A New Linearization Technique for MOSFET RF Amplifier Using Multiple Gated Transistors

Bonkee Kim, Jin-Su Ko, and Kwyro Lee, *Senior Member, IEEE*

***Abstract*—A simple linearization technique using multiple gated common source transistors is proposed where gate width and gate drive $(V_{gs} - V_{th})$ of each transistor are chosen to compensate for the nonlinear characteristics of the main transistor. To demonstrate the feasibility of this approach, a prototype double-gated RF amplifier using two MOSFETs is implemented and its RF characteristics are compared with those of a single one. The results show that, compared with a conventional single-gate transistor amplifier, the third order intermodulation (IMD_3) is improved by 6 dB with similar gain, fundamental output power, and dc power consumption. Because the auxiliary transistor is smaller than the main one and biased at subthreshold, adding this does not affect amplifier characteristics appreciably other than the nonlinearity. With further optimization using multiple gated transistors, much better nonlinear performance per power consumption would be expected.**

***Index Terms*—Intermodulation, linearization, multiple gated, nonlinearity.**

I. Introduction

As DIGITAL communication is used increasingly, the linearity of an RF amplifier becomes more and more important. Recently, high linearity is required even for LNA's, in addition to power amplifiers and driver amplifiers. There were many system-level techniques to increase the linearity of the amplifier, such as predistortion [1], feedforward [2], and Cartesian feedback [3]. However, they all require complex hardware, so those methods are better suited to base station rather than handset.

For the handset application, high linearity at low power consumption is very important. Several linearization techniques suitable for this purpose have been proposed in the literature. For instance, use of an auxiliary triode region MOSFET to compensate for the nonlinearity of the main RF amplifier was proposed in [4], and an auxiliary low frequency amplifier to feedforward the second order intermodulation terms was adopted to reduce third order nonlinearity [5]. However, they all need additional circuits which inevitably increase dc power consumption.

In this letter, a new linearization method using multiple gated common source MOSFETs is proposed, where gate width and gate drive $(V_{gs} - V_{th})$ of each gate is adjusted to compensate for the nonlinear characteristics of the main transistor. The gate drive can be varied either by changing V_{gs} or by changing V_{th}. Then, we demonstrate its feasibility by implementing a prototype double-gated RF amplifier using two transistors. Since the auxiliary MOSFETs are smaller than the main one and are biased below threshold voltage, the proposed topology consumes no additional dc current. In Section II, we describe the principle of linearization using multiple gated transistors. The implementation results using two transistors are described in Section III, followed by conclusions.

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B. Kim and K. Lee are with the Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, Taejon 305-701, Korea (e-mail: bk71@samsung.co.kr; krlee@ee.kaist.ac.kr).

J.-S. Ko is with MEDIA team, System LSI Business, Semiconductor, Samsung Electronics, Kyunggi-do, Korea.

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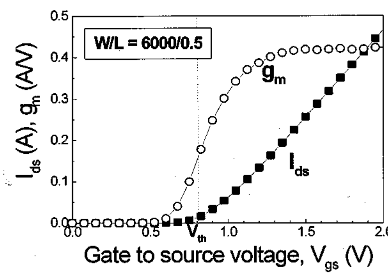
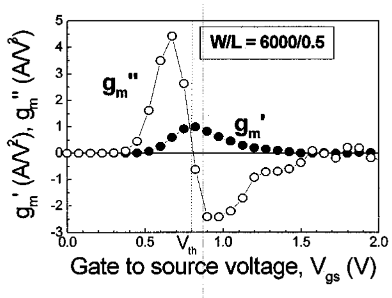


(a)



(b)

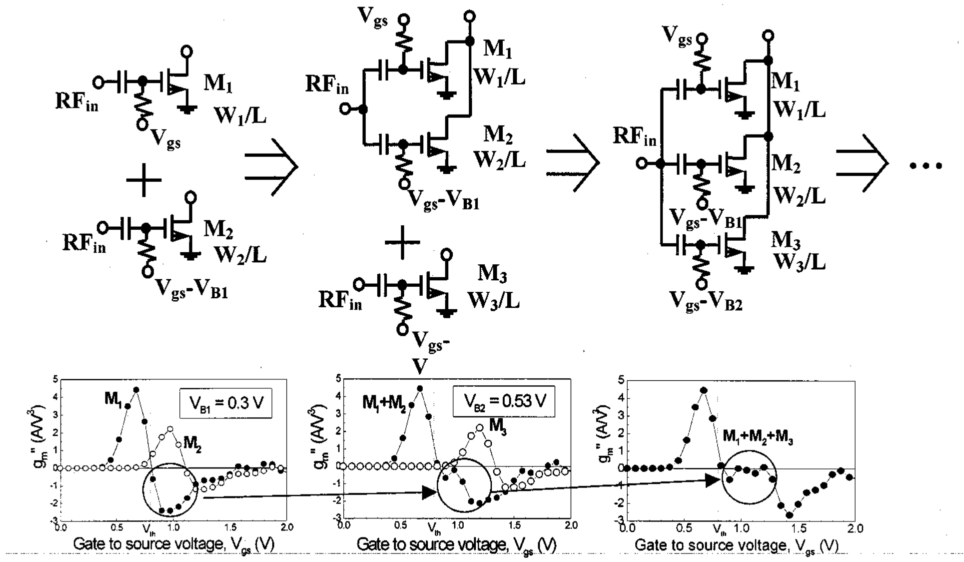
Fig. 1. Measured dc characteristics of W/L (6000/0.5) NMOSFET: (a)I_{ds} and g_m of MOSFET; (b)g'_m and g''_m of MOSFET.

II. Method of Linearization Using Multiple Gated Transistor

In general, the drain current i_{DS} of a common source MOSFET is expressed as

$$i_{DS} = I_{\rm dc} + g_m v_{gs} + \frac{g'_m}{2!} v_{gs}^2 + \frac{g''_m}{3!} v_{gs}^3 + \cdots \quad (1)$$

where $'$ and $''$ are, respectively, the first and the second derivatives with respect to gate to source voltage v_{gs}. It is well known [4] that the coefficient of v_{gs}^3 in (1) plays an important role in the third order intermodulation (IMD_3) distortion of an RF amplifier.



(a) (b) (c)

Fig. 2. Circuit topology and the measured g_m'' of (a) M_1 and M_2; (b) combined M_1 and M_2, and M_3; and (c) combined M_1, M_2, and $M_3 (W_1 = 6000, W_2 = 3000, W_3 = 3000)$.

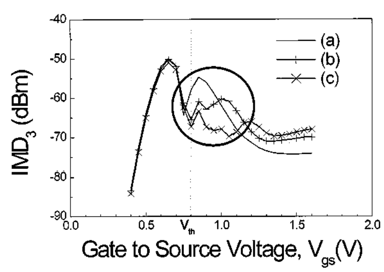


Fig. 3. Simulation results of the third order intermodulation distortion power (input frequency = 900 MHz, input power = -15 dBm): (a) M1 only; (b) M1 and M2; and (c) M1, M2, and M3.

A typical measured current and its derivatives (g_m, g_m', and g_m'') characteristics of a modern NMOSFET are shown in Fig. 1. It shows that the g_m'' goes to the positive peak value at subthreshold region, then crosses zero near the threshold voltage (V_{th}), then shows negative peak value at the gate voltage which is slightly larger than V_{th}. To reduce dc power consumption without losing RF gain, the gate bias voltage of RF amplifier is usually biased at gate drive ($V_{gs} - V_{th}$) in the range between 0.1 and 0.4 V. Unfortunately, the g_m'' in this bias region has negative peak value, as shown in Fig. 1, degrading the linearity of an amplifier significantly.

In this letter, it is proposed that this negative g_m'' of the main transistor can indeed be canceled by the positive g_m'' of another auxiliary MOSFET which is biased at smaller gate drive, as shown in Fig. 2(a) and (b), where it has peak positive value of g_m''. In this figure, M_1 is biased at V_{gs}, and M_2 is at $V_{gs} - V_{B1}$, so the transfer characteristic curves for M_2 is shifted to the right by amount of V_{B1}. Once the bias point for M_2 is determined, the amount of compensation for g_m'' value can be chosen by adjusting the width of M_2. Because positive and negative characteristics of g_m'' are not symmetrical, compensated flat region for the gate bias is rather narrow (about 0.2 V) with only one auxiliary MOSFET. This flat region can be extended farther by adding multiple gated MOSFETs with proper bias voltage as well as size, as shown in Fig. 2(c). The IMD_3 characteristics of the topologies in Figs. 2(a)-(c) are compared using a commercial simulator (HPADS), and the simulated results are in Fig. 3. However, adding too many MOSFETs can give worse characteristics due to other effects, such as parasitic capacitance as well as loss increase in the auxiliary transistors. Simulation results using 0.5 μm n-well CMOS technology show that more than two auxiliary MOSFETs degrade the RF gain significantly above 900 MHz.

III. Experimental Results of Prototype Multiple Gated Amplifier

To demonstrate the feasibility of multiple gated transistor amplifier, a prototype RF MOSFET amplifier using only two MOSFETs is implemented and the RF characteristics are measured and compared with those with a single one. In this experiment, W/L of MOSFETs are 6000/0.5 for M_1, and 3000/0.5 for M_2. Measured dc characteristics of M_1 are shown in Fig. 1. The g_m'''s of M_1 and M_2 are shown in Fig. 2(a), and that of the combined M_1 and M_2 is in Fig. 2(b), respectively. V_{th} for both transistors are 0.8 V. In this experiment, V_{B1} is chosen as 0.3 V and V_{dd} is 4 V.

To measure the RF amplifier performance, discrete MOSFET devices are bond wired directly to the PCB, and input and output are power matched at 900 MHz using Focus microwave tuner (model 1808). IMD_3 was measured using two-tone signal.

Both the single-gate amplifier and the double-gated one show same gains of 11.3 dB at gate bias voltages of $V_{gs}(M_1) = 1V$, $V_{gs}(M_2) = 0.7$ V. Current consumption is 90 mA and

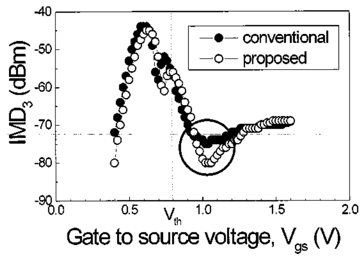


Fig. 4. Comparison of the measured third order intermodulation distortion power between the conventional common source amplifier and the proposed linearized amplifier (input power $= -15$ dBm, $V_{dd} = 4$ V).

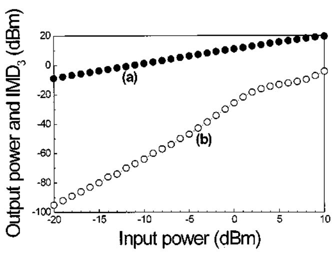


Fig. 5. (a) Fundamental and (b) the third order intermodulation power of proposed linearized amplifier ($V_{gs}(M_1) = 1$ V, $V_{gs}(M_2) = 0.7$ V, $V_{dd} = 4$ V, $I_{dd} = 97$ mA).

TABLE I
RF PERFORMANCE OF THE CONVENTIONAL COMMON SOURCE AMPLIFIER AND THE PROPOSED LINEARIZED AMPLIFIER

	Conventional common source amplifier	Proposed linearized amplifier
V_{dd} (V)	4	4
I_{dd} (mA)	90	97
Gain (dB) @ 900 MHz	11.3	11.3
IMD_3 (dBm) @ P_{out} = -4.7dBm	-74	-80
Output IP_3 (dBm)	30	33

97 mA for the single-gate amplifier and the proposed one, respectively. Note that the current increase due to M_2 is negligible because it is biased below threshold and it is smaller than M_1.

Fig. 4 shows the IMD_3 distortion power as the gate bias voltage varies (input power $= -15$ dBm). As expected, near the region where gate voltage is slightly larger than V_{th}, IMD_3 is reduced significantly. Fig. 4 shows that IMD_3 is reduced by 6 dB at $V_{gs} = 1$ V, and this enhances the third order intermodulation intercept point (IP_3) by 3 dB. The improved region of double-gated amplifier is for gate drive ranges from 0.15 to 0.5 V, which is very desirable bias region for RF amplifier, as we discussed earlier.

Fig. 5 shows fundamental output power and IMD_3 of the proposed topology as input power varies ($V_{gs} = 1$ V). As the input power increases, the IMD_3 deviates from the straight line characteristic because this amplifier is biased at class AB region [6].

Table I summarizes the comparison of performances between the conventional single-gated common source amplifier and the proposed double-gated one, which shows that the linearity improvement is obtained in the proposed double-gated amplifier without appreciable change in other RF characteristics.

For LNA or driver amplifier application, total dc current consumption can be reduced using smaller-size MOSFETs.

IV. CONCLUSIONS

A simple new linearization method for RF MOSFET amplifier using multiple gated transistors is proposed. To demonstrate this feasibility, a prototype double-gated amplifier using two transistors is implemented and its RF performances are compared with those of a single one. At 900 MHz, IMD_3 of our prototype amplifier is suppressed by 6 dB with similar gain, fundamental output power, and dc power consumption, compared with the conventional common source amplifier. With further optimization using multiple gated transistors, much better nonlinear performance per power consumption would be expected.

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REFERENCES

[1] N. Nojima and T. Konno, “Cuber predistortion linearizer for relay equipment in 800 MHz band land mobile telephone system,” *IEEE Trans. Veh. Technol.*, vol. VT-34, no. 4, pp. 169–177, 1985.

[2] H. Seidel, “A microwave feedforward experiments,” *Bell Syst. Tech. J.*, vol. 50, pp. 2879–2916, 1971.

[3] M. Minowa, *et al.*, “Backoff improvement of an 800 MHz GaAs FET amplifier for a QPSK transmitter using adaptive nonlinear distortion canceller,” in *IEEE Veh. Technol. Conf.*, 1990, pp. 542–546.

[4] S. Tanaka, F. Behbahani, and A. A. Abidi, “A linearization technique for CMOS RF power amplifiers,” in *IEEE Symp. VLSI Circuits Dig. Technical Papers*, 1997, pp. 93–94.

[5] Y. Yang and B. Kim, “A new linear amplifier using low-frequency second-order intermodulation component feedforwarding,” *IEEE Microwave Guided Wave Lett.*, vol. 9, no. 10, pp. 419–421, 1999.

[6] N. B. de Carvalho and J. C. Pedro, “Large- and small-signal IMD Behavior of microwave power amplifiers,” *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 2364–2374, Dec. 1999.