A New Linear Amplifier Using Low-Frequency Second-Order Intermodulation Component Feedforwarding

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***Abstract*—A new linearization method by feedforwarding low-frequency second intermodulation component ($f_2 - f_1$) is proposed. Drain voltage modulation by the forwarding second intermodulation voltage improves linearity significantly. This new technique, which adopts a simple circuit configuration, has advantages in the stability and bandwidth due to the feedforwarding nature and shows a very good performance in comparison with other harmonic tuning circuits. Analytical derivation of low-frequency feeding voltage gain (β) to obtain perfect cancellation of IMD$_3$ is presented. For verification of the proposed circuit topology, a two-tone test and a CDMA signal test at carrier frequency 2.15 GHz are performed and show about 18- and 10-dB improvement of IMD$_3$ and adjacent channel power ratio (ACPR), respectively.**

***Index Terms*— Feedforwarding, harmonic, intermodulation, linear amplifier, nonlinear.**

I. Introduction

As the use of the digital modulation, such as QPSK, QAM, etc., increases quite rapidly, the linearity becomes more and more important figure of merit of power amplifier. Many works have been reported to reduce the third-order intermodulation using the second-order harmonic components, such as the harmonic feedback and the harmonic tuning [1], [2]. Generally, the second harmonic tuning is introduced to improve just a few decibels of IMD$_3$. The harmonic feedback can improve linearity by 10–15 dB, but it has serious stability and bandwidth problems. The feedforward system has been used in many applications because of its unconditionally stable characteristics and ability to produce a broad-band and highly linear amplifier [3]. But the feedforward approach is very sensitive to component tolerance and drift, and requires adaptive control [3], [4].

In this letter, a new linearization method using the second harmonic component $(f_2 - f_1)$ is suggested. This feedforwarding amplifier, which amplifies the gate's second intermodulation term and feeds to the drain, has advantages over both harmonic feedback and general feedforward methods. This method is very stable because of the feedforwarding nature and also has no gain loss and no need for phase adjustment by selection of the low-frequency intermodulation term.

Circuit description and analysis using the Taylor series expansion is presented in the Section II. Analysis shows how C_{gs} generates nonlinear gate current and forwarding second-order term can cancel third-order intermodulation. Finally, the optimum voltage gain β is derived. In the Section III, circuit implementation and measurement results are presented. A two tone test and CDMA signal test results are also shown.

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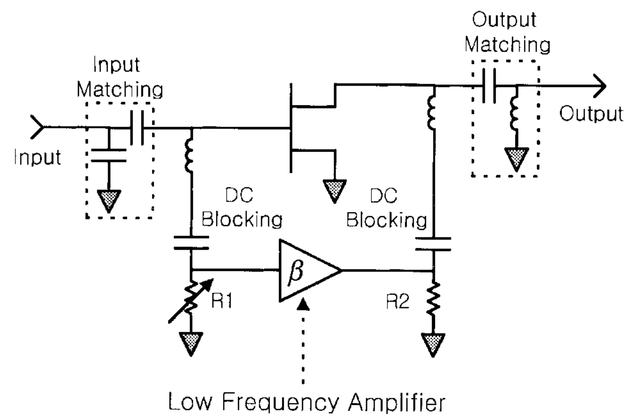

Fig. 1. Circuit diagram of the second-order intermodulation feedforwarding amplifier.

II. Analysis

Fig. 1 shows a simplified circuit diagram of the second intermodulation component feedforwarding amplifier. Low-frequency second intermodulation component $(f_2 - f_1)$ is loaded by R1 and is then amplified by voltage gain of β. The component is injected to the drain bias circuit. Matching circuits are located at the outer part of the low-frequency forwarding path.

Fig. 2 shows the equivalent circuit of the low-frequency second intermodulation component feedforwarding amplifier. Fig. 2(a) is the equivalent circuit at the fundamental frequency and (b) at the low frequency. For the equivalent circuit analysis, we can assume that $Rs = Rd = Rg = Ri = 0$ since capacitive impedances are dominant terms. Based on the above equivalent circuits, the nonlinear channel current using the Taylor series expansion is expressed as follows [5]–[8]:

$$\begin{aligned} i_{ds}[v_{gs}, v_{ds}] = {} & gm \cdot v_{gs}(t) + gd \cdot v_{ds}(t) + gm_2 \cdot v_{gs}(t)^2 \\ & + gmd \cdot v_{gs}(t) \cdot v_{ds}(t) + gd_2 \cdot v_{ds}(t)^2 \\ & + gm_3 \cdot v_{gs}(t)^3 + gm_2d \cdot v_{gs}(t)^2 \cdot v_{ds}(t) \\ & + gmd_2 \cdot v_{gs}(t) \cdot v_{ds}(t)^2 + gd_3 \cdot v_{ds}(t)^3 \\ & + \cdots \end{aligned} \quad (1)$$

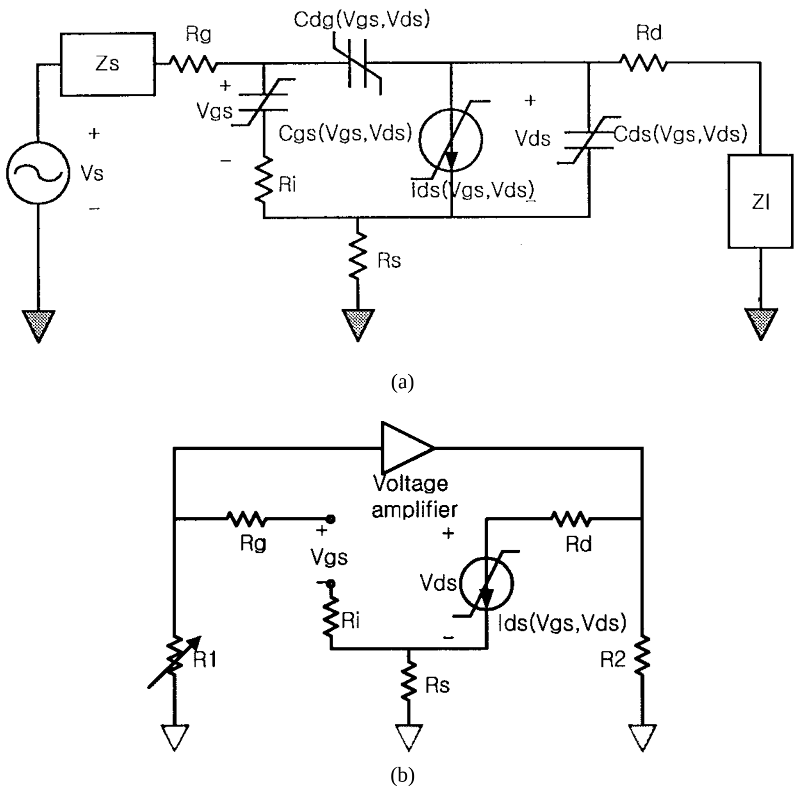

Fig. 2. Equivalent circuit for nonlinear analysis. (a) Fundamental frequency. (b) Low frequency.

where v_{gs} and v_{ds} are ac components of gate and drain voltages, respectively.

Now, the two tone input signal at the gate is given by

$$\begin{aligned} v_{gs}(t) &= A_1 \cdot \cos(2\pi f_1 t) + A_2 \cdot \cos(2\pi f_2 t) \\ &= \tfrac{1}{2}[A_1 \cdot \exp(j2\pi f_1 t) + A_1 \cdot \exp(-j2\pi f_1 t)] \\ &\quad + \tfrac{1}{2}[A_2 \cdot \exp(j2\pi f_2 t) + A_2 \cdot \exp(-j2\pi f_2 t)] \end{aligned} \quad (2)$$

where A_1 and A_2 are the magnitude of the f_1 and f_2 frequency components, respectively. Equation (2) can be rewritten as

$$v_{gs}(t) = \tfrac{1}{2}(V_{gs-f_1} + V_{gs-f_1}^*) + \tfrac{1}{2}(V_{gs-f_2} + V_{gs-f_2}^*) \quad (3)$$

with

$$\begin{aligned} V_{gs-f_1} &= A_1 \cdot \exp(j2\pi f_1 t) \\ V_{gs-f_2} &= A_2 \cdot \exp(j2\pi f_2 t). \end{aligned}$$

Substituting $v_{gs}(t)$ from (3) to (1), the dominant IM_3 current ($2f_2 - f_1$ component only) generated by the coefficient gm_3 is expressed as

$$\begin{aligned} i_{ds}(t)|_{2f_2-f_1}^{gm_3} &= \tfrac{1}{8}\, gm_3 \cdot (V_{gs-f_2}^2 \cdot V_{gs-f_1}^* + V_{gs-f_2}^{2*} \cdot V_{gs-f_1}) \\ &= \tfrac{1}{4}\, gm_3 \cdot A_2^2 \cdot A_1 \cdot \cos[2\pi(2f_2 - f_1)t]. \end{aligned} \quad (4)$$

The harmonic terms of the gate current generated by the C_{gs} nonlinearity is generated and can be formulated as [9]

$$i_{gs}(t) = [C_0 + C_1 \cdot v_{gs}(t) + C_2 \cdot v_{gs}(t)^2 + \cdots]\, \frac{dv_{gs}(t)}{dt} \quad (5)$$

where, $C_{gs}[v_{gs}(t)] = C_0 + C_1 \cdot v_{gs}(t) + C_2 \cdot v_{gs}(t)^2 + \cdots$. Thus, the $f_2 - f_1$ component of current from (5) is

$$\begin{aligned} i_{gs}(t)|_{f_2-f_1} &= j\frac{\pi}{2}\, C_1(f_2 - f_1)[V_{gs-f_2} \cdot V_{gs-f_1}^* \\ &\quad - V_{gs-f_2}^* \cdot V_{gs-f_1}]. \end{aligned} \quad (6)$$

Using (6), the second-order harmonic component of gate voltage can be written approximately by

$$\begin{aligned} v_{gs}(t)|_{f_2-f_1} &\approx \frac{1}{C_0} \int i_{gs}(t)|_{f_2-f_1}\, dt \\ &= \frac{C_1}{4C_0}\, [V_{gs-f_2} \cdot V_{gs-f_1}^* + V_{gs-f_2}^* \cdot V_{gs-f_1}] \\ &= \frac{C_1}{2C_0}\, A_2 \cdot A_1 \cdot \cos[2\pi(f_2 - f_1)t]. \end{aligned} \quad (7)$$

This harmonic component is amplified and is fed to the drain. The drain voltage $\hat{v}_{ds}(t)$ can be written as

$$\hat{v}_{ds}(t) = v_{ds}(t) - \beta \cdot v_{gs}(t)]_{f_2-f_1} \quad (8)$$

where β is the voltage gain of the auxiliary low-frequency amplifier and $v_{ds}(t)$ is the drain voltage at the normal operation. Substituting the new $\hat{v}_{ds}(t)$ from (8) and $v_{gs}(t)|_{f_2-f_1}$ from (7) to (1), we have a new third-order intermodulation current generated by the interaction of the amplified harmonic voltage through the nonlinear coefficients of gmd and gd_2 (gm_2 is related to gate voltage only). Since $gmd \gg gd_2$ [1], [6], it is clear that the major second-order coefficient is gmd. Then, IM_3 current by gmd from the interaction is given by

$$\begin{aligned} \hat{i}_{ds}(t)|_{2f_2-f_1}^{gmd} & \\ &= \frac{gmd \cdot \beta \cdot C_1}{8C_0}\, (V_{gs-f_2}^2 \cdot V_{gs-f_1}^* + V_{gs-f_2}^{2*} \cdot V_{gs-f_1}) \\ &= \frac{gmd \cdot \beta \cdot C_1 \cdot A_2^2 \cdot A_1}{4C_0}\, \cos[2\pi(2f_2 - f_1)t]. \end{aligned} \quad (9)$$

From (4), we already have the formula of the dominant IM_3 current generated by the third-order coefficient gm_3.

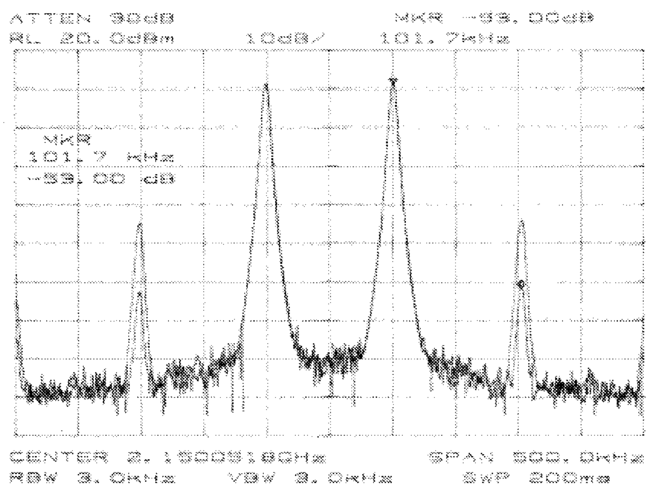

Fig. 3. The measurement results of a two-tone test with and without feedforwarding circuit.

For theoretically perfect cancellation of IMD_3, the following condition should be satisfied:

$$i_{ds}(t)|_{2f_2-f_1}^{gm_3} + \hat{i}_{ds}(t)|_{2f_2-f_1}^{gmd} = 0. \tag{10}$$

The β, which satisfies the above condition, is consequently derived

$$\beta = \frac{gm_3 \cdot C_0}{gmd \cdot C_1}. \tag{11}$$

It is very clear to see from (11) that β is a real value with zero phase and has no relation with input power level of A_1 and A_2. Therefore, a constant gain amplifier can maintain the harmonic cancellation within the moderate change of the input power level. Furthermore, the phase variation at a very low frequency $(f_2 - f_1)$ is not a problem.

III. Experimental Results

For the verification of the proposed linearization method, an amplifier is fabricated using the Stanford's SHF-0289 FET at the center frequency 2.15 GHz. The amplifier has harmonic tuning circuits at the input and output. At a average output power level of 20.33 dBm, it has IMD_3 of 35 dBc with gain of 14.5 dB and power efficiency of 19.23%. A low-frequency amplifier is made by the conventional OP amp. And low-frequency voltage gain β is extracted from the large-signal simulation of the circuit using MDS. The optimum value of β is 147 in this experiment.

General two-tone test results show 18-dB improvement of IMD_3 from 35 to 53 dBc (see Fig. 3). Fig. 4 shows a CDMA signal test results. A nine-channel forward-link CDMA signal, which has chip rate of 500 Kcps, is used. Its IMD, before forwarding a second-order component, is about 20 dBc at the frequency offset 313 KHz. It is improved by more than 10 dB to 31.33 dBc after feedforwarding. When the average output power is further backed off by 10 dB, the improvement is degraded somewhat to 7 dB of ACPR without adjusting β, from 40.5 to 47.5 dBc at the frequency offset 313 KHz. This improvement is maintained for the lower power level.

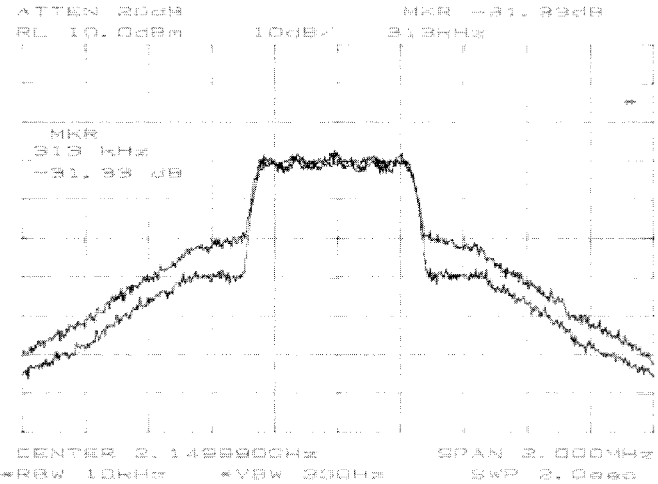

Fig. 4. The measurement results of a CDMA signal test at a chip rate of 500 Kcps with and without feedforwarding circuit.

IV. Conclusion

In this letter, we have proposed a very simple method to linearize power amplifier by feedforwarding an amplified second-order gate intermodulation term to its drain. Based on its equivalent circuits at the fundamental and the low frequency, this circuit is analyzed and consequently a low-frequency forwarding voltage gain for perfect cancellation of IMD_3 is derived. For experimental verification, a power amplifier is built at 2.15 GHz and a two-tone test and CDMA signal test are performed. A two-tone test spectra show more than 18-dB improvement of IMD_3. And a CDMA signal test results also show more than 10-dB improvement of ACPR.

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