A New Low Voltage Operational Transresistance Amplifier and Its Applications in Analog Circuit Design

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Abstract

In this paper, a low voltage Operational Transresistance Amplifier with class-AB output stage is proposed. The usefulness of the amplifier is illustrated by providing its applications in variable gain amplifier, biquad and oscillator design. The circuits are suitable for low voltage operation and operate with a single 0.5 V power supply. In order to show the usefulness of the proposed circuits, detailed simulation results with Spectre in Cadence Design environment are obtained.

1. Introduction

Operational Transresistance Amplifiers (OTRAs) play a vital role in many applications, such as electro optical receiver front ends, acoustic receivers [1, 2]. The OTRA is often used as current-to-voltage converter (*I-V*) and it is highly demanding active device as a result of high data rate communications required in today's optical communication system. OTRA is one of the most critical building block at electro optical interface on the receiver side, which determines the performance of the whole system on a large scale.

Although recently some open-loop OTRAs are proposed to accommodate requirements of high-speed operation, most conventional approach to realize OTRA is based on closed-loop configuration, in order to avoid issues related to the nonlinearity. Following up to this discussion, we propose a OTRA which operates in closed-loop, which provides a large open-loop transresistance.

On the other hand, variable gain amplifiers (VGAs) are the key sub-blocks used in the implementation of automatic gain control (AGC) feedback loops, which are widely used in hearing aids, imaging and wireless communication systems. In these applications, the transmission signal power can be controlled and the received signal amplitude can be adjusted by the VGA [3]. One another application area of the VGAs is disk drivers. In the disk driver systems, VGA normalizes the read channel average amplitude of the read pulses to a reference value before they are sent to the peak detector [4, 5]. As an extended summary of applications, variable gain amplifiers can be widely used in WCDMA systems [6-8], audio/video analog signal processing circuits [7], portable communication drivers [8], hard disk drivers [4, 5, 9-12], medical equipments [12, 13], digital cable TV, satellite television [14], wireless LAN [15], broadband residential communications [14], radio communicated system [16]. VGAs, as well as other circuits, are required to operate with low power supply voltage and low power consumption.

Indeed, class-AB has become very significant alternative for any application requiring VGA over the last few years [17, 18]. It is very challenging to design a VGA with high linearity and wide bandwidth with low supply voltage and low power consumption. For this purpose, a VGA employing improved class-AB OTRA is proposed.

The paper is organized briefly as follows: In section II, the proposed class-AB OTRA and its main characteristics are given. Architecture of the proposed VGA stage is provided in Section III and the second-order filter realization using OTRA is studied in Section IV. As a final example to illustrate the usefulness of the OTRA, a sinusoidal oscillator is provided in Section V. Furthermore, the simulation results were performed using Spectre simulator in Cadence design environment in order to prove the proper operations of proposed circuits.

2. Proposed Class-AB Operational Transresistance Amplifier

The proposed OTRA is shown in Fig. 1. The circuit consists of a current-differencing block followed by an output stage. Transistor dimensions are given in Table I and biasing current and voltage values are chosen as $I_0 = 10\ \mu\text{A}$ and $V_b = 0.8$ V, respectively. The transistors at the input terminals, i.e. M_{1n}, M_{2n} for the inverting and M_{1p} and M_{2p} form the non-inverting terminals, realize local negative feedbacks in order to reduce the value of the input impedances. In these configuration, the input impedances can be kept as low as a couple of hundred ohms.

An important advantage of the OTRA is the use of class-AB output stage. Output current sinking capability of the OTRA is substantially improved owing to the use of the additional feedback, consisting of M_7, $M_{8a,b}$ and $M_{9a,b}$, which adaptively biases gate-source voltage of M_7. Thank to this feature, output buffer operates in class-AB.

In all simulations, the current sources in Fig.1 are realized using simple current mirrors. We have first studied the frequency dependency of the OTRA's transresistance. The results are shown in Fig. 2. This characteristic can be approximated by a single-pole model:

$$Z_{tr} = \frac{R_0}{1 + s/\omega_0}, \qquad (1)$$

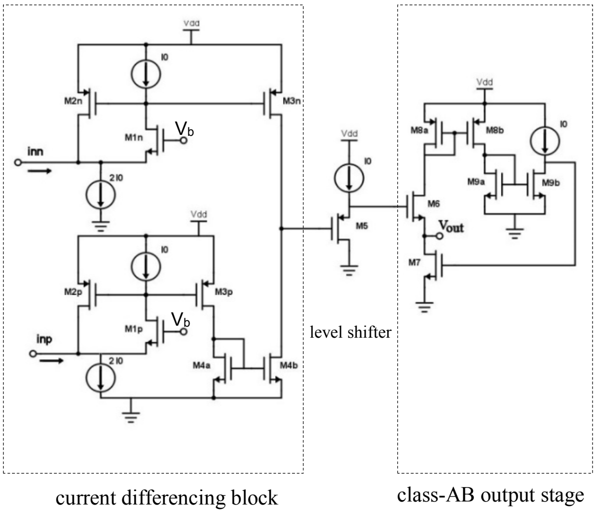

Fig. 1. Proposed class-AB OTRA

where DC operational transresistance is $R_0 = 150$ kΩ and −3 dB bandwidth f_0 is 1.2 MHz.

Table 1. Dimensions of MOS transistors

$M_{1n,p}$	15 μm/0.5 μm
$M_{2n,p}$	10 μm/0.5 μm
$M_{3n,p}$	10 μm/0.5 μm
$M_{4a,b}$	10 μm/0.5 μm
M_5	15 μm/0.5 μm
M_6	10 μm/0.5 μm
M_7	20 μm/1 μm
$M_{8a,b}$	10 μm/0.5 μm
$M_{9a,b}$	10 μm/0.5 μm

Then, we have simulated input impedances of the presented OTRA. Since input stages of both inputs are of the same configuration, input impedances are equal. Therefore, we have obtained only impedance of the non-inverting input stage as in Fig. 3. From these results, it is seen that OTRA provides very low input resistances at its input terminals, around 150 Ω, thanks to the local negative feedback realized by transistors $M_{1n,p}$ and $M_{2n,p}$ in Fig. 1. Note from Fig. 3 the inductive feature of the input impedance, which stems from the pole involving with this local feedback.

3. Class-AB VGA realization using OTRA

Figure 4 shows the VGA architecture, which is composed of a transconductance stage and a OTRA with a shunt-feedback resistor R connected in cascade. The transconductance gain (g_m) and the transresistance gain (R_0) are used to adjust the voltage gain of the VGA circuit.

The transfer function of the circuit gain is given by:

$$\frac{V_{out}}{V_{in}^{+} - V_{in}^{-}} = \frac{R_0 g_m}{(1+R_0/R)} \frac{1}{\left(1+\frac{s}{\omega_0(1+R_0/R)}\right)}, \qquad (2)$$

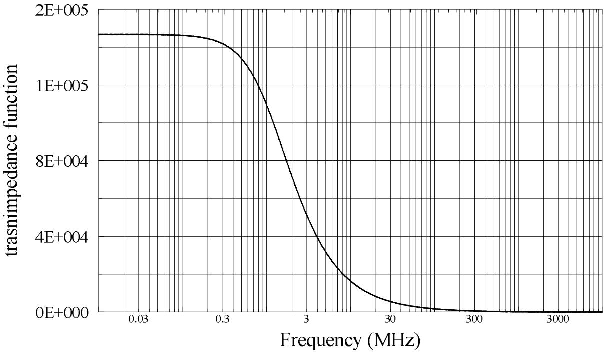

Fig. 2. Frequency dependency of the OTRA's transresistance

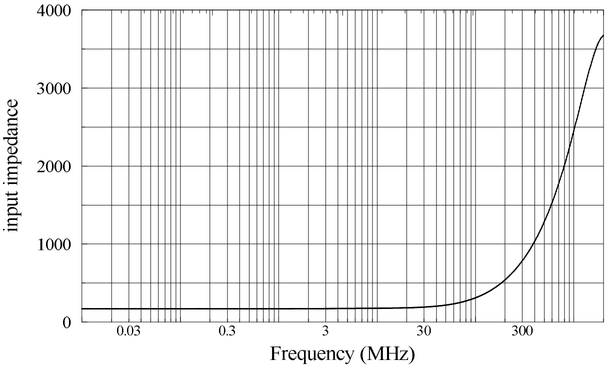

Fig. 3. Input impedance of the OTRA (non-inverting terminal)

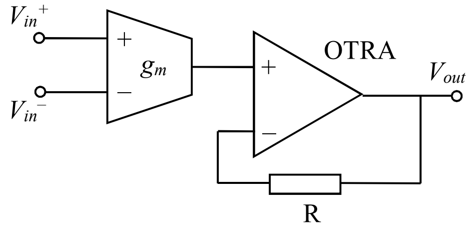

Fig. 4. Architecture of the VGA stage

which shows that the gain at low frequencies, $R_0 g_m$, can be electronically adjusted with OTA transconductance, while the bandwidth of the amplifier is constant. Therefore, the circuit is free from constant gain-bandwidth limitation.

The CMOS realization of the OTA is depicted in Fig. 5. The dimensions of the MOS transistors are shown in Table. 2 and the circuit is biased with 0.5 V DC power supply.

Fig. 6 shows gain response of VGA, which was obtained by setting the biasing current (I_0) from 2 μA to 10μA so that g_m is changed from 100 μS to 1 mS with a step size of 200 μS. It can be seen that voltage gain control with constant bandwidth can be achieved by varying OTA's biasing current I_0.

Table 2. Dimensions of MOS transistors

$M_{1,2}$	15 μm/0.5 μm
$M_{3,4}$	10 μm/0.5 μm
$M_{5,6}$	10 μm/0.5 μm
$M_{7,8}$	30 μm/0.5 μm

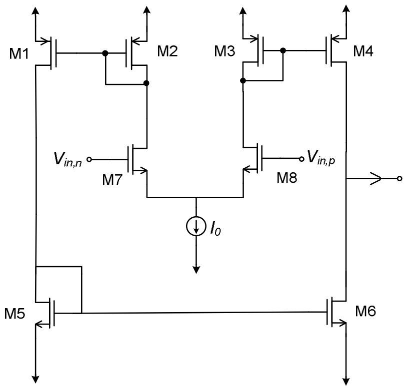

Fig. 5. CMOS OTA block used in the VGA

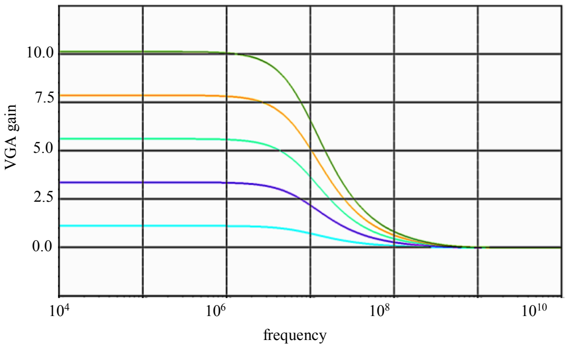

Fig. 6. The variation of VGA gain with OTA's transconductance (g_m)

4. Second-order filter realization using OTRA

When the proposed OTRA is employed in the filter design shown in Fig. 7, the obtained circuit realizes the second-order band-pass filter function. After routine analysis the transfer function (TF) of the filter is obtained as follows:

$$\frac{V_{out}}{V_{in}} = -\frac{Y_1 Y_2 R_0\, \omega_{01}}{(Y_1+Y_2+Y_3)(s+\omega_0)+Y_1 Y_3 R_0 \omega_0}, \tag{3}$$

Assuming the following selection of passive elements $Y_1 = G_1$, $Y_2 = sC_2$, $Y_3 = G_3$, (3) turns to:

$$\frac{V_{out}}{V_{in}} = -\frac{sG_1 R_0\, \omega_0}{s^2 + s(\omega_0 + \omega_{RC}(1+K)) + \omega_0 \omega_{RC}(1+K+\frac{R_0}{R_3})}, \tag{4}$$

which indicates a TF of second-order band-pass filter, where $K = R_1/R_3$, $\omega_{RC} = 1/R_1C_2$.

To verify the theoretical study, the biquad in Fig. 7 was simulated using Spectre simulation tool in Cadence design environment using the parameters of a standard CMOS 0.35 µm p-well process. The filter is biased with 0.5 V DC power supply and all the current sources shown in Fig. 1 were realized using simple CMOS current mirrors. The filter is designed to realize a band-pass filter with a center frequency of 33 MHz and Q of 1.2 by choosing $R_1 = R_3 = 2.5$ kΩ, $C_2 = 4$ pF. Simulated band-pass output of the filter shown in Fig. 8 verifies theoretical expression.

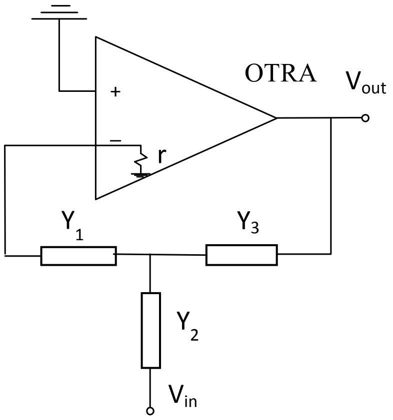

Fig. 7. Band-pass filter circuit with the proposed OTRA

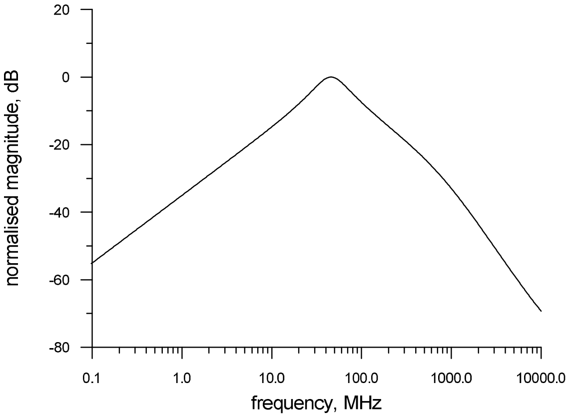

Fig. 8. Simulation results of the bandpass filter in Fig. 7

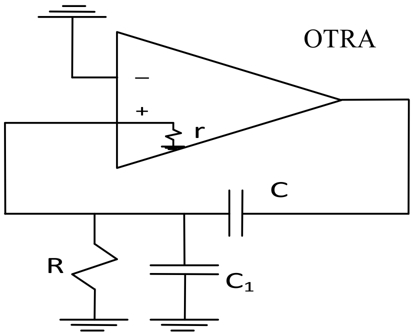

Fig. 9. Proposed OTRA-based sinusoidal oscillator

5. Proposed Sinusoidal Oscillator using the Operational Transresistance Amplifier

By employing the proposed OTRA in oscillator design, it is obtained the sinusoidal-oscillator circuit shown in Fig. 9. Characteristic equation of the oscillator is given by:

$$D(s) = s^2 + s\omega_0(1+\omega_{RC}/\omega_0 - KM) + \omega_0\omega_{RC}, \tag{5}$$

where $\omega_{RC} = (G + 1/r)/(C_1 + C)$, $M = 1/(1 + C_1/C)$, $K = R_0/r$ and ω_0 is the −3 dB pole of the OTRA. Note that the parameter r is the resistance seen at the non-inverting input terminal of OTRA, as shown in Fig. 9.

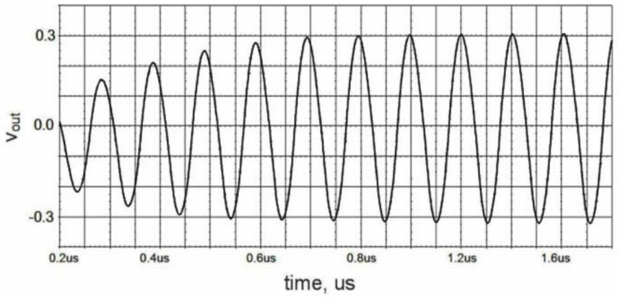

Fig. 10. Simulation results of the sinusoidal oscillator in Fig. 9

Frequency and condition of oscillation are obtained as:

$$\begin{aligned} &\text{FO}: \quad \omega_0 = \sqrt{\omega_0 \omega_{RC}}, \\ &\text{CO}: \quad M = \frac{(1+\omega_{RC}/\omega_0)}{K}. \end{aligned} \tag{6}$$

Simulation results for $C_1 = 7$ pF, $C = 1$ pF, $R = 5$ kΩ are given in Fig. 10. Oscillation frequency is found to be 10.5 MHz, which is close to the theoretical value 13.2 MHz.

6. Conclusions

A new design of a low voltage class-AB Operational Transresistance amplifier (OTRA) implemented from a three stage architecture is proposed. Additionally, a new variable gain amplifier, a band-pass filter, and an oscillator circuit by employing the proposed OTRA are obtained. The proposed circuits are simulated in Cadence design environment to verify their proper operations. According to the simulation results, it has been shown that the circuit is suitable for wide bandwidth operation. The results also verify that, the voltage gain of the VGA can be tuned while the bandwidth remains constant.

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8. References

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