Wideband Doherty Power Amplifier Design for Base Station Application

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By

Xiaobo Deng
Student Number: 1530445

Supervisors:
Associate Prof. Dr. ing. Leo de Vreede, TU Delft
John Gajadharsing, NXP Semiconductors
Dr. Edmund Neo, NXP Semiconductors

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Abstract

Doherty Power Amplifier (DPA) is employed to improve the efficiency when operated with complex modulated signals. Due to its simplicity and high efficiency performance, it has become the preferred choice of industry. However, practical implementations of DPA only provide limited RF bandwidth, especially at high power level. The traditional narrow band device matching network, required phase shift for proper load modulation and impedance inverter seriously limit the bandwidth of DPA.

In this work, the frequency behavior of the ideal 2-way symmetrical DPA is analyzed in detail, followed by the introduction of two new impedance inverters used to improve the bandwidth of DPA. In order to fully exploit the wideband potential of the new impedance inverters, the phase relation between the main and peak amplifier should be adjusted according to the power level at every frequency, which can be stored in a lookup table. Based on a previous wideband 20W DPA with mixed-signal input drive, in which the device output capacitance is incorporated into the impedance inverter, a modified DPA using the idea of compensated impedance inverter is designed and simulated. The prototype DPA design is implemented with NXP LDMOS bare die device. Simulation results have shown more than 50% 6dB back off efficiency from 1.5GHz to 2.2GHz, compared with the original case whose 50% efficiency bandwidth is from 1.9GHz to 2.3GHz.

Since the prototype DPA is implemented at a low power level with bare die devices and mixed-signal input drive, it cannot be used for the practical base station applications. Traditional high power discrete DPA design method is introduced and the frequency behavior is analyzed. It is found that for the high power DPA, the matching network and the offset line are more important than the impedance inverter for the narrow bandwidth of DPA. A new DPA structure was proposed for wideband operation. Simulation results show smaller gain and power added efficiency spread in a 200MHz frequency band from 2.04GHz to 2.24GHz than the traditional DPA.

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Bibliography

[1] K. L. Du and M. N. S. Swamy, *Wireless Communications Systems*, Cambridge University Press, 2009.

[2] W. Webb, *The Complete Wireless Communications Professional: A Guide for Engineering and Managers*, Norwood, MA: Artech House, 1999.

[3] W. C. E. Neo, "Highly Efficient and Highly Linear RF Power Amplifiers," Ph.D. dissertation, Delft University of Technology, Delft, The Netherlands, 2010.

[4] S. C. Cripps, *RF Power Amplifiers for Wireless Communications*, Norwood, MA: Artech House, 2nd edition, 2006.

[5] D. M. Pozar, *Microwave Engineering*, John Wiley & Sons, Inc, 3rd edition, 2004.

[6] F. H. Raab, P. Asbeck, S. Cripps, P. B. Kenington, Z. B. Popovic, N. Pothecary, J. F. Sevic and N. O. Sokal, "Power Amplifiers and Transmitters for RF and Microwave," *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 3, pp. 814–826, Mar. 2002.

[7] M. J. Pelk, W. C. E. Neo, J. R. Gajadharsing, R. S. Pegnelly, and L. C. N. de Vreede, "A High-Efficiency 100-W GaN Three-Way Doherty Amplifiers for Base-Station Applications," *IEEE Trans. Microw. Theory Tech.*, vol. 56, no. 7, pp. 1582–1591, July. 2008.

[8] N. Li, "Wideband Doherty Power Amplifier Design," M.S. thesis, Department of Microelectronics, Delft University of Technology, Delft, The Netherlands, 2009.

[9] J. Qureshi, N. Li, W. C. E. Neo, F. van Rijs, I. Blednov and L. C. N. de Vreede, "A Wideband 20W LDMOS Doherty Power Amplifier," *IEEE MTT-S Int. Microw. Symp. Dig.*, May. 2010.

[10] M. Sarkeshi, O. B. Leong and A. van Roermund, "A Novel Doherty Amplifier for Enhanced Load Modulation and Higher Bandwidth," *IEEE MTT-S Int. Microw. Symp. Dig.*, pp. 1893–1896, Jun. 2008.

[11] W. C. E. Neo, J. Qureshi, M. J. Pelk, J. R. Gajadharsing, and L. C. N. de Vreede, "A Mixed-Signal Approach Towards Linear and Efficiency N-way Doherty Amplifiers," *IEEE Trans. Microw. Theory Tech.*, vol. 55, no. 5, pp. 866–879, May. 2007.

[12] W. H. Doherty, "A New High Efficiency Power Amplifier for Modulated Waves," *Proc. IRE*, vol. 24, no. 9, pp. 1163–1182, Nov. 1936.

[13] J. Zhao, "High Efficiency Three-way Doherty Amplifier with a Passive Input Splitter," M.S. thesis, Department of Microelectronics, Delft University of Technology, Delft, The Netherlands, 2008.

[14] H. Park, J. Van, S. Jung, M. Kim, H. Cho, S. Kwon, J. Jeong, K. Lim, C. Park and Y. Yang , "A New Compact Load Network for Doherty Amplifiers Using an Imperfect Quarter-Wave Line," *IEEE Trans. Microw. Theory Tech.*, vol. 55, no. 11, pp. 2313–2319, Nov. 2007.

[15] N. Srirattana, A. Raghavan, D. Heo, P. Allen, and J. Laskr, "Analysis and Design of a High-Efficiency Multistage Doherty Power Amplifier for Wireless Communications," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 3, pp. 852–860, Mar. 2005.

[16] M. Iwamoto, A. Williams, P. Chen, A. G. Metzger, L. E. Larson, and P. M. Asbeck, "An Extended Doherty Amplifier with High Efficiency over a Wide Power Range," *IEEE Trans. Microw. Theory Tech.*, vol. 49, no. 12, pp. 2472–2479, Mar. 2001.

[17] J. R. Gajadharsing, "Theory and Design of Doherty Amplifiers," Tech. Rep., MST RF Power BST, NXP Semiconductors, May. 2009.

[18] Y. Yang, J. Cha, B. Shin and B. Kim , "A Fully Matched N-Way Doherty Amplifier With Optimized Linearity," *IEEE Trans. Microw. Theory Tech.*, vol. 51, no. 3, pp. 986–993, Mar. 2003.

[19] J. Kim, J. Cha, I. Kim and B. Kim , "Optimum Operation of Asymmetrical-Cells-Based Linear Doherty Power Amplifiers–Uneven Power Drive and Power Matching," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 5, pp. 1802–1809, May. 2005.

[20] Y. Yang, J. Yi, Y. Y. Woo, and B. Kim, "Optimum Design for Linearity and Efficiency of Microwave Doherty Amplifier using A New Load Matching Technique," *Microwave Journal.*, vol. 44, pp. 20–36, Dec. 2001.

[21] K. S. Ang, C. H. Lee, and Y. C. Leong, "Analysis and Design of Coupled Line Impedance Transformers," *IEEE MTT-S Int. Microw. Symp. Dig.*, vol. 3, pp. 1951–1954, 2004.

[22] T. Jensen, V. Zhurbenko, V. Krozer and P. Meincke, "Coupled Transmission Lines as Impedance Transformer," *IEEE Trans. Microw. Theory Tech.*, vol. 55, no. 12, pp. 2957–2965, Dec. 2007.

[23] V. Zhurbenko, V. Krozer and R. Meincke, "Broadband Impedance Transformer Based on Asymmetric Coupled Transmission Lines in Nonhomogeneous Medium," *IEEE MTT-S Int. Microw. Symp. Dig.*, pp. 1893–1896, 2007.

[24] I. Blednov, "Integrated Doherty Type Amplifier Arrangement with High Power Efficiency," Patent WO 2008/062371 A2.

[25] I. Blednov and J. van der Zanden, "High Power LDMOS Integrated Doherty Amplifier for W-CDMA," in *Radio Frequency Integrated Circuits (RFIC) Symposium, 2006 IEEE*, 11-13 2006, p. 4 pp.

[26] C. Tongchoi, M. Chongcheawchamnan, and A. Worapishet, "Lumped Element Based Doherty Power Amplifier Topology in CMOS Process," in *Circuits and Systems, 2003. ISCAS '03. Proceedings of the 2003 International Symposium on*, 25-28 2003, vol. 1, pp. I–445 – I–448 vol.1.

[27] F. van Rijs and S. J. C. H. Theeuwen, "Efficiency Improvement of LDMOS Transistors for Base Stations: Towards the Theoretical Limit," *IEDM*, 2006.

[28] R. van der Sanden, "Report RF-test Circuit BLF7G22LS-130," Tech. Rep., MST RF Power BST, NXP Semiconductors, July. 2009.

[29] J. R. Gajadharsing, G. Kemna, J. van Velzen, "BLF7G22LS-130 Loadpull Data Summary," Tech. Rep., MST RF Power BST, NXP Semiconductors, June. 2009.

[30] C. Burns, A. Chang, and D. Runton, "A 900 MHz, 500 W Doherty Power Amplifier Using Optimized Output Matched Si LDMOS Power Transistors," *IEEE MTT-S Int. Microw. Symp. Dig.*, pp. 1577–1580, 2007.

[31] S. J. C. H. Theeuwen and H. Mollee, "LDMOS Transistors in Power Microwave Applications," *Microwave Journal.*, Dec. 2008.

[32] J. Bi, "Chireix's/LINC Power Amplifier for Base Station Application Using GaN Devices with Load Compensation," M.S. thesis, Department of Microelectronics, Delft University of Technology, Delft, The Netherlands, 2008.

[33] A. Z. Marcos, "Efficient Enhancement of Linear GaN RF Power Amplifiers Using the Doherty Technique," Ph.D. dissertation, Kassel University, Kassel, Germany, 2008.

[34] Nitronex Corporation, "AN-013: Broadband Performance of GaN HEMTs," May. 2009, http://www.nitronex.com/pdfs/AN-013%20Braodband.pdf.

[35] M. Weyers, "Substrates for GaN Technology," Tech. Rep., Ferdinand-Braun-Institut, Oct. 2005.

[36] Nitronex Corporation, "AN-011: Substrates for GaN RF Devices," Jun. 2008, http://www.nitronex.com/pdfs/AN-011%20GaN%20Substrates.pdf.

[37] R. Heeres, "Integrated Doherty," Tech. Rep., MST RF Power BST, NXP Semiconductors, Aug. 2007.