LETTER
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A linearized amplifier using self-mixing feedback technique

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Abstract: A linearized amplifier using self-mixing feedback technique is presented to cancel out third-order intermodulation distortion (IMD3) terms. Second harmonic terms, which are generated by the self-mixing mixer between base and collector of a BJT amplifier, can be used as a source for IMD3 cancellation. The amplifier is based on a common emitter BJT amplifier with a passive FET mixer and an emitter follower for self-mixing feedback. The amplifier has been implemented with discrete transistors on an FR-4 PCB. Up to 16-dB IMD3 rejection has been achieved by the self-mixing feedback technique at 2 GHz with peak output power of 20 dBm.

Keywords: amplifiers, linearity, intermodulation, cancellation, feedback, second harmonic
Classification: Microwave and millimeter wave devices, circuits, and systems

References

[1] Cisco White Paper: FLGD 10855 (2013) http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.html
[2] S. C. Cripps: *RF Power Amplifiers for Wireless Communications* (Artech House, Norwood, 2006) 2nd ed. 397.
[3] A. Abuelma'atti, I. Thayne and M. T. Abuelma'atti: Microwaves and RF **49** [9] (2010) 66.
[4] C.-S. Leung and K.-K. M. Cheng: IEEE Microw. Wireless Compon. Lett. **12** [9] (2003) 336.
[5] B. Koo, Y. Na and S. Hong: IEEE Trans. Microw. Theory Tech. **60** [2] (2012) 340.
[6] M. R. Moazam and C. S. Aitchison: IEEE MTT-S IMS Dig. (1996) 827.

1 Introduction

Wireless data traffic is almost doubled every year recently [1]. To send more data at higher speed, modulation technologies have been advanced from analog FM (Frequency Modulation) of AMPS (Advanced Mobile Phone System) to recent OFDM (Orthogonal Frequency Division Multiplexing) of Mobile WiMAX (Worldwide Interoperability for Microwave Access) in mobile applications. The advanced modulation requires high

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PAPR (Peak to Average Power Ratio) and high linearity as the result of high data rate. In the nature of amplifiers, as the output power of the amplifiers goes up, nonlinearity increases. The nonlinearity is shown as the form of third-order intermodulation (IMD3) that is not easily filtered out in RF systems. Allowing more current is the easiest way to improve linearity, however, power consumption also increases and talk time decreases in mobile devices. Quite a number of effective methods have been proposed to improve linearity in RF amplifiers [2]. A feedforward amplifier is a popular architecture to achieve high linearity with at least 20-dB IMD3 rejection in basestation applications. However, it is complex and requires bulky couplers and delay lines, which are not suitable for mobile applications. Digital predistortion is one of the most effective linearity enhancement techniques when an additional digital signal processor is available. Therefore, it is very valuable that linearity improvement is achieved with simple analog circuits which do not include any complex systems or digital signal processing.

This letter presents a self-mixing feedback technique which generates second harmonics and injects them to the input of an amplifier to cancel out IMD3s. An amplifier with the self-mixing feedback technique was implemented with discrete transistors on a PCB.

2 Proposed amplifier with self-mixing feedback

Third-order intermodulation distortion (IMD3) terms are generated by several mixing mechanisms in a two-tone test [3]. Transistors have nonlinearity including second-order distortion, third-order distortion, fourth-order distortion, and so on. Among those distortions, the second-order and the third-order distortions are dominant to contribute IMD3s. Adding difference frequency or second harmonic terms to the input of a nonlinear system results in the generation of new additional IMD3 terms as presented in [4, 5, 6]. If the new IMD3 terms have the same magnitude and the opposite phase of the original IMD3 terms which are generated by original two-tone signals, the overall IMD3 terms can be cancelled out and linearity can be enhanced as shown in Fig. 1. In this letter, the second harmonic frequency terms are generated by a simple passive mixer to perform self-mixing and fed back to the input as shown in Fig. 2. The mixer gets two inputs from the input and the output of the amplifier. The terms of the mixing results are the new second harmonic and difference frequency terms, however, the latter is not used. The magnitude of the new second harmonic frequency terms can be adjusted by the gate voltage of the mixer to control mixer loss. An RC phase shifter provides proper phase shifting to the consequent IMD3s. At the output of the amplifier, the original IMD3s are cancelled out with the new IMD3s.

The linearization can be illustrated using a simple third degree model of an amplifier as follows:

$$v_o = a_1 v_i + a_2 v_i^2 + a_3 v_i^3 \tag{1}$$

where v_o and v_i are output voltage and input voltage, respectively. The coefficients, a_n, represent linear and nonlinear characteristics of the amplifier. Original input signal is assumed as two-tone sinusoid signal as

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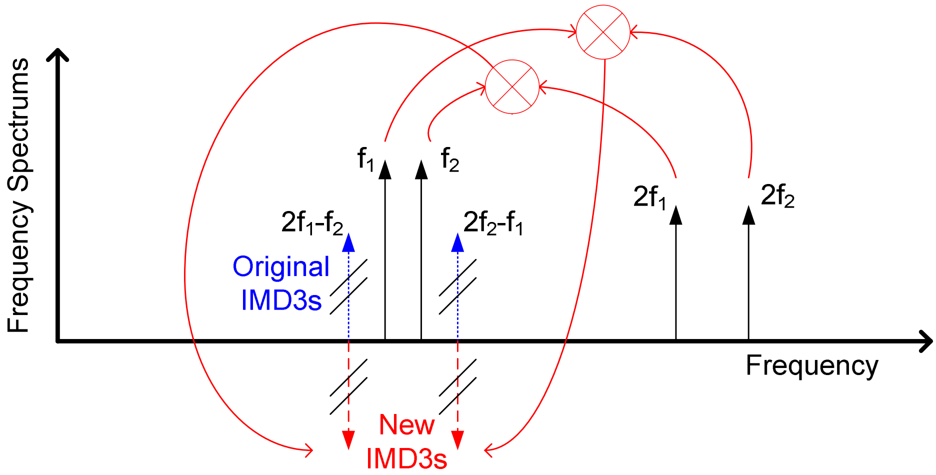

Fig. 1. Frequency spectrums show that the original 3rd order intermodulations are canceled out with the new opposite-phased 3rd order intermodulations generated from 2nd order harmonics.

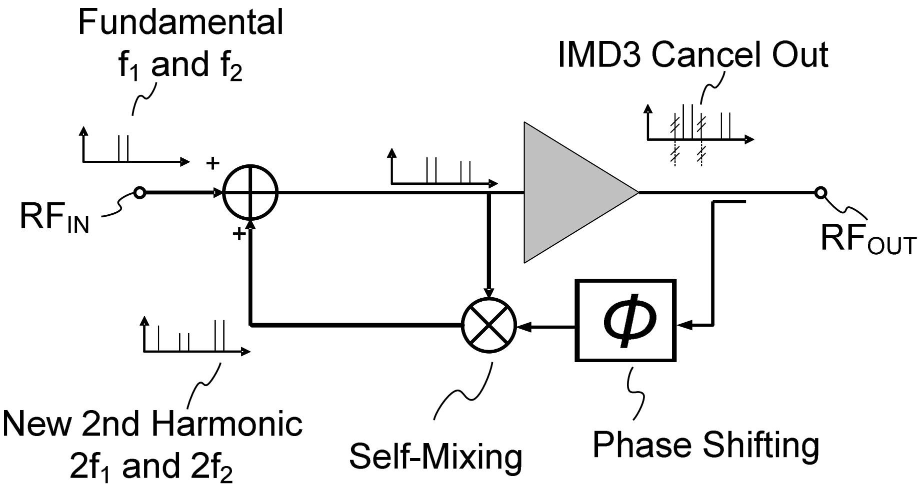

Fig. 2. Blockdiagram of the amplifier with self-mixing feedback technique.

follows:

$$v_{in} = V\cos(\omega_1 t) + V\cos(\omega_2 t). \tag{2}$$

Assuming feedback signal has only second order harmonics, the feedback signal can be given by

$$v_{fb} = bV^2\cos(2\omega_1 t) + bV^2\cos(2\omega_2 t). \tag{3}$$

Then, the output will be presented as

$$v_o = a_1(v_{in} + v_{fb}) + a_2(v_{in} + v_{fb})^2 + a_3(v_{in} + v_{fb})^3. \tag{4}$$

One of the output IMD3 terms will be

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$$v_{o,IMD3} = \frac{3}{4}a_3V^3\cos(2\omega_2-\omega_1)t + a_2bV^3\cos(2\omega_2-\omega_1)t + \frac{3}{2}a_3b^2V^5\cos(2\omega_2-\omega_1)t. \quad (5)$$

The first term comes from the original IMD3 and the second and the third terms are the results of the feedback signal. The third term can be neglected because it is comparably small at back-off region. The first and the second terms can be cancelled out while the following condition is satisfied.

$$b = -\frac{3a_3}{4a_2} \quad (6)$$

3 Design of the amplifier with self-mixing feedback

The amplifier was implemented on an FR-4 PCB with three discrete transistors as shown in Fig. 3. The main amplifier is a common emitter amplifier. A SiGe HBT transistor, NESG2101M05 from Renesas, was used for the main amplifier with 3.6-V supply. A hetero junction FET, Renesas NE4210S01, was used for a passive mixer to perform self-mixing without power consumption. A Si BJT, Avago AT-32033, was adopted as an emitter follower to feedback the second harmonics to the input of the main amplifier. Passive components are 1608 SMT components.

A simple RC network shifts the phase of the fundamental frequency signal before the mixer. The mixer generates second harmonics from fundamental frequency signals from the base and the collector of the main amplifier. The mixer loss can be controlled by the gate bias of the mixer, then, the magnitude of the second harmonics can be tuned by the gate bias. The emitter follower passes the second harmonics and keeps high reverse isolation. Adjusting Vsd and Vg of the mixer bias varies IMD3 shapes and the location of IMD3 sweet spots. The best IMD3 performance can be achieved by tuning the bias voltages of the mixer.

To prove the IMD3 cancellation achieved by the second harmonic from the mixer, the nonlinear contents at the input of the main amplifier has been observed by two-tone simulation. Fig. 4 shows the magnitudes of fundamental (f1), 2^{nd}-harmonic (2f1), IMD3 (2f2-f1), and difference frequency (f2-f1) components at the base of the common emitter amplifier with and without the self-mixing feedback block. The fundamental components are almost the same in both cases; however, the 2^{nd}-harmonic component at the base of the amplifier with the self-mixing feedback block is 4.3 dB higher than that from the amplifier without the feedback block. The difference frequency component is negligibly small and seems not to contribute to IMD3 cancelling because the difference frequency component is shorted to ground through the base bias choke inductor. Furthermore, the IMD3 at the base of the amplifier with the feedback shows 5 to 9 dB higher magnitude than that from the amplifier without the feedback at P_{OUT} of 9 to 17 dBm. The IMD3 may come from the drain of the main amplifier, and the nonlinearity of the mixer and the source follower. But, the linearity enhancement at P_{OUT} of 16 dBm looks independent from the fed-back IMD3 as shown in Fig. 5. Fig. 5 shows IMD3 simulation results of the amplifier with the feedback, the amplifier without the feedback, and the

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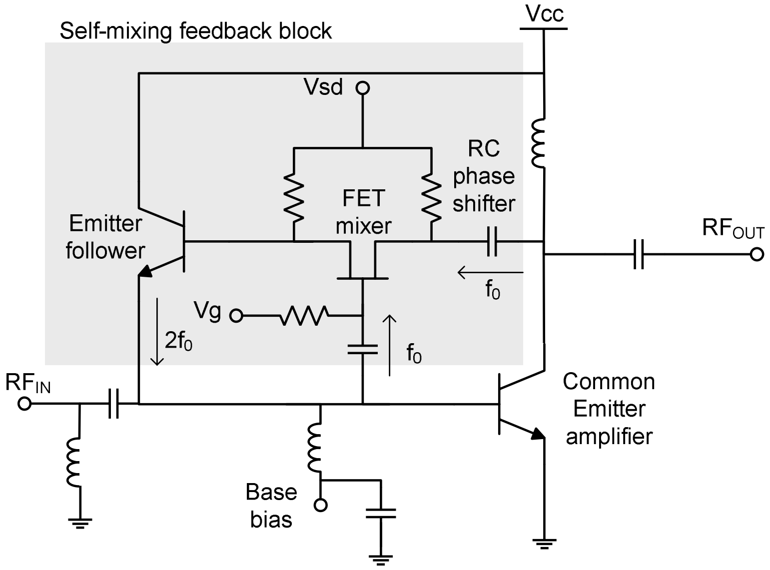
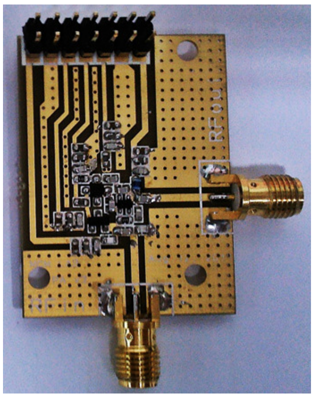


(a)



(b)

Fig. 3. (a) Schematic of the amplifier with self-mixing feedback. (b) Photograph of the amplifier with self-mixing feedback.

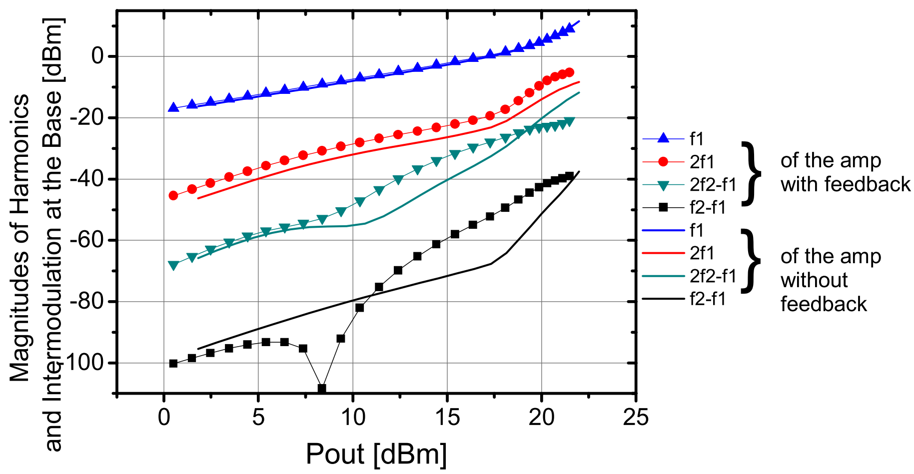


Fig. 4. Simulated magnitudes of fundamental, 2nd harmonic, 3rd-order intermodulation, and difference frequency components at the base of the amplifier with/without feedback.

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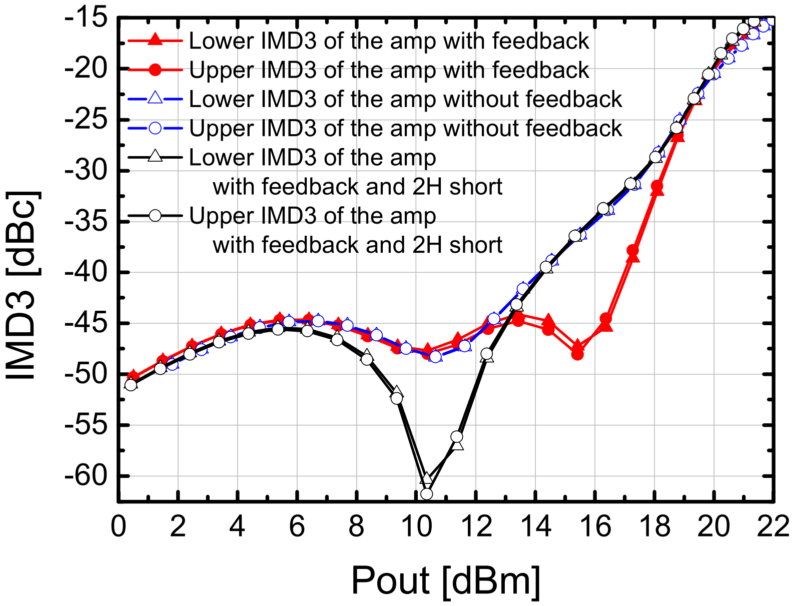

Fig. 5. Third-order intermodulation simulation results of the amplifier with feedback, the amp without feedback, and the amplifier with feedback and 2nd-harmonic short at the base.

amplifier with the feedback and additional 2nd-harmonic short circuit at the base of the main amplifier. The 2nd-harmonic short circuit consists of a 20-nH inductor and a 79-fF capacitor, which are resonated at 4 GHz as a series resonant circuit and suppress 30 dB of the 2nd-harmonic components without changing any other harmonic components. Though the amplifier with the feedback and the 2nd-harmonic short circuit has very low IMD3 at P_{OUT} of 10 dBm, it follows the IMD3 slope of the amplifier without the feedback beyond 14 dBm. Therefore, it can be considered that major IMD3 cancellation at 16 dBm is achieved by the 2nd-harmonic components. Furthermore, the simple 2nd-harmonic short circuit at input can generate IMD3 sweet spot. However, if the 2nd-harmonic component at input is controlled properly, we can put IMD3 suppression where we want.

4 Measurement results

The amplifier with self-mixing feedback was tested and compared with the amplifier without the self-mixing feedback. The amplifiers were measured at 2 GHz while its quiescent current was 10 mA for both cases with 3.6-V supply. Vg and Vsd in the self-mixing feedback are 1.8 V and 1.3 V, respectively. The amplifier with the feedback shows maximum 16-dB IMD3 rejection at 15 dBm of output power in Fig. 6 (a), while two-tone spacing is 1 MHz. The linear output power satisfying IMD3 of −30 dBc increases from 14.2 dBm to 16.5 dBm with the aid of the feedback and the power satisfying IMD3 of −25 dBc increases from 16 dBm to 17 dBm. Fig. 6 (b) shows that gain decreases from 13 dB to 11.6 dB and average PAE decrease is 2% due to the feedback, however, the large linearity improvement results in better PAE at the same IMD3 conditions. Fig. 6 shows 27.8% PAE without the feedback and 30% PAE with the feedback at −25 dBc of IMD3.

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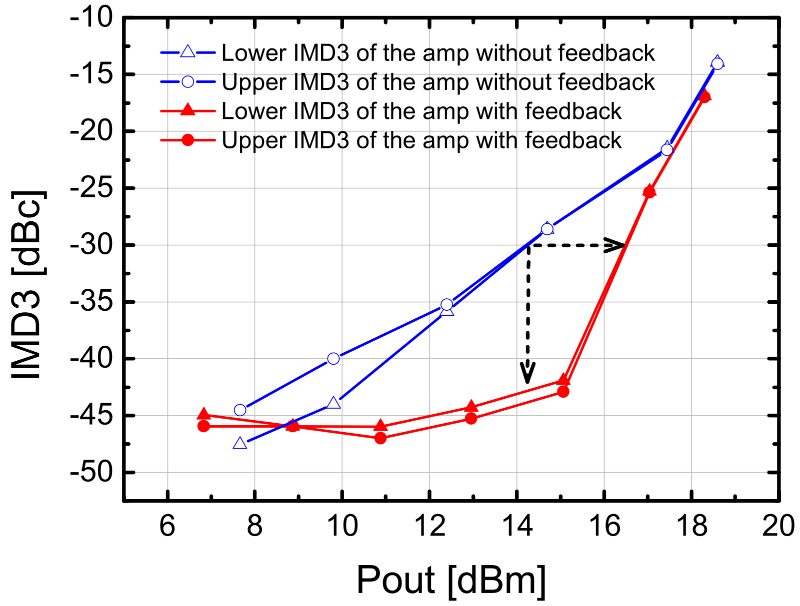
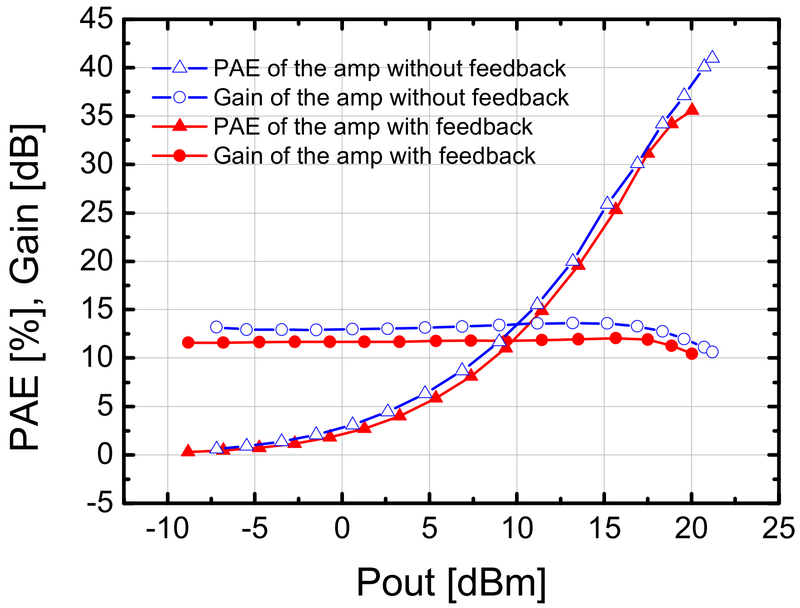


(a)



(b)

Fig. 6. (a) Measured IMD3s versus output power of the amplifier without self-mixing feedback and the amplifier with self-mixing feedback. (b) Measured gain and PAE versus output power of the amplifier without self-mixing feedback and the amplifier with self-mixing feedback.

5 Conclusion

A linearized amplifier using self-mixing feedback technique has been proposed to improve linearity with minimum circuit addition. Properly injected second harmonics to input may generate additional IMD3s with the opposite phase and the same magnitude of the original IMD3s. The self-mixing feedback circuit is composed of a passive FET mixer, an emitter follower, and a phase shift network. The amplifier was implemented on a

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PCB with discrete transistors. The measurement shows maximum 16-dB IMD3 rejection at 2 GHz with peak output power of 20 dBm.

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