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Performance Comparison between Inverse Class-F and Class-F Amplifiers Based on the Waveform Analysis

Youngoo Yang · Young Yun Woo · Bumman Kim

Abstract

We have analyzed the inverse class-F and class-F amplifiers using their waveforms. From the analytic equations derived from the analysis, we have calculated the efficiencies, output powers, DC power dissipations, and optimum fundamental load impedances of the inverse class-F and class-F amplifiers. We also have compared them for various operation conditions, which include the same peak current, same DC power dissipation, same fundamental RF output power, and same fundamental load impedance with different *Ron*(on-resistance). These analyses have clearly shown the performance limitations, advantages, and guide to the optimized design of the inverse class-F amplifiers.

Key words: inverse class-F amplifier, class-F amplifier, waveform analysis, high efficiency amplifier, on-resistance.

Ⅰ. Introduction

The recent popularity of the wireless communication systems makes the high efficiency microwave power amplifiers to be a very important RF component. The class-F amplifiers, which have short load at even-order harmonics(current peaking) and open load at odd-order harmonics(voltage peaking), have become a representative of the high efficiency amplifiers[1],[2]. Very recently, the inverse class-F amplifiers become a hot research item. Ideally, the efficiencies of both the class-F and inverse class-F amplifiers are 100 %. However, the on- resistance(*Ron*) of a transistor degrades the efficiency[3]. As the operation voltage becomes lower, the effect of Ron on the efficiency and output power becomes significant. The *Ron* is main reason for the different performances of the two modes of operations.

It is commonly known that the inverse class-F amplifiers, which have open load at even-order harmonics and short load at odd-order harmonics, can deliver higher efficiency than class-F operation. Partial analysis and simulation, which showed superior performance of the inverse class-F amplifier, have been reported[3],[4]. But there have been no reports treating full waveform analysis for the clear explanation of better efficiency and the design guide for the optimized performance of the inverse class-F amplifiers.

The purposes of this paper are to provide the quantitative and clear explanation of better efficiency, and the design guide for optimizing the output power or efficiency of the inverse class-F amplifiers in comparison to the class-F amplifiers based on waveform analysis. For the purposes, the efficiencies, fundamental output powers, DC power dissipations, and fundamental load impedances of the inverse class-F and conventional class-F amplifiers are derived using the ideal time domain waveforms. Then, the comparisons are made using the analytic equations for various operation conditions: identical peak current, identical DC power dissipation, identical fundamental RF output power, and identical fundamental load impedance. Finally, the performance advantages of the inverse class-F are visualized and then, the conclusions are drawn using the observed results.

Ⅱ. Waveform Analysis

Fig. 1 shows the ideal time domain current and voltage waveforms and load line for a given on-resistance(*Ron*) of the class-F and inverse class-F amplifiers. The class-F amplifiers have half sinusoidal current and square wave voltage signals. On the contrary, the inverse class-F amplifiers have square wave current and half sinusoidal voltage signals. In appendix, the waveforms of the class-F and inverse class-F amplifiers are analyzed using Fourier series expansion, and DC current and fundamental current and voltage components are derived with the parameters of V_{dc}, $i_{d,peak}$, and R_{on}. Here, $i_{d,peak}$ and *Ron* are determined by the device parameters and *Vdc* is the supply voltage. From the appendix, the DC power dissipation, fundamental RF output power, and fundamental load impedance of the class-F amplifiers can be calculated as following equations.

$$P_{dc} = I_{dc} \cdot V_{dc} = \frac{i_{d,peak}}{\pi} V_{dc} \tag{1}$$

$$P_{fund} = \frac{i_{d,peak}}{\pi}\left(V_{dc} - Ron \cdot i_{d,peak}\right) \tag{2}$$

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Department of Electronic and Electrical Engineering and Microwave Application Research Center, POSTECH, Korea, e-mail: alice@postech.ac.kr

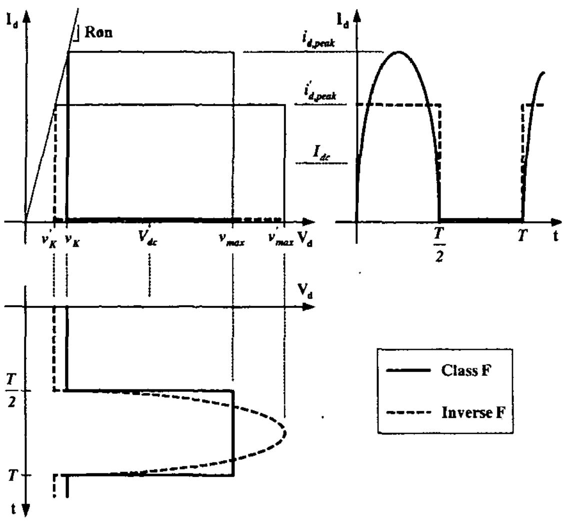


Fig. 1. Ideal time domain current and voltage waveforms and load line with on-resistance(*Ron*) of the class-F (solid line) and inverse class-F(dotted line) at the identical DC power dissipation(same I_{dc} and V_{dc}) condition.

$$R_{L,fund} = -\frac{V_{fund}}{I_{fund}} = \frac{8\cdot\left(V_{dc} - Ron\cdot i_{d,peak}\right)}{\pi\cdot i_{d,peak}} \tag{3}$$

By the same way, those of the inverse class-F amplifiers can be calculated as following equations using *Vdc*, $i_{d,peak}$, and *Ron*.

$$P'_{dc} = I'_{dc}\cdot V_{dc} = \frac{i'_{d,peak}}{2}V_{dc} \tag{4}$$

$$P'_{fund} = \frac{i'_{d,peak}}{2}\left(V_{dc} - Ron\cdot i'_{d,peak}\right) \tag{5}$$

$$R_{L,fund} = -\frac{V'_{fund}}{I'_{fund}} = \frac{\pi^2\cdot\left(V_{dc} - Ron\cdot i'_{d,peak}\right)}{4\cdot i'_{d,peak}} \tag{6}$$

Using above equations (1), (2) and (4), (5) the efficiencies of the class-F and inverse class-F amplifiers can be easily calculated:

$$\eta = 100\frac{\left(V_{dc} - Ron\cdot i_{d,peak}\right)}{V_{dc}}(\%) \tag{7}$$

$$\eta' = 100\frac{\left(V_{dc} - Ron\cdot i'_{d,peak}\right)}{V_{dc}}(\%) \tag{8}$$

From (7) and (8), if *Ron* is zero, the efficiencies of the class-F and inverse class-F amplifiers are 100 %. The difference in efficiency is due to the different knee voltage originated from the different peak current levels.

Ⅲ. Performance Comparison

Using equations (1)~(8), we have compared the performance of the class-F and inverse class-F amplifiers for various operation conditions. For the calculation, 5V is supplied as V_{dc} and $i_{d,peak}$ is 1A with a uniform transconductance. The $i_{d,peak}$(peak current of the class-F operation, which provides reference for the performance comparison; set as 1A for all operation conditions) should be no less than $i_{d,peak}$, and all operation conditions obey this restriction, which is a very important pre-condition of this work.

3-1 Identical Peak Current Condition

Generally, the peak current of the transistors determines the maximum RF output power with a proper load impedance. Hence, this is the most general operation condition to achieve maximum RF power for both class-F and inverse class-F amplifiers. We have calculated DC power dissipations, RF fundamental powers, optimum load impedances, and efficiencies of the class-F and inverse class-F amplifiers while maintaining the peak current level($i'_{d,peak}$ = $i_{d,peak}$ for all classes). The calculated results with varying *Ron* from 0 to 2 Ω are shown in Fig. 2. Fig. 2(a) is the efficiencies and load impedances. Efficiencies are identical and load impedance of the class-F amplifier is slightly higher than that of the inverse class-F to maintain a constant peak current level. As the *Ron* increases, the

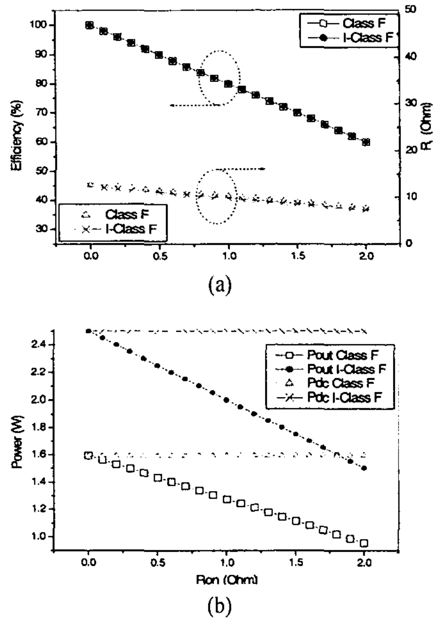


Fig. 2. Performances of the class-F and inverse class-F amplifiers for the identical peak current with varying *Ron* from 0 to 2 Ω. (a) Efficiency and fundamental load impedance, (b) DC power dissipation and fundamental RF output power.

efficiencies decreases from 100 % to below 70 % and the optimum load impedance decreases to support the constant peak current. The difference of the RF output power between class-F and inverse class-F amplifiers is very large. The inverse class-F amplifier has much more output power and DC dissipation. The DC power dissipations for both amplifiers are slightly increased while the RF output powers are significantly decreased as the Ron increases.

3-2 Identical DC Power Dissipation Condition

From the condition of $P_{dc} = P'_{dc}$, the peak current of the inverse class-F amplifier is determined:

$$i'_{d,peak} = \frac{2}{\pi} i_{d,peak} \tag{9}$$

Substituting (9) to (5), (6) and (8), the inverse class-F formula become as:

$$P'_{fund} = \frac{i'_{d,peak}}{\pi}\left(V_{dc} - \frac{2\cdot Ron\cdot i'_{d,peak}}{\pi}\right) \tag{10}$$

$$R'_{L,fund} = \frac{\pi^3}{8\cdot i'_{d,peak}}\left(V_{dc} - \frac{2\cdot Ron\cdot i'_{d,peak}}{\pi}\right) \tag{11}$$

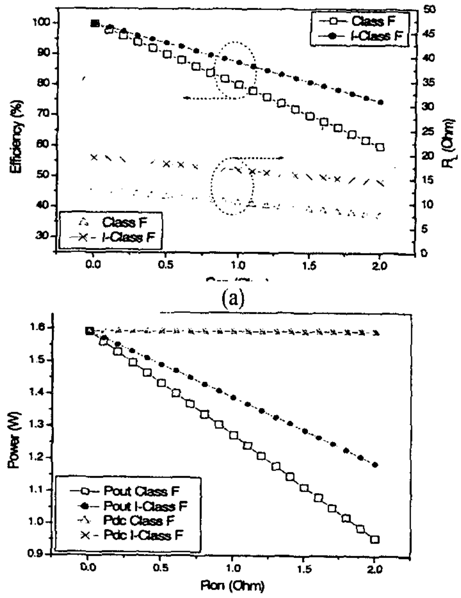
$$\eta' = 100\frac{\left(V_{dc} - \frac{2\cdot Ron\cdot i'_{d,peak}}{\pi}\right)}{V_{dc}}(\%) \tag{12}$$

The comparison of the performances between the class-F and inverse class-F amplifiers with identical P_{dc} is described in Fig. 3. The efficiency of the inverse class-F amplifier becomes better than that of class-F amplifier with increasing *Ron* due to the higher load impedance of the inverse class-F amplifier to maintain identical P_{dc} as shown in Fig. 3(a). Fig. 3(b) shows superior RF power performance of the inverse class-F amplifier, as the *Ron* increases. The inverse class-F amplifier can deliver an improved efficiency and RF output power with identical P_{dc} condition. The waveforms described in Fig. 1 clearly shows the lower power dissipation of transistor for the inverse class-F case.

3-3 Identical RF Output Power Condition

This condition is for the generation of identical RF output powers by fitting the circuit conditions of inverse class-F and class-F amplifiers. The condition($P_{fund} = P'_{fund}$) can be met by arranging the 2nd order equation of $i'_{d,peak}$ for the fixed drain biases and $i_{d,peak}$.

$$Ron\cdot i'^{2}_{d,peak} - V_{dc}\cdot i'_{d,peak} + \frac{2}{\pi} i_{d,peak}(V_{dc} - Ron\cdot i_{d,peak}) = 0 \tag{13}$$



(a)

(b)

Fig. 3. Performances of the class-F and inverse class-F amplifiers for the identical DC power dissipation condition with varying *Ron* from 0 to 2 Ω. (a) Efficiency and fundamental load impedance, (b) DC power dissipation and fundamental RF output power.

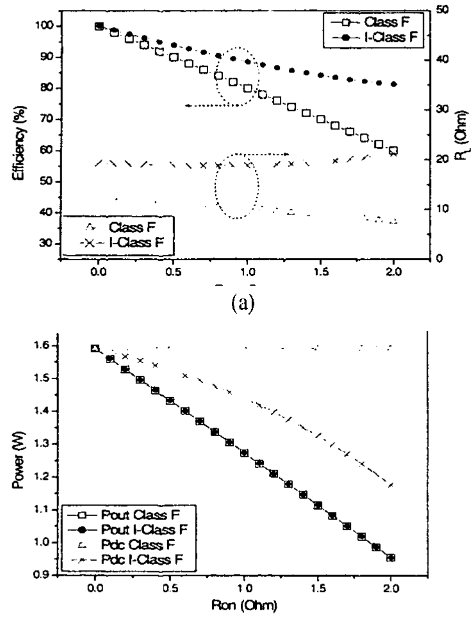
The solution of (13) can be represented as:

$$i'_{d,peak} = \frac{V_{dc} \pm \sqrt{V_{dc}^{2} - \frac{8\cdot i_{d,peak}}{\pi}\left(V_{dc} - Ron\cdot i_{d,peak}\right)}}{2\cdot Ron} \tag{14}$$

Omitting positive sign of (13) to pick reasonable value of $i'_{d,peak}$ and adding the $Ron = 0$ case, (13) is rewritten as:

$$i'_{d,peak} = \begin{cases} \dfrac{V_{dc} - \sqrt{V_{dc}^{2} - \frac{8\cdot i_{d,peak}}{\pi}\left(V_{dc} - Ron\cdot i_{d,peak}\right)}}{2\cdot Ron} & \text{if } Ron \neq 0 \\ \dfrac{2}{\pi} i_{d,peak} & \text{if } Ron = 0 \end{cases} \tag{15}$$

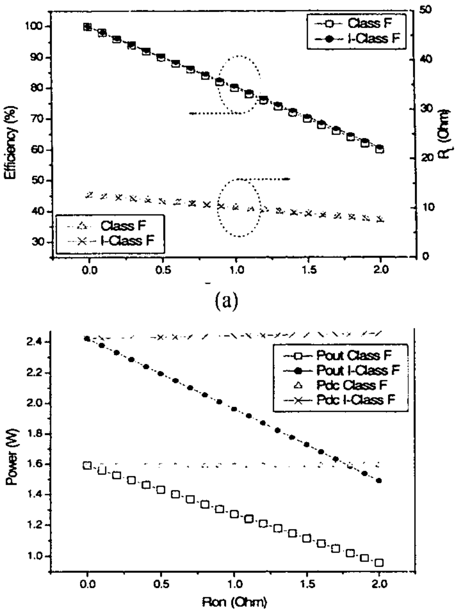
If (15) is substituted to inverse class-F formula of (4)~(6) and (8), we can easily obtain the analytic forms of DC power dissipation, RF output power, load impedance, and efficiency of inverse class-F amplifier in identical RF output power condition. The resulting equations are not expressed in this paper because of complex external shapes. The calculation is numerically performed using MATLAB. The comparison results of performances between the class-F and inverse class-F amplifiers with Identical P_{fund} are presented by Fig. 4. The efficiency of inverse class-F amplifier becomes better than that of class-F amplifier with increasing *Ron* due to the higher load impedance of inverse



(a)

(b)

Fig. 4. Performances of the class-F and inverse class-F amplifiers for the identical fundamental RF output power with varying *Ron* from 0 to 2 Ω. (a) Efficiency and fundamental load impedance, (b) DC power dissipation and fundamental RF output power.



(a)

(b)

Fig. 5. Performances of the class-F and inverse class-F amplifiers for the identical fundamental load impedances with varying *Ron* from 0 to 2. (a) Efficiency and fundamental load impedance, (b) DC power dissipation and fundamental RF output power.

class-F amplifier to maintain an identical P_{fund} as shown in Fig. 4(a). Fig. 4(b) shows a significantly decreasing DC power consumption of the inverse class-F amplifier for the same RF output power, as the *Ron* increases.

3-4 Identical Fundamental Load Impedance Condition

This is very straightforward condition of fixing the fundamental load impedance of the inverse class-F amplifier to have the same one of class-F amplifier. The expression for $i'_{d,peak}$ can be derived from the condition($R_{L,fund} = R'_{L,fund}$) as follows:

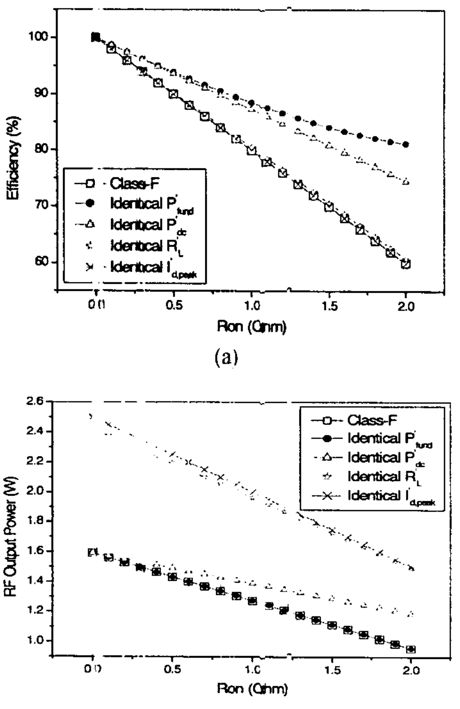
$$i'_{d,peak} = \frac{\pi^3 \cdot V_{dc} \cdot i_{d,peak}}{32 \cdot \left(V_{dc} - Ron \cdot i_{d,peak}\right) + \pi^3 \cdot Ron \cdot i_{d,peak}} \qquad (16)$$

If (16) is substituted into the inverse class-F formula of (4)~(6) and (8), we can easily obtain the analytic forms of DC power dissipation, RF output power, optimum load impedance, and efficiency of inverse class-F amplifier. The calculation is numerically performed. The performances of the class-F and inverse class-F amplifiers with identical $R_{L,fund}$ are compared in Fig. 5. The efficiency of the inverse class-F amplifier is slightly better than that of class-F amplifier with increasing *Ron* as shown in Fig. 5(a). Fig. 5(b) shows a significantly higher RF output power of the inverse class-F amplifier with the same fundamental load line, as the *Ron* increases. These are very similar characteristics to the identical peak current condition.

For summary, the efficiency and fundamental RF output power performances of the various operation conditions are plotted in Fig. 6. For the highest efficiency of the inverse class-F amplifier without losing RF output power than class-F amplifier, we should choose the identical fundamental RF power condition by optimizing load impedance of the inverse class-F amplifier. For the highest RF power, we should choose the identical peak current condition by optimizing load impedances of the inverse class-F amplifier. For the simultaneous improvement of efficiency and RF output power, we should choose the identical DC power dissipation condition by adjusting load impedance of the inverse class-F amplifier.

Ⅳ. Conclusions

For the first time, we have fully analyzed the time domain waveforms of inverse class-F amplifier. Then, we have compared the analysis results with those of class-F amplifier for the well-chosen 4 different operation conditions. They are the identical peak current, identical DC power consumption, identical fundamental RF output power, and identical fundamental load impedance conditions. The analysis has shown the



(a)

(b)

Fig. 6. Performances of the class-F and inverse class-F amplifiers in the various conditions with varying *Ron* from 0 to 2 Ω. (a) Efficiency, (b) fundamental RF output power.

clear performance limitations, advantages, and guide for optimizing fundamental load impedance of the inverse class-F amplifiers.

On the contrary to the previous knowledge, the inverse class-F amplifier has no better efficiency than class-F amplifier but just has much higher output power level due to a large voltage swing, when it is fully driven to the peak current level with the same supply voltage as class-F. To get a better efficiency using inverse class-F mode, the fundamental load impedance should be increased to reduce parasitic loses of the transistor's knee voltage with sacrificing surplus RF output power of the inverse class-F amplifier. This work provides the clear explanation of the limitations and advantages of the inverse class-F amplifier and will be a guide to design and to optimize the performance of the inverse class-F amplifier.

Appendix

A. Class-F Analysis

Fig. A.1 shows the ideal current and voltage waveforms of conventional class-F amplifiers. To separate each frequency components, the current and voltage waveforms of the Fig. A.1 are expanded using Fourier series as follows:

$$i_D = i_{d,peak}\cdot\left(\frac{1}{\pi}+\frac{1}{2}\sin\omega_0 t-\frac{2}{\pi}\sum_{n=2,4,6,\ldots}\frac{1}{n^2-1}\cos n\omega_0 t\right) \quad (A.1)$$

$$v_D = V_{dc}-\frac{4\cdot(V_{dc}-v_K)}{\pi}\sum_{n=1,3,5,\ldots}\frac{1}{n}\sin n\omega_0 t \quad (A.2)$$

where i_D and v_D are the time domain current and voltage waveforms including DC and RF components, respectively. $Ron \cdot i_{d,peak}$ can be substituted for the knee voltage v_K(see Fig. 1). Hence, the current and voltage waveform equations can be separated for the each harmonic components. The DC and fundamental RF components of (A.1) and (A.2) are separated as the functions of peak current, DC voltage, and *Ron* by

$$I_{dc} = \frac{i_{d,peak}}{\pi} \quad (A.3)$$

$$I_{fund} = \frac{i_{d,peak}}{2}\sin\omega_0 t \quad (A.4)$$

$$V_{fund} = -\frac{4\cdot(V_{dc}-Ron\cdot i_{d,peak})}{\pi}\sin\omega_0 t \quad (A.5)$$

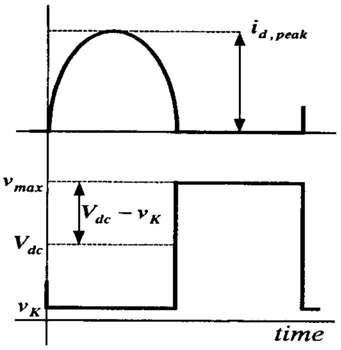


Fig. A. 1. Ideal current(upper) and voltage(lower) waveforms of the class-F amplifiers.

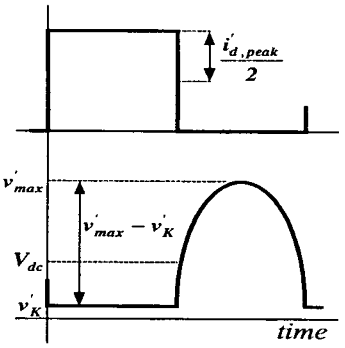


Fig. A. 2. Ideal current(upper) and voltage(lower) waveforms of the inverse class-F amplifiers.

B. Inverse Class-F Analysis

Fig. A.2 shows the ideal current and voltage waveforms of the inverse class-F amplifiers. The current and voltage waveforms are expanded using Fourier series as follows:

$$i'_D = \frac{i'_{d,peak}}{2}\left(1+\frac{4}{\pi}\sum_{n=1,3,5,..}\frac{1}{n}\sin n\omega_0 t\right) \quad (A.6)$$

$$v'_D = v'_K + \left(v'_{\max} - v'_K\right)\cdot\left(\frac{1}{\pi}-\frac{1}{2}\sin\omega_0 t+\frac{2}{\pi}\sum_{n=2,4,6,..}\frac{1}{n^2-1}\cos n\omega_0 t\right) \quad (A.7)$$

$Ron \cdot i'_{d,peak}$ can be substituted to the knee voltage v'_K. From (A.7), the v'_{max} can be written using DC supply voltage.

$$v'_{\max} = \pi\cdot V_{dc} - (\pi - 1)\cdot Ron\cdot i'_{d,peak} \quad (A.8)$$

Here, the current and voltage waveform equations can be separated for the each harmonic components. The DC and fundamental RF components of (A.6) and (A.7) are separated as the functions of peak current, DC voltage, and *Ron* by

$$I'_{dc} = \frac{i'_{d.peak}}{2} \quad (A.9)$$

$$I'_{fund} = \frac{2\cdot i'_{d,peak}}{\pi}\sin\omega_0 t \quad (A.10)$$

$$V'_{fund} = -\frac{\pi\cdot\left(V_{dc} - Ron\cdot i'_{d,peak}\right)}{2}\sin\omega_0 t \quad (A.11)$$

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Youngoo Yang

was born in Hamyang, Korea, in 1969. He received his BS degree in electronic engineering from Han-Yang University, in 1997. He also received Ph.D. degree in electronic and electrical engineering from Pohang University of Science and Technology, in 2002. Currently, he is working as a post doctoral researcher with POSTECH. His research interests include linearization techniques and behavioral modeling of the high power amplifiers, large signal modeling of the microwave devices, and RFIC design.

Young Yun Woo

was born in Taegu, Korea, in 1976. He received his BS degree in electronic and electrical engineering from Han-Yang University and is currently working toward M.S. degree in Pohang University of Science and Technology (POSTECH), Korea. His current research interests include RF power amplifier design and LPA control circuits design.

Bumman Kim

received the PH.D. degree in electrical engineering from Carnegie-Mellon Univerisity. Pittsburgh, PA, in 1979. From 1978 to 1981, he was engaged in fiber-optic component research at GTE Laboratories Inc. In 1981, he joined the Central Research Laboratories, Texas Instruments Incorporated, where he was involved in development of GaAs power FET's and MMIC's. He has developed a large-signal model of a power FET, dual-gate FET's for gain control, and high-power distributed amplifiers, and various millimeter-wave MMIC's. In 1989, he joined the Pohang University of Science and Technology (POSTECH), Pohang, Korea, where he is currently a Professor in the Electronic and Electrical Engineering Department, and Director of the Microwave Application Research Center, where he works on device and circuit technology for MMIC's. He has published over 100 technical papers in this area.

Dr. Kim is a member of the Korean Academy of Science and Technology.