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A comprehensive, adjustable approach for linearizing and broadening the gain characteristic of variable gain amplifiers

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ABSTRACT

In this paper a comprehensive approach is presented to linearize and adjust gain characteristic of variable gain amplifiers (VGAs). It is also capable of increasing the output linear dynamic range of VGAs and modifying variation range of control voltage. The approach is able to change the voltage gain characteristic of an amplifier, even after fabrication, to a desired one by means of a digital control signal and a digital to analog converter. Using this approach, the gain of basic differential amplifier is controlled by two different predistorters, and adjustable dB-linear characteristics in range of greater than 60 dB are achieved. The approach, also, is applied to two conventional VGAs, the gain characteristic of first VGA is linearized, and in the second VGA, the linear dynamic range is expanded about 26 dB. The controller uses 1.2 V voltage supply, and simulations are done using 0.13 μm CMOS process model. The other characteristics of each mode of control are reported completely.

1. Introduction

The variable gain amplifier (VGA) is a significant analog block in wireless communication receivers. Applications of this block in Bluetooth, UWB, WLAN, and WSN (Wireless Sensor Network) indicate its substantial role [1–3]. In such wireless links, as a result of channel fading, the amplitude of received signal varies greatly. In conjunction with an automatic gain control (AGC) feedback loop, VGA is implemented to compensate variations and provide fairly constant amplitude for ADC in order that the dynamic range of receiver will be increased [4].

It is desired to a have dB-linear gain characteristic for VGA to achieve a constant settling time for AGC loop [1]. It may be possible to achieve this gain characteristic by using the exponential relation between collector current and base–emitter voltage in BJT or BiCMOS technology [3]. Nevertheless, an all-CMOS integration of digital and analog circuits is easier and more economical. The other solution is a subthreshold-biased MOS device, which has an exponential transconductance versus gate–source voltage [5]. However, it suffers from undesired effects such as poor noise performance and limited bandwidth. The final solution is a parasitic BJT in deep n-well CMOS technology which can imitate the function of an inherent BJT, but imperfect effects of lateral NPN/PNP transistors degrade the gain characteristic [6].

Based on mentioned difficulties, designers commonly use the square or linear characteristics of MOS devices, which inherently are not dB-linear. Several approaches have been proposed to realize a linear-in-decibel gain characteristic. These approaches are divided into two categories: the first approach is predistortion [6–8], and the second is topology modification and the combination of VGA elements characteristics [9–11]. In some cases a combination of both approaches is used [12–14].

In the first category, the transfer function of a predistorter block converts V_C to a secondary voltage or current in such a way that if it is applied to the VGA, a dB-linear gain characteristic will be achieved. In the second category, the circuit topology of VGA is changed and modified to provide the desired gain characteristic. Examples of such categories are a differential amplifier modified by diode-connected loads (G_m-Ratioed amplifier) and Cherry–Hooper amplifier [15] with tunable resistive feedback, which are shown in Fig. 1.

Among described categories, in the former, the application of the proposed predistorter block is limited to the VGA circuit topology, so it is not feasible to use the predistorter as the controller of other VGAs, which have different circuit topologies. In addition, the utilized predistorters dissipate significant amount of DC power that increases the total power consumption of VGA [7,8]. On the other hand, in the latter, the proposed approach is unique for a specific VGA, and cannot be applied to others.

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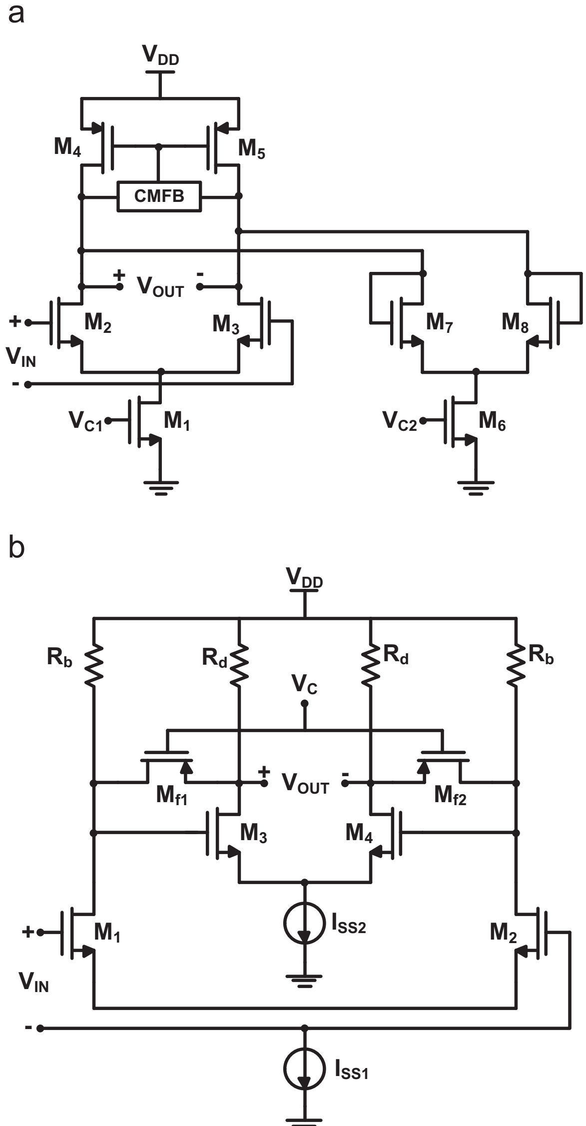

Fig. 1. (a) Modified Cherry–Hooper gain cell and (b) G_m-Ratioed amplifier.

In this paper, a comprehensive approach is proposed to realize a dB-linear VGA. In addition to low power consumption, by some simple modifications, the proposed controller is capable to be applied to other VGAs. Using this approach, the slope of the linear gain characteristic as well as control voltage range can be adjusted arbitrarily even after fabrication to facilitate the AGC loop design. Moreover, this approach has the ability of linearization and linear dynamic-range extension of traditional VGAs.

The remainder of this paper is organized as follows. In Section 2, the gain equations and general forms of fundamental amplifiers are calculated to find the optimum mathematical function for the predistorter based on the circuit of VGA. Section 3 describes advantages of this approach and how the predistorter of the proposed approach can be implemented. In Section 4, simulation results are presented, and Section 5 concludes the paper.

2. Systematic analysis of control scheme

To obtain a general solution for the controller that can convert the VGA to a dB-linear high dynamic range one, the total form of diverse MOS amplifier formulas must be obtained so that it will be possible to devise an exhaustive controller.

2.1. Gain analysis

A variable gain could be realized by changing the transfer function of the transconductor (G_m) or the load resistance by control voltage. Depending on the nodes where this voltage is applied (transconductor, active load, or tail current source), the operation and the characteristics of VGA will be different. According to the intrinsic properties of MOS devices, and regardless of how it operates in the circuit (saturation or triode), the relation between the logarithm of the voltage gain and control voltage will be nonlinear. As shown in Fig. 2, the control voltage can be applied to three different nodes of circuit. The analysis of each control voltage effect on the gain characteristic enables us to have a deep insight into how the circuit operates and how its gain depends on the control voltages, and as a result, a general form for predistorter operation will be obtainable. Moreover, more complex VGAs could be designed by applying a couple of the control voltages as shown in Fig. 2, and there will be several scenarios. It must be noted that active loads (M_4 and M_5) can be replaced by resistive loads occasionally.

In Fig. 2, the input small signal is applied to the gate of transistors M_2 and M_3, and the output is obtained from drains of them. In the simplest scenario, each control signal is applied individually while others are fixed. According to the large signal relation between drain current and gate–source voltage in a MOS device, the amplifier gain can be calculated in terms of V_{Ci} $(i=1{:}3)$. First, when V_{C1} is applied to the gate of the current source of the amplifier, the gain is calculated by (1) and (2). RL and AL suffixes depict whether the load of the amplifier is a resistive load or an active load respectively

$$Av_{1,RL}=\frac{\mu_n C_{ox}}{L}\sqrt{\frac{W_1W_2}{2}}(V_{C1}-V_{TH})R_L \tag{1}$$

$$Av_{1,AL}=\sqrt{2\frac{W_2}{W_1}}\frac{1}{\lambda(V_{C1}-V_{TH})} \tag{2}$$

where W_i, L and V_{TH} are the widths, length and threshold voltage of the MOS devices, $i=1$, 2, and R_L is the resistive load of the amplifier. Second, in the case of applying V_{C2}, (3) and (4) are obtained for the voltage gain of the amplifier

$$Av_{2,RL}=\mu_n C_{ox}\frac{W_2}{L}(V_{GS2}-V_{TH})R_L \tag{3}$$

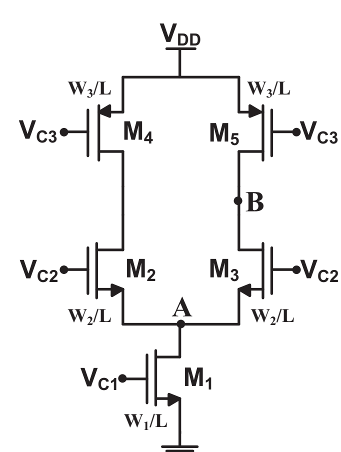

Fig. 2. Differential amplifier with current-source and three nodes which control signals can be applied.