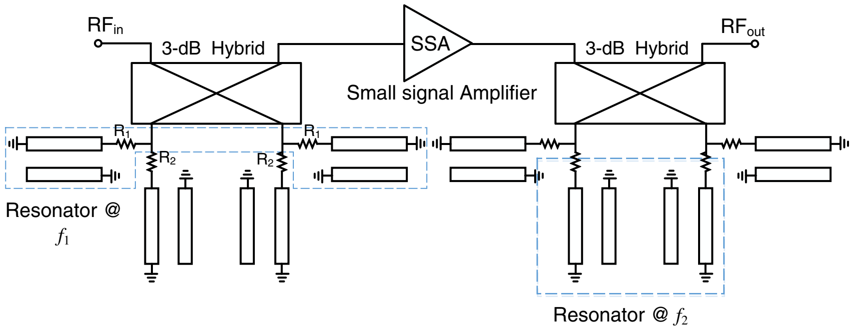

FIGURE 3 Block diagram of two-stage negative group delay [Color figure can be viewed at wileyonlinelibrary.com]

power at the saturation point. The input fundamental and second harmonic matching impedances are 3.2 + j0.37 Ω and 2 + j100 Ω by source-pull simulation.

Impedance matched MPAs are combined with 3 dB quadrature hybrid couplers and 20 dB directional couplers for the CCPA operation. As the measurements, the peak output power, gain, drain efficiency (DE), and PAE of main BPA are 44.37 dBm, 12.89 dB, 71.3%, and 68% at 2.14 GHz, respectively. Moreover, the measured output power, gain, DE, and PAE variations over 20 MHz BW are 44.2 ± 0.4 dBm, 12.5 ± 0.3 dB, 72.1 ± 2%, and 68.1 ± 2%, respectively.

To obtain the precise GD matching on each loop of the CCPA, the NGDCs with low signal attenuation are employed.[11] Figure 3 shows the block diagram of a two-stage NGDC with small signal amplifier (SSA). The single stage NGDC consists of a 3 dB quadrature hybrid coupler and two pairs of coupled line resonators. The shorted coupled line resonator (CLR) with serial resistance generates the negative group delay (NGD) characteristic. To cancel distortion signals of MPAs, NGDCs should cover three times of the operating signal BW at least. Therefore, two pairs of CLRs were designed at the slightly offset frequencies f_1 ($<f_0$) and f_2 ($>f_0$) from f_0 to enhance the NGD BW. The SSA was used to compensate the insertion loss of the NGDC. NGDC 1 and NGDC 2 were designed as a two-stage NGDC with SSA and a single-stage NGDC without SSA, respectively. As the measurements, NGDC 1 and NGDC 2 showed −7.35 ± 1.5 and −3.3 ± 0.9 ns of NGD, 21.2 ± 0.32 and 14.3 ± 0.2 dB of insertion loss, and more than 24 and 17 dB of return losses in the 30 MHz BW. The NGD values were chosen by the measured GD values as described in previous, and estimated the tolerances of NGDs and insertion losses for 50 and 30 dB signal cancellations in the loops 1 and 2.

To amplify the extracted distortion signals, the EPA was designed. As the measurement results, the peak output power, gain, DE, and PAE are 31.27 dBm, 26 dB, 23.43%, and 23.3% at 2.14 GHz, respectively. Additionally, the measured output power, gain, DE, and PAE variations are 31.3 ± 0.5 dBm, 25.8 ± 0.5 dB, 22 ± 2%, and 21.8 ± 2% in 50 MHz BW, respectively.

The signal cancellation characteristics of loop 1 measured from RF_{in} to subtracter output. The signal cancellations are 43.4 ± 17.6 and 48.8 ± 12.3 dB at 30 and 10 MHz BW, respectively. In particular, the 10 and 20 MHz BW cancellation performance is enough to cancel out the input signals. Moreover, the measured GD of the error signal path in loop 2 from NGDC 1 input to coupler 3 output is −0.26 ± 1.54 and −1.6 ± 3.74 ns in 30 and 60 MHz BW.

Figure 4 compares the measured power spectrum density result of the proposed CCPA using WCDMA 2-FAs (10 MHz) downlink signal. Due to the 9 dB peak-to-average

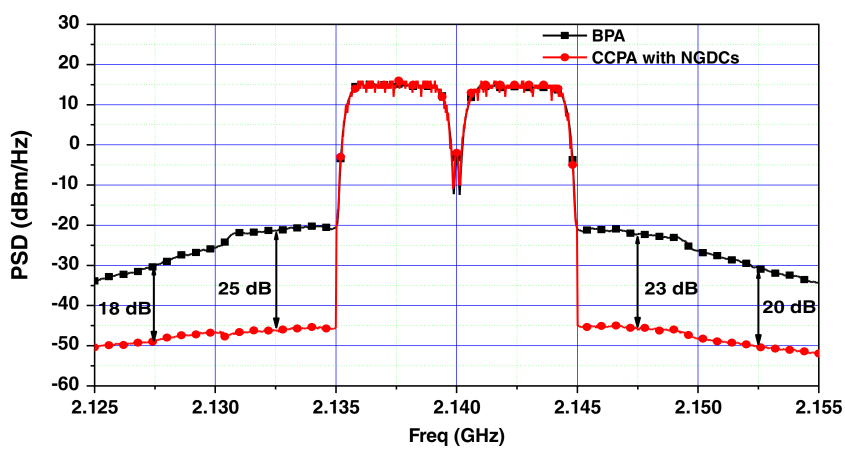

FIGURE 4 Compared power spectrum densities of BPA and CCPA with NGDCs using WCDMA 2-FAs (10 MHz) signal [Color figure can be viewed at wileyonlinelibrary.com]

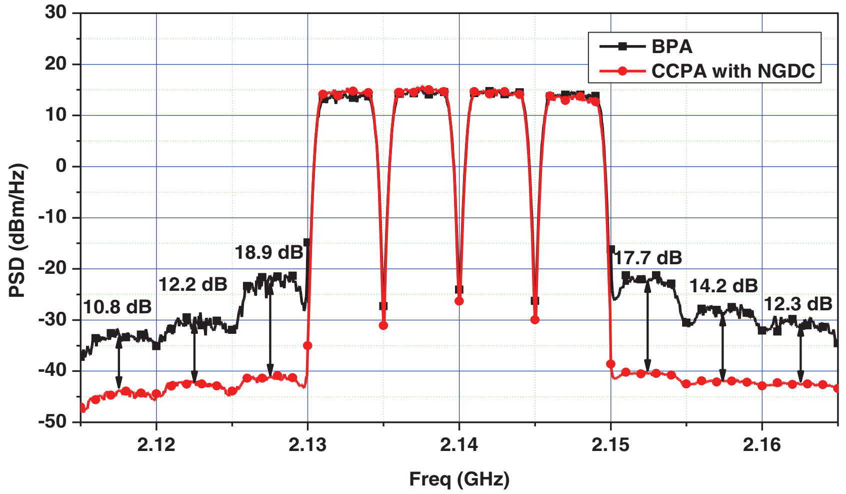

FIGURE 5 Compared power spectrum densities of BPA and CCPA with NGDCs using WCDMA 4-FAs (20 MHz) signal [Color figure can be viewed at wileyonlinelibrary.com]

power ratio of the used WCDMA signal, the BPA and CCPA with NGDCs were operated at 35.2 dBm average output power. Compared with the BPA, the adjacent channel leakage ratios (ACLRs) of the proposed CCPA are improved by 18, 25, 23, and 20 dB at −10, −5, +5, and +10 MHz offset points, respectively.

The overall DEs of the BPA and proposed CCPA with NGDCs were 21.7% and 19.5% with 35.2 dBm average output power. The proposed CCPA has slightly lower efficiency performance than the BPA, because of the additional DC power consumptions of EPA, MPCCs, and SSA. However, the CCPA with NGDCs has better ACLR performance than the BPA. If the BPA is backed off to obtain the same ACLR performance as like the proposed CCPA, the efficiency of the BPA is much lower than the proposed CCPA. From Figure 1A, it can predict the efficiency of the conventional CCPA not employing NGDCs by the power reduction of Equation 1. To compensate the GD mismatching on loop 2, the GD of DL 2 is around 10 ns. When 0.141″ coaxial cable is used to match 10 ns GD, 1.8 dB insertion loss is added. As a result, it predicts the DE of the conventional CCPA to be 12.8% with 33.4 dBm. Even though the conventional CCPA can show similar linearization performance, its efficiency and output power are much inferior to the proposed CCPA.

Figure 5 shows the power spectrum density result of the proposed CCPA using WCDMA 4-FAs (20 MHz) downlink signal. Compared with the BPA, the ACLRs of the proposed CCPA with 34.4 dBm average output power are improved by 12.2, 18.9, 17.7, and 14.2 dB at −10, −5, +5, and +10 MHz offset points, respectively.

4 | CONCLUSION

In this article, a CCPA with NGDCs for an efficiency enhancement is proposed. The proposed CCPA is analyzed, fabricated, and measured at 2.14 GHz with wideband code division multiple access downlink 2-FAs (10 MHz) and 4-FAs (20 MHz) signals. To verify the efficiency enhancement, two-stage and single-stage NGDCs are realized to remove delay elements of the conventional CCPA. The measurement results show that the proposed CCPA with NGDCs has similar linearization and higher efficiency performances than the conventional CCPA. If the broadband NGDC can be designed, the proposed CCPA with NGDCs can be applicable to the wireless communication systems.

ACKNOWLEDGMENT

This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2016R1D1A1A09918818).

ORCID

Junhyung Joeng https://orcid.org/0000-0003-2383-1635

REFERENCES

[1] H. Choi, S. Shim, Y. Jeong, J. Lim, and C. D. Kim, “A compact DGS load-network for highly efficient class-E power amplifier,” Proceeding of European Microwave Conference, pp. 492–495, 2009.

[2] Jeong Y, Chaudhary G, Lim J. A dual band high efficiency class-F GaN power amplifier using a novel harmonic-rejection load network. *IEICE Trans Electron*. 2012;E95-C(11):1783-1789.

[3] Wright P, Lees J, Bendikt J, Tasker PJ, Cripps SC. A methodology for realizing high efficiency class-J in a linear and broadband PA. *IEEE Trans Microwave Theory Techn*. 2009;57(12):3196-3204.

[4] Moon J, Kim J, Kim B. Investigation of a class-J power amplifier with a nonlinear Cout for optimized operation. *IEEE Trans Microwave Theory Techn*. 2010;58(11):2800-2811.

[5] Chen K, Morris KA, beach MA. Combining envelope elimination and restoration and predistortion techniques for use in IEEE

802.11g systems. *IET Microwave Antennas Propag*. 2007;1(4):832-838.

[6] Zhu A, Draxler PJ, Hsia C, Brazil TJ, Kimball DF, Asbeck P. Digital predistortion for envelope-tracking power amplifiers using decomposed piecewise Volterra series. *IEEE Trans Microwave Theory Techn*. 2008;56(10):2237-2247.

[7] Y. Jeong, D. Ahn, C. Kim, and I. Chang, Feedforward amplifier using equal group-delay signal canceller. IEEE International Microwave Symposium Digest, pp. 1530–1533, 2006

[8] M. Billsberry and M. Beach, "Balanced distortion reduction circuit" United States Patent, U.S. Patent 6 734 726 B2, 2004.

[9] H. Choi, Y. Jeong, J. S. Kenney, and C. Kim, "Cross post-distortion balanced power amplifier," IEEE International Microwave Symposium Digest, pp. 1115-1118, Jun. 2007.

[10] Choi H, Jeong Y, Kenney JS, Kim C. Cross cancellation technique employing an error amplifier. *IEEE Microwave Wireless Compon Lett*. 2008;18(7):488-490.

[11] Chaudhary G, Jeong Y. Low signal attenuation negative group delay network topologies using coupled lines. *IEEE Trans Microwave Theory Techn*. 2014;62(10):2316-2324.

How to cite this article: Joeng J, Chaudhary G, Jeong Y. Efficiency enhancement of cross cancellation power amplifier using negative group delay circuit. *Microw Opt Technol Lett*. 2019;61:1673–1677. https://doi.org/10.1002/mop.31765