

Design of Dualband Class-F PAs for Cellular and WLAN Applications

Chang-Min Lee¹ · Young-Cheol Park¹ · Hoijin Yoon²

Abstract

In this paper, highly efficient class-F power amplifiers(PAs) with harmonic-controlling transmission lines(TLs) were built for cellular and WLAN applications at 840 MHz and 2.4 GHz each. Also, based on these single-band PAs, a dualband class-F PA was designed after a careful investigation into the harmonics of the two frequencies. The harmonic-controlling TL was designed for the class-F operation at dualband by switching the length of the shunt $\lambda/4$ TL part, while the series $\lambda/4$ TL is optimized for both frequencies. To verify the performance, two class-F PAs optimized at each frequency and a dualband class-F PA at the corresponding frequencies were built with the second- and the third-harmonic control circuits at each frequencies. As a result, the PA#1 at 840 MHz has a peak drain efficiency of 81.2 % with an output power of 24.4 dBm, while the PA#2 at 2.35 GHz shows a drain efficiency of 94.5 % with an output of 22.8 dBm. Finally, the dualband class-F PA#3 showed 60.5 % and 50.9 % drain efficiencies at 840 MHz and 2.4 GHz, with powers of 23.8 dBm and 19.62 dBm, respectively.

Key words : Class-F, Efficiency, Power Amplifiers.

I. Introduction

The expansion of mobile communication service systems as well as the recent interest in low energy consumption, high-efficiency RF devices are getting attention in battery-powered handsets and in base stations. Of all RF devices, power amplifiers(PAs) consume the most power in the RF chain, and thus massive efforts have been focused on increasing the efficiency of PAs while maintaining linearity^[1].

So far, various operational modes have been proposed to improve the efficiency of PAs and the class-F, and the inverse class-F technique has become one of the major design methods in sub-microwave frequencies because of its simplicity and highest class performance^{[2],[3]}.

In general, a class-F PA is designed with transmission lines(TLs) to control the harmonics, which are short at even-order harmonics and open at odd-order harmonics. As such, ideal class-F PAs achieve 100 % efficiency by controlling all harmonics so that the voltage and the current waveforms have no overlapping period in the time domain and by keeping all harmonic powers at zero. However, due to the physical length of the $\lambda/4$ TL, matching with a TL is difficult to implement for multiple bands. Moreover, matching with lumped elements cannot achieve good performance beyond gigahertz frequencies. As such, only a few studies have been reported to work at multiband frequencies, which mostly depend on special TL materials such as composite right-/left-handed

transmission line metamaterial^{[4],[5]}.

Thus, in this paper, as an extension of the previously published class-F PA at 840 MHz^[6], a dualband class-F PA with harmonic-controlling dualband TLs is suggested for the output frequencies of 840 MHz and 2.4 GHz. Following the class-F PA theories in Section II, single-band PAs optimized at 840 MHz and 2.4 GHz were designed as a step-by-step approach to the dualband design. Based on those single-band PAs, a dualband PA at the corresponding frequencies was introduced, in Section III. Then, Section IV compares measurement results.

II. Class-F Power Amplifier

The definition of class F is that even-harmonic impedances are short and odd-harmonic impedances are open. As a result, the drain voltage is shaped toward a square wave and the drain current is shaped toward a half-sine wave as shown in Fig. 1^{[7]~[11]}. With these given conditions, power loss at the drain is zero from the minimized overlap between the current and the voltage waveforms, and the harmonic power loss is also zero for zero-harmonic components in either voltage or current. As such, the DC power is perfectly converted into the output power, reaching 100 % drain efficiency as in (1)^[7].

$$\eta = \frac{P_{out}}{P_{DC}} = \frac{P_{DC} - P_{drain} - P_{har.}}{P_{DC}} \times 100(\%) \quad (1)$$

where P_{out} represents the transferred power to the load,

Manuscript received September 24, 2009 ; revised February 17, 2010. (ID No. 20090924-043J)

¹Dept. of Electronics and Information Engineering, Hankuk University of Foreign Studies, Yongin, Korea.

²Dept. of Computer Engineering, Hyupsung University, Hwasung, Korea.

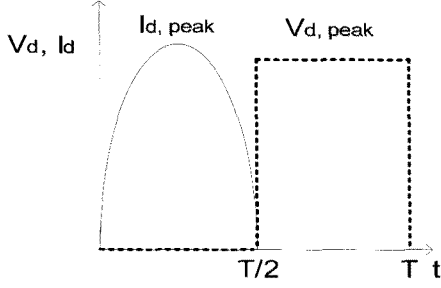


Fig. 1. Ideal output voltage and current waveforms of class-F PA.

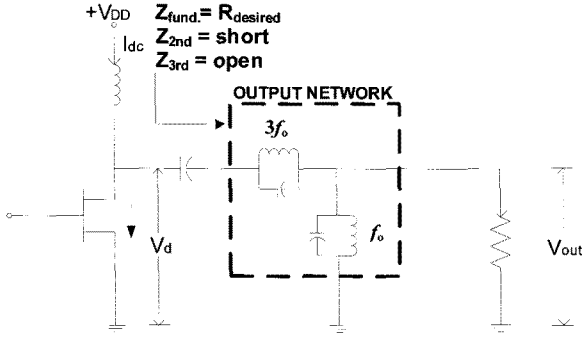


Fig. 2. Simplified circuit of a class-F PA.

P_{har} is the sum of harmonic powers, and P_{drain} is the loss at the drain.

However, since it is generally impractical to perfectly control all the harmonics, only the second and third harmonics are managed in most cases. Thus, as in Table 1, which shows theoretical efficiencies with limited harmonics, many studies with only the second and the third harmonic resonators have reported efficiencies of around 75 %^{[7]–[9]}. Thus, the general class-F PA is shown in Fig. 2, where the short-circuit and open-circuit terminations are expected only at the second harmonic($2f_0$) and at the third harmonic($3f_0$), respectively.

III. Design and Simulation

3-1 Single-band Class-F PA#1 at 840 MHz

For application to the 4 G transmitter in cellular frequen-

Table 1. Estimated efficiency of class-F PA with combinations of harmonics^[7].

	1	3	5	∞
1	50 %	56.3 %	58.6 %	63.7 %
2	66.7 %	75 %	78.1 %	84.9 %
4	71.1 %	80 %	83.3 %	90.5 %
∞	78.5 %	88.4 %	92 %	100 %

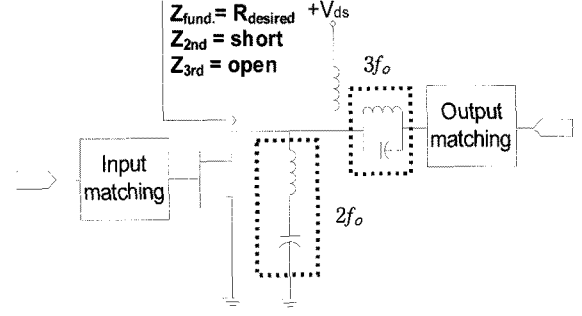


Fig. 3. Schematic diagram of the class-F PA#1 with LC components.

cy, a class-F PA at 840 MHz(PA#1) was designed with a commercial E-pHEMT transistor model, the schematic of which is shown in Fig. 3.

In this design, in order to minimize the circuit area, the $\lambda/4$ transmission line is replaced with carefully designed LC resonators, the performance of which can still be reasonable as mentioned in Section I. Also, although only the LC resonator is used in the circuit, the simulation confirmed that the designed harmonic circuit could locate third-harmonic impedance near the open and second-harmonic impedance near the short.

$$Z_{fund} = R_{desired}$$

$$Z_{2nd} = 0$$

$$Z_{3rd} = \infty \quad (2)$$

Besides, fundamental output impedance was designed for maximum fundamental power.

As in conventional class-F cases^{[12],[13]}, the designed circuit has the class-B bias point at $V_{gs}=0.49$ V and $V_{ds}=3$ V.

From the simulation, the drain current showed ideal waveforms of Fig. 1, while the voltage waveform has higher harmonic components, which are believed to be due to

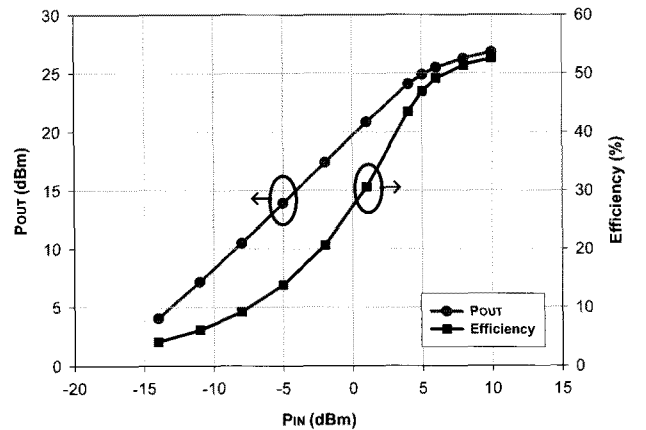


Fig. 4. Simulated drain efficiency and P_{OUT} of PA#1.

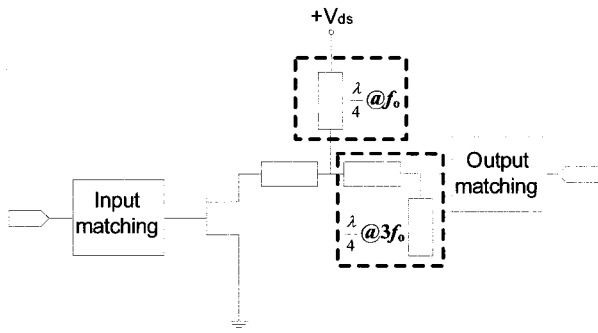


Fig. 5. Schematic diagram of the class-F PA#2.

the limited Q of the resonators of the discrete LC components. The simulated maximum efficiency of 52.5 % and the output power of 26.8 dBm are shown in Fig. 4.

In any cases, compared to the circuit with TL at this frequency, this design dramatically reduced the footprint of the circuit while maintaining efficiency and power.

3-2 Single-band Class-F PA#2 at 2.4 GHz

In order to verify the performance of the transistor at the mWiMAX frequency, a single-band PA at 2.4 GHz (PA#2) with a transistor identical to that of PA#1 was designed, the schematic of which is shown in Fig. 5. In contrast, because of shorter wavelength with higher frequency, the LC components used in PA#1 were replaced with the $\lambda/4$ transmission lines at 2.4 GHz to control the output harmonics better. As well, with identical class-B biasing of PA#1, the simulated drain efficiency was 69.4% and output power was 26.3 dBm as shown in Fig. 6, showing even better performance at this frequency.

3-3 Dualband Class-F PA#3 at 840 MHz and 2.4 GHz

For successful dualband operation at 840 MHz and 2.4 GHz, the design of a dualband harmonic control circuit

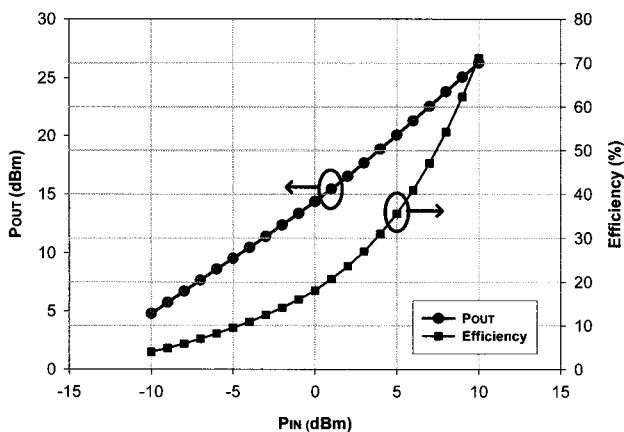


Fig. 6. Simulated drain efficiency and P_{OUT} of PA#2.

circuit cannot be overemphasized. For this reason, careful optimization on each transmission line of the circuit has to be done, and thus the variable-length TL designs are adopted to implement the quarter-wave TLs so that the impedance inversion at TL1 and TL2 can be achieved at dualband. As shown in Fig. 7, the variation in length can be achieved by a single-pole double-throw (SPDT) switch in the midst of the TLs so that each quarter-wavelength at the third harmonics of the dualband frequencies can invert the open termination. As well, the length of another shunt $\lambda/4$ TL (TL2) at the fundamental frequencies is appropriately switched to have the short impedance at the second harmonics of two frequencies.

In addition, for the last TL in the series path (TL3), the inversion of impedances at the third harmonics is implemented through the investigation of harmonics of two frequencies, as shown in Table 2.

From the table, it can be noticed that 2.4 GHz is close to the third harmonic of the first frequency 840 MHz, and thus it can be approximated as shown below.

$$\frac{\lambda_{(3f_1)}}{4} \cong \frac{\lambda_{(f_2)}}{4} \quad (3)$$

The Q from this approximation can be expressed as below.

$$Q_{appr.} = \frac{\sqrt{(3f_1 f_2)}}{\Delta f} = \frac{\sqrt{(3f_1 f_2)}}{3f_1 - f_2} \cong 20.49 \quad (4)$$

Compared to the Q of a conventional TL, the calcula-

Table 2. The dual mode harmonic frequencies (GHz).

	f_1	$2f_1$	$3f_1$	$4f_1$	$5f_1$	$6f_1$	$7f_1$	$8f_1$	$9f_1$
0.84 GHz mode	0.84	1.68	2.52	3.36	4.2	5.04	5.88	6.72	7.56
2.35 GHz mode	-	-	f_2	-	$2f_2$	-	-	-	$3f_2$
	-	-	2.4	-	4.8	-	-	-	7.2

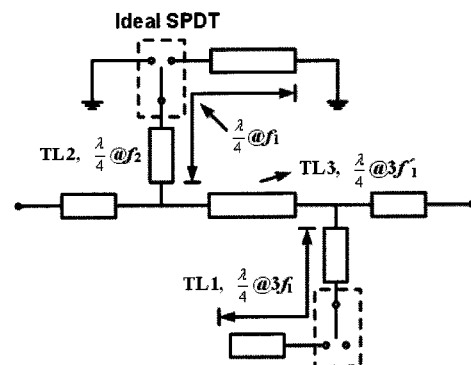


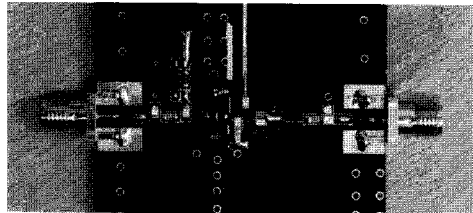
Fig. 7. Schematic diagram of the output harmonic control circuit for dualband operation.

ted Q is relatively high, which means that the dualband approximation in (3) is acceptable^[14]. As such, it can be said that the $\lambda/4$ TL would perform almost equally at both frequencies when the length is properly designed at the geometric mean frequency of $(3f_1)$ and (f_2) .

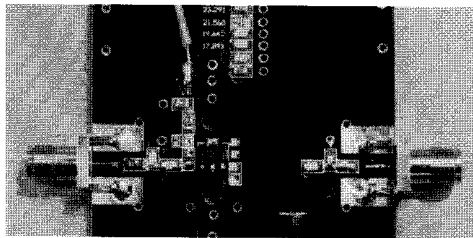
As a result of the optimized series TL3 and the variable-length shunts TL1 and TL2, the output network can maintain necessary harmonic impedances for class-F operation at both 840 MHz and 2.4 GHz.

IV. Implementation and Experimental Results

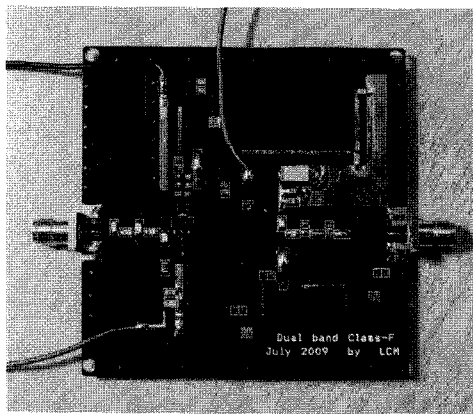
The pictures of actual fabricated PAs are shown in Fig. 8. As a result, the measured harmonic impedances at the drain of PA#1 are shown in Fig. 9, where the impedances at the second and third harmonics are read as 4.2Ω and 379Ω , respectively. As such, up to the third harmonic, it is expected that the discrete LC resonator is able to control the harmonics as well as the $\lambda/4$ transmission lines can. With these implemented PAs, the



(a) PA#1 at 840 MHz



(b) PA#2 at 2.4 GHz



(c) Dualband PA#3 at 840 MHz and 2.4 GHz

Fig. 8. Picture of the implemented class-F(PAs).

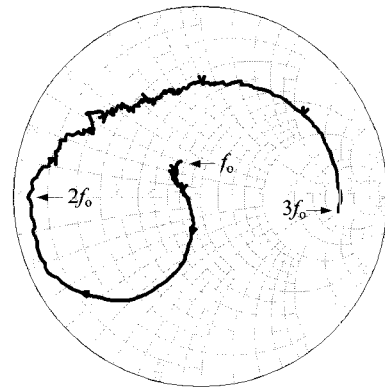


Fig. 9. Measured impedance of PA#1 at the drain.

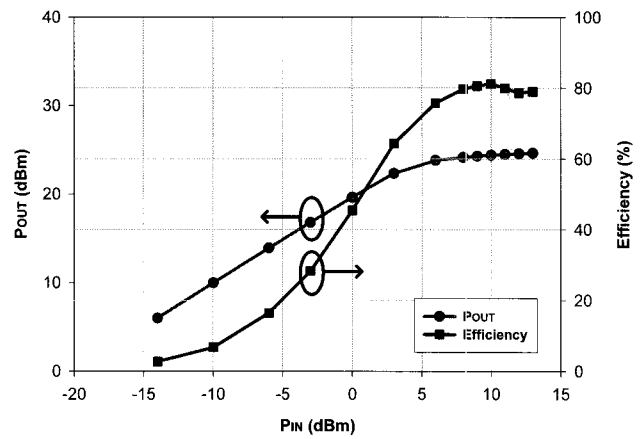


Fig. 10. Measured drain efficiency and output power of PA #1.

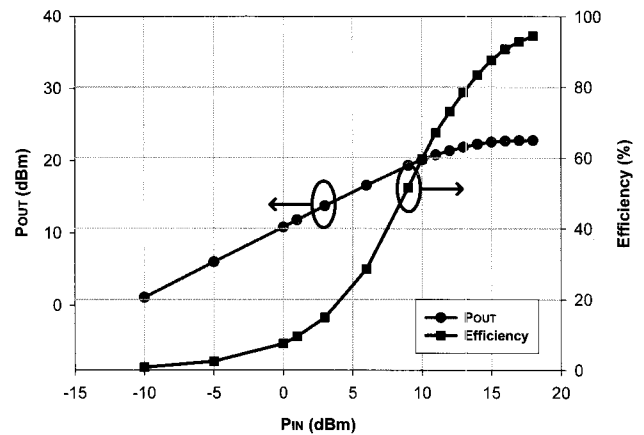


Fig. 11. Measured drain efficiency and output power of PA#2.

output powers and the efficiencies of PA#1, PA#2, and PA#3 are measured at 840 MHz and 2.4 GHz. Firstly, the measured performances of PA#1 are illustrated in Fig. 10, where the 81.2 % maximum efficiency is shown

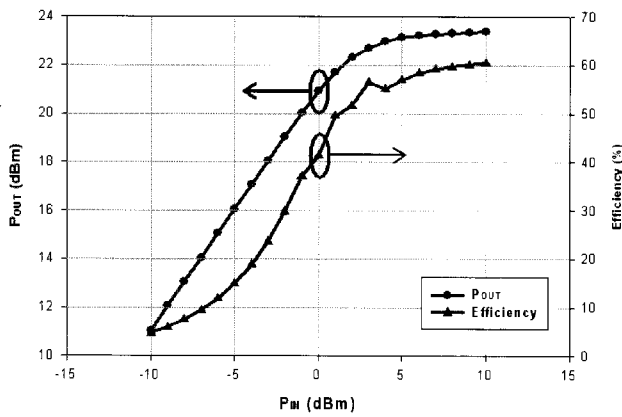


Fig. 12. Measured drain efficiency and output power of PA #3 in 840 MHz mode.

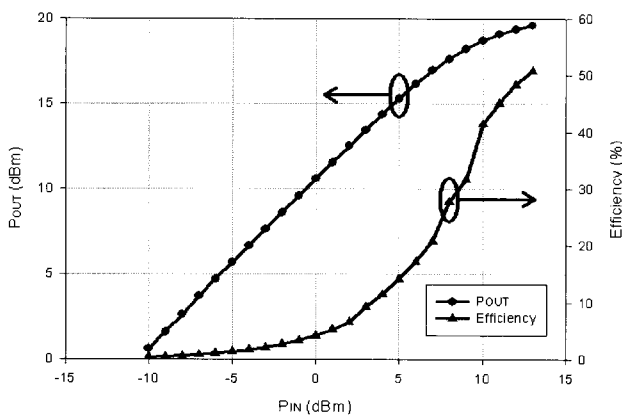


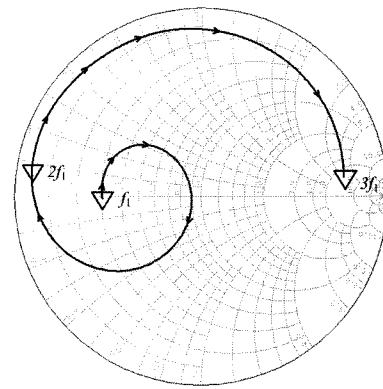
Fig. 13. Measured drain efficiency and output power of PA#3 in 2.4 GHz mode.

at 24.4 dBm of output power. Considering that the harmonic control is performed only up to the third harmonic and that the circuit is fabricated on FR-4 substrate, the result can be regarded as the best in its class.

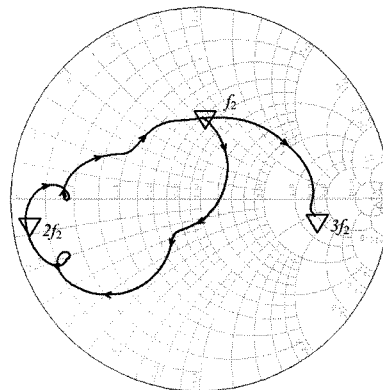
The differences between simulation and measurement are believed to be from the inaccuracy of the transistor models with strong nonlinear information under the extreme operating conditions like class-F.

As shown in Fig. 8(b), the single-frequency class-F PA(PA#2) was built for output at 2.4 GHz, the measured results of which are shown in Fig. 11. The maximum drain efficiency reached up to 94.5 % with an output power of 22.8 dBm, results that are also among the best in the class reported so far. In any case, as well as the PA#1, it is proven that high efficiency with the class-F technique can be obtained at 2.4 GHz in the application of mWiMAX signal transmission.

The dualband class-F PA(PA#3), as shown in Fig. 8(c), can switch the mode with the variable $\lambda/4$ transmission line, the performances of which are measured via the manual switching. The matching for the fun-



(a) 840 MHz mode



(b) 2.4 GHz mode

Fig. 14. Measured impedance at the drain of PA#3 at 840 MHz and 2.4 GHz modes.

damental frequencies was done in a broadband approach for two frequencies.

The measured performances are shown in Fig. 12 and Fig. 13, which respectively show the results at 840 MHz, 2.4 GHz. In the 840 MHz mode, the peak efficiency was 60.5 % with an output power of 23.38 dBm, whereas the 2.4 GHz mode showed the maximum efficiency of 50.9 % with an output power of 19.62 dBm. It is noticeable that the efficiency is not as good as the output power of single-band PA cases, and this is because the output matching was designed at the geometrical mean of 3×840 MHz and 2.4 GHz, resulting in sub-optimized harmonic termination at each frequency.

Although the mode switching was done manually, and assuming ideal operation, a practical SPDT switch with a proper control circuit is expected to show equivalent results. The harmonic impedance at the drain is shown in Fig. 14.

V. Conclusion

In this paper, in wireless applications of cellular and WLAN bands, highly efficient class-F PAs, two single-

band class-F PAs as well as a dualband PA are implemented with commercial E-pHEMT FET transistors. From the precise modelling and optimization of harmonic control circuits at the output, the efficiencies of two single-band PAs are 81.2 % at 24.4 dBm for the 840 MHz PA and 94.5 % at 22.8 dBm for the 2.4 GHz PA. For the dualband implementation, dualband TLs were designed for the output harmonic control circuit, the length of which is switched for the dualband operation. As a result, the operation in the 2.4 GHz mode showed a peak efficiency of 50.9 % with 19.62 dBm, while in the 840 MHz mode the efficiency reached 60.5 % with 23.38 dBm.

Consequently, it is noticeable that the drain efficiency of the single-band PA at 2.4 GHz fabricated on the low-cost FR-4 substrate showed astonishing efficiency of 94.5 %, and thus this opens the possibility of commercialization of PAs of this kind for wireless terminals.

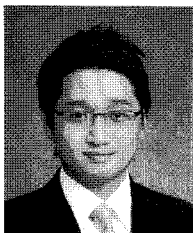
This work was supported by the Korea Research Foundation Grant funded by the Korean Government(MOEHRD)(KRF-2007-331-D00314).

This work was supported by Hankuk University of Foreign Studies Research Fund. of 2010.

References

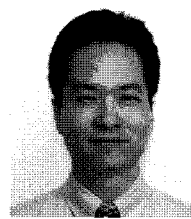
- [1] F. H. Raab, P. Asbeck, S. Cripps et al., "Power amplifiers and transmitters for RF and microwave", *IEEE Trans. Microwave Theory Tech.*, vol. 50, no. 3, pp. 814-826, Mar. 2002.
- [2] F. H. Raab, "Linearity of X-band class-F power amplifiers in high-efficiency transmitters", *IEEE Trans. Microwave Theory Tech.*, vol. 49, no. 6, pp. 1174-1179, Jun. 2001.
- [3] Y. G. Yang, Y. Y. Woo, and B. M. Kim, "Performance comparison between inverse class-F and Class-F amplifiers based on the waveform analysis", *JKIEES*, vol. 2, no. 1, pp. 5-10, May 2005.
- [4] C. Caloz, T. Itoh, *Electromagnetic Metamaterials*, Wiley, Hoboken, 2006.
- [5] S. H. Ji, C. S. Cho, J. W. Lee et al., "Concurrent dual-band class-E power amplifier using composite right/left-handed transmission lines", *IEEE Trans. Microwave Theory Tech.*, vol. 55, no. 6, pp. 1341-1347, Jun. 2007.
- [6] C. M. Lee, Y. C. Park, "Design of compact-sized class-F PA for wireless handset applications", in *2009 IEEE MTT-S Int. Microwave Symp. Dig.*, Jun. 2009.
- [7] F. H. Raab, "Class-F power amplifiers with maximally flat waveforms", *IEEE Trans. Microwave Theory Tech.*, vol. 45, no. 11, pp. 2007-2012, Nov. 1997.
- [8] F. H. Raab, "Maximum efficiency and output of class-F power amplifiers", *IEEE Trans. Microwave Theory Tech.*, vol. 49, no. 11, pp. 1162-1166, Jun. 2001.
- [9] F. H. Raab, "Class-E, class-C, and class-F power amplifiers based upon a finite number of harmonics", *IEEE Trans. Microwave Theory Tech.*, vol. 49, no. 8, pp. 1462-1468, Aug. 2001.
- [10] S. C. Cripps, *RF Power Amplifiers for Wireless Communications*. Norwood, MA: Artech House, 1999.
- [11] D. Barataud, F. Blache, and A. Mallet et al., "Measurement and control of current/voltage waveforms of microwave using a harmonic load-pull system for the optimum design of high efficiency power amplifiers", *IEEE Trans. Instrum. Meas.*, vol. 48, no. 4, pp. 835-842, Aug. 1999.
- [12] P. Colantonio, F. Giannini, and E. Limiti, "HF class-F design guidelines", in *Conf. MIKON-2004*, vol. 1, pp. 27-37, May 2004.
- [13] Gomes Luis Ramos, J. C. Pedro, "Design rules for highly efficiency power amplifiers driven by low voltage supplies", in *Proc. European Microwave Conf.*, vol. 2, pp. 267-270, Oct. 1999.
- [14] D. M. Pozar, *Microwave Engineering*, Wiley, New York, 1998.

Chang-Min Lee



received his B.S. and MS degrees in electronics engineering from the Hankuk University of Foreign Studies, Korea in 2008 and 2010 respectively, and is joining LG Electronics. His research interests include class-F power amplifier design.

Young-Cheol Park



received the B.S. degree in electrical engineering from the Yonsei University, Korea in 1992, and completed M.S. and Ph.D. in electrical engineering at Georgia Tech. in 2002, and 2004, respectively. He is currently an Assistant Professor at Hankuk University of Foreign Studies, Korea. From 2004 to 2007 and from 1994 to 2000, he was with Samsung Electronics, Korea, where he designed 3G and 4G handsets. His research interests include dual-mode power amplifiers, behavioral modeling, predistortion, and frequency multiplication.

Hoijin Yoon



received B.S. and M.S. degrees in Computer Science and Engineering from Ewha Womans University in 1993 and 1998, respectively. She also received her Ph.D. about component testing from Ewha Womans University. Afterwards, she was at Georgia Institute of Technology and Ewha Womans University before she joined the faculty at Hyupsung University in 2007. Her research interests include optimization and testing of Matlab codes.