DIGITALLY CONTROLLED BALANCED OUTPUT TRANSCONDUCTOR: CMOS REALIZATION AND APPLICATIONS

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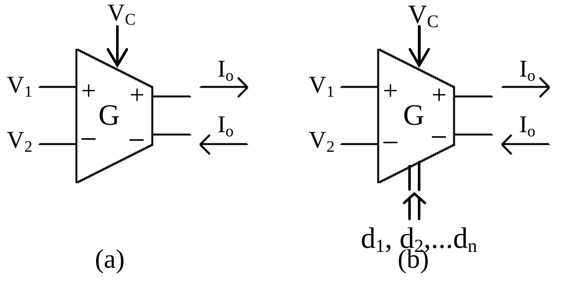
Abstract- A digitally controlled balanced output transconductor (DCBOTA) is proposed and analyzed. The proposed DCBOTA is based on the BOTA given in [1] and MOS switches. The DCBOTA transconductance is tunable in a range of 2^{n-1} times using n bits control word. A wide band digitally controlled variable gain amplifier (DCVGA) and a six order lowpass filter based on the DCBOTA are presented. The proposed filter has the advantage of independent control of gain and cutoff frequency. Simulations results are included to verify the analysis.

I. INTRODUCTION

Programmable characteristic of an analog cell is a key feature that is used in so many useful applications. Temperature and process variations are the main limiting problems in the field of analog VLSI. To compensate for these variations, analog and/or digital tuning of the parameters of an analog cell is employed. However, there is a limitation on the allowable range of the analog tuning voltage. Hence in these applications, digital control is attractive [2]. In this paper, a digitally controlled balanced output transconductor (DCBOTA) is presented. The DCBOTA is based on the BOTA given in [1]. The BOTA is a versatile building block for continuous time analog signal processing. Based on the BOTA, CMOS floating and grounded resistors, balanced output integrators, adders, subtractors, amplifiers, Gm-C active filters, and the active realization of passive filters with minimum number of the BOTAs, and Gm-C oscillators can be built [1, 3-4].



(a) (b)

Fig. 1 The symbol of; (a) The BOTA (b) The DCBOTA

The BOTA, whose symbol is shown in Fig. 1(a) has two voltage inputs and provides two balanced output currents through the two output terminals. The output current is given by:

$$I_o = G(V_c)\,(V_1 - V_2) \tag{1}$$

Where $G(V_C)$ is the transconductance value which is controlled through the analog voltage V_C.

The symbol of the proposed DCBOTA is shown in Fig. 1(b), where the output current is given by:

$$I_o = G(V_C, d_1, d_2, \cdots, d_n)\,(V_1 - V_2) \tag{2}$$

Where $G(V_C, d_1, d_2, \cdots, d_n)$ is the transconductance value which is controlled through the analog voltage V_C and the digital word $d_1\ d_2\ ...\ d_n$.

In this paper, the CMOS realization of DCBOTA is presented in section II. The Simulation results of the proposed DCBOTA using CMOS 0.35μm technology are given in section III. In section IV, a digitally controlled variable gain amplifier (DCVGA) circuit based on the DCBOTA is introduced while in section V, a six order lowpass filter with variable gain and tunable cutoff frequency is presented.

II. CMOS REALIZATION OF THE DCBOTA

The structure of the proposed DCBOTA is based on the BOTA given in [1] and shown in Fig.2.

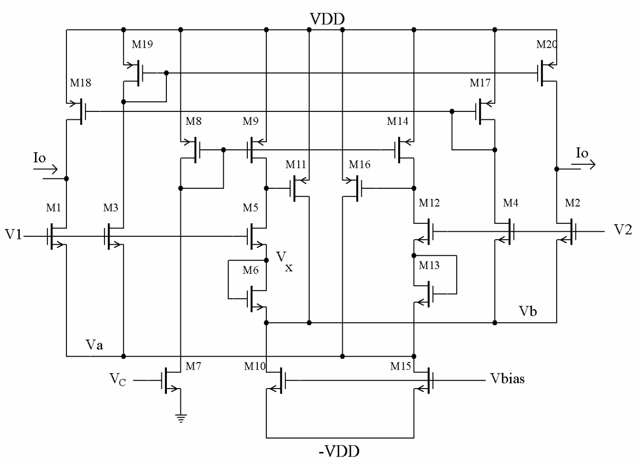


Fig. 2 The CMOS circuit of the BOTA [1].

As shown in Fig. 2, the CMOS realization of the BOTA is based on the current linearization of the basic transistors (M1, M2, M3, M4) by generating a suitable biasing voltages (V_a and V_b) in terms of the input voltages (V_1 and V_2) using the biasing circuit

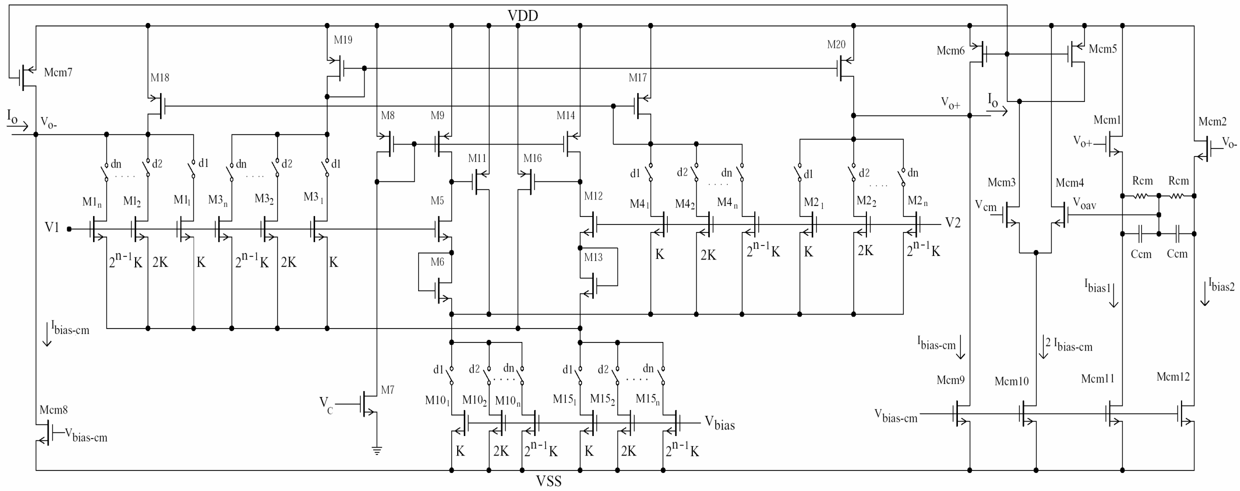


Fig. 3 The CMOS circuit of the DCBOTA with CMFB circuit.

formed from transistors (M5 to M16) to bias the sources of the basic transistors and the current mirror action is performed using transistors (M17 to M20). The output current of the BOTA is given by:

$$I_o = 2KV_C(V_1 - V_2) \tag{3}$$

Where K=$\mu_n C_{ox}(W/L)$ is the transconductance parameter of the basic transistors, μ_n is the electron mobility, C_{ox} is the oxide capacitance per unit area and (W/L) is the aspect ratio. Therefore, the transconductance value is given by:

$$G = 2KV_C \tag{4}$$

Therefore, the transconductance is function of K and V_C .

The basic design idea of the proposed DCBOTA is controlling the transconductance parameter K by replacing the basic transistors with transistor arrays associated with switches as shown in Fig. 3. The transconductance value of the proposed DCBOTA for the case of n-bit digital control word is given by:

$$G = K\,(2^1 *d_1 + 2^2 *d_2 +....+ 2^n *d_n)\,V_C \tag{5}$$

Therefore, the transconductance value can be controlled either by analog voltage V_C or digital word ($d_1, d_2,...,d_n$). As a result the control voltage V_C affects the linearity of the transconductance [1], the design method is based on choosing an optimum value of V_C to obtain a wide linear range and then controlling the transconductance value through the digital word. Also, for proper operation of the biasing circuits the current source formed from M10 and M15 in Fig. 2 is replaced by the digitally controlled current source shown in Fig. 3 to bias the sources of the basic transistors with a suitable biasing current depending on the control word.

To prevent the drift in the output common mode (CM) voltage, the common mode feedback (CMFB) circuit formed from transistors Mcm1 to Mcm12 is used. The CMFB circuit determines the output CM voltage and controls it to a specified value V_{cm} (usually mid-rail) even with the presence of large differential signals. When dual power supplies are used V_{cm} is set to zero Volt. The two resistors (R_{cm}) and two capacitors (C_{cm}) are used to control the CM voltage of the outputs (V_{o+} and V_{o-}). Transistors Mcm1 and Mcm2 are employed to isolate the CMFB circuit from the basic circuit. This is essential to make the input current of the CMFB circuit equal to zero. Therefore the output currents of the DCBOTA are not affected. The CMFB circuit generates the CM voltage of the output signals at node V_{oav} via the two equal resistors (R_{cm}). This voltage is then compared to V_{cm} using differential amplifier Mcm3 and Mcm4 with negative feedback forcing V_{oav} to follow V_{cm}.

III. SIMULATION RESULTS

The performance of the proposed DCBOTA circuit was verified by PSpice simulations with supply voltages of ±2.5V and using 0.35μm CMOS technology parameters. The output current of the DCBOTA versus the input differential voltage $V_{id} = V_1 - V_2$ with $V_C = 1.35$V and different control words is shown in Fig. 4. The magnitude responses of the DCBOTA output current are shown in Fig. 5 with 3-dB frequency 146MHz at 001 control word and 81 MHz at 111 control word. The input referred noise voltage spectral densities for the DCBOTA when terminated by 10KΩ is 80nV/$\sqrt{\text{Hz}}$ at 50MHz and control word 001.

The linearity of the DCBOTA was determined by calculating the third-order inter- modulation (IM3) distortion. Two single tone signals of frequency 49 MHz and 51MHz were applied to the inputs of the DCBOTA. The simulated frequency spectrum of the output is shown in Fig. 6 and the IM3 is around 40dB. The power supply rejection ratio (PSRR) from positive supply is around 124dB and from the negative supply is around 154dB. The current consumption is 330μA at 001 control word and 1.95 mA at 111 control word.

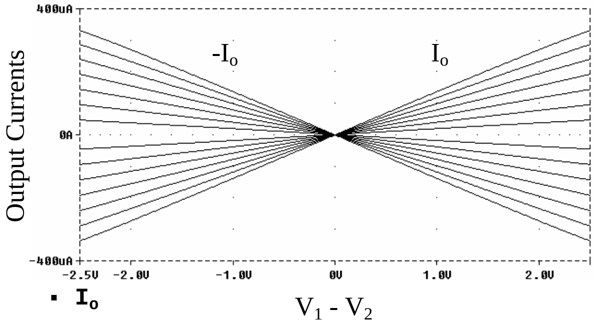


Fig. 4 The DC output currents of the DCBOTA.

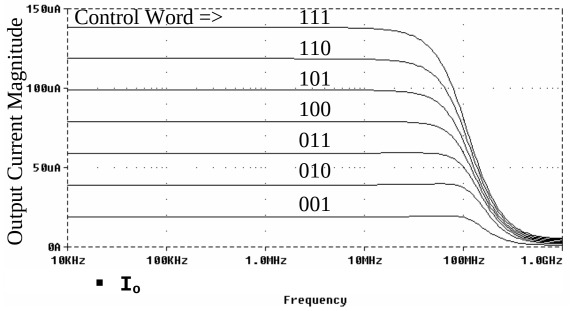


Fig. 5 The magnitude responses of the DCBOTA.

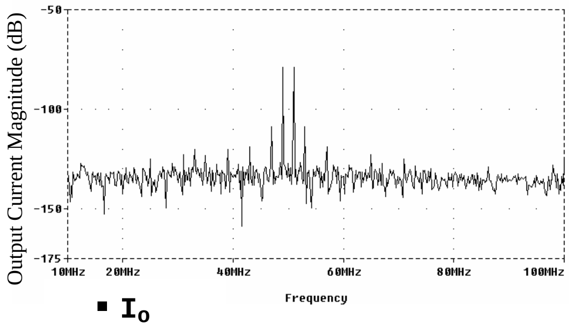


Fig. 6 The simulated IM3 frequency spectrum of the DCBOTA output current with control word 111**.**

IV. DIGITALLY CONTROLLED VARIABLE GAIN AMPLIFIER (DCVGA)

The DCVGA based on the DCBOTA is shown in Fig.7. The DCVGA consists of two DCBOTA and one fully differential Buffer [5]. The voltage transfer characteristic given by:

$$\frac{V_o}{V_i}=\frac{G_1}{G_2}=\frac{V_{C1}(a_1*2^1+a_2*2^2+.............a_n*2^n)}{V_{C2}(b_1*2^1+b_2*2^2+............b_n*2^n)} \quad (6)$$

The VGA gain is programmed by changing the control words ($a_1, a_2, ..., a_n$) and ($b_1, b_2, ..., b_n$).

Fig.8 shows the simulated dc transfer characteristics of the DCVGA. Clearly, the circuit exhibits high linearity for all possible gain settings. The linearity of the DCVGA was determined by calculating the IM3. Two single tones of frequencies 9MHz and 11MHz were applied to the inputs of the DCVGA.

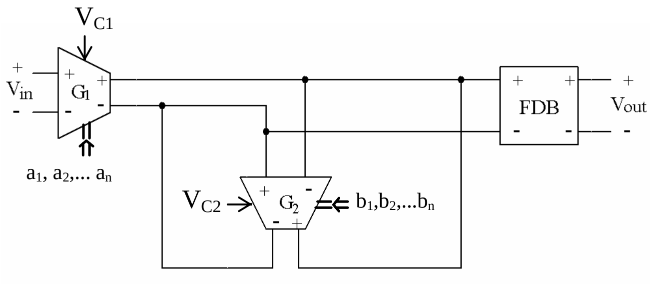


Fig. 7 The DCVGA circuit

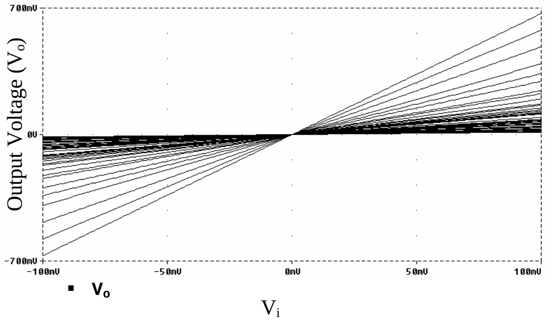


Fig. 8 The simulated DC transfer characteristics of the DCVGA.

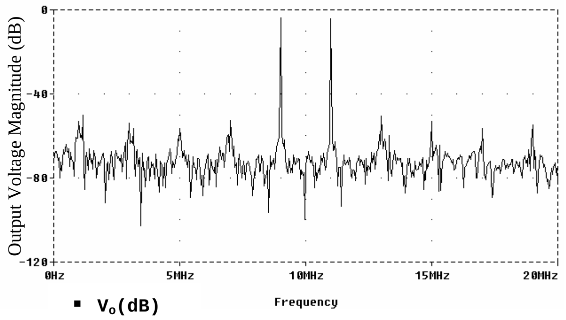


Fig. 9 The simulated IM3 frequency spectrum of the DCVGA output.

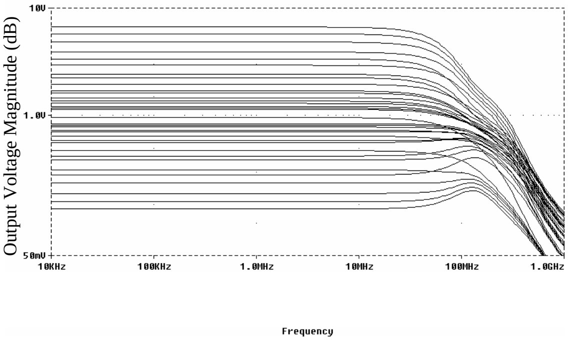


Fig. 10 The simulated frequency responses of the DCVGA.

The frequency spectrum of the output is shown in Fig. 9. The IM3 is around 50dB at the maximum gain setting. The maximum gain is 17dB, the minimum gain is -17dB, and the maximum current consumption is 1.55mA at the maximum gain setting. Fig. 10 shows the simulated frequency responses of the DCVGA. It can be seen that the DCVGA based on the ratio between two digitally controlled transconductanes features high bandwidth.

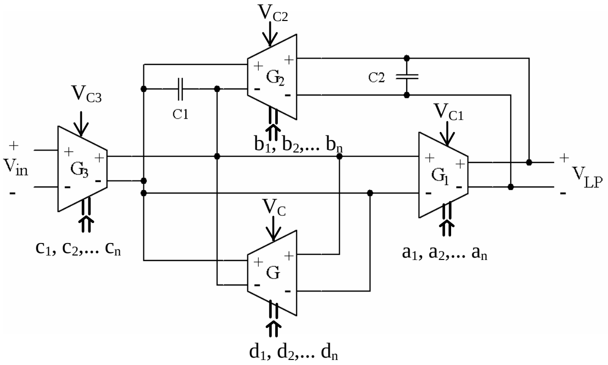


Fig. 11 Second order fully differential lowpass filter.

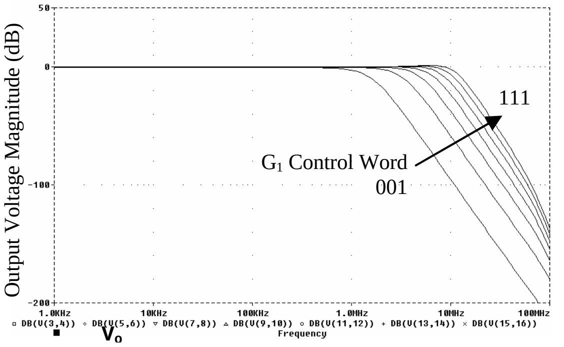


Fig. 12 The frequency response of the sixth order filter with tuned cutoff frequency from 1Mhz to 7MHz.

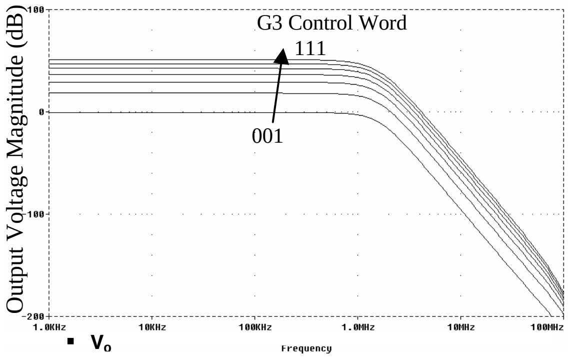


Fig. 13 The frequency response of the sixth order filter for different values of the DC gain.

V. DCBOTA- BASED LOWPASS FILTER

Fig. 11 represents a second order fully differential lowpass filter based on the DCBOTA. The circuit includes four DCBOTAs and two capacitors. By direct analysis, the following transfer function is obtained:

$$\frac{V_o}{V_i} = \frac{\frac{G_1 G_3}{C_1 C_2}}{S^2 + S\frac{G}{C_1} + \frac{G_1 G_2}{C_1 C_2}} \tag{7}$$

From the above equation, the center frequency ω_o, quality factor Q and the DC gain H of the filter are given by:

$$\omega_o = \sqrt{\frac{G_1 G_2}{C_1 C_2}} \tag{8}$$

$$Q = \frac{1}{G}\sqrt{\frac{G_1 G_2 C_1}{C2}} \tag{9}$$

$$H = \frac{G_3}{G_2} \tag{10}$$

From the above equations the filter shown in Fig.11 has the following advantage, the gain of this filter H can be programmed without disturbing ω_o and Q via G_3**.** Therefore this circuit can be viewed as a lowpass filter with an embedded VGA. The merged filtering and controlled gain result in improving the overall dynamic range, and reduces the required number of amplifier stages of a system.

The simulated frequency spectrum of a sixth order maximally flat lowpass filter consisting from three cascaded sections of the filter shown in Fig. 11 with $G_1=G_2=G_3=G$, and $C_2=2C_1$ is shown in Fig. 12. The cutoff frequency in tuned from 1 MHz to 7 MHz. The frequency response of the sixth order filter for different values of DC gain from 0dB to 51dB obtained by programming G_3 is shown in Fig. 13.

VI. CONCLUSION

A high frequency digitally controlled balanced output transconductor (DCBOTA) has been analyzed and simulated. The transconductance of the proposed DCBOTA is tunable in a range of 2^{n-1} times using n bits control word. The analog control voltage can be then used to provide fine-tuning of the transconductance gain. Simulations results showed that the DCBOTA has a transconductance tuning range from 20µA/V to 140µA/V using 3 bits control word and a 3-dB bandwidth larger than 80MHz. A DCVGA with a gain controllable in the range from -17dB to 17dB has been presented. Also, a sixth order lowpass filter with variable gain from 0dB to 51dB and tunable center frequency from 1 MHz to 7 MHz has been introduced.

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