DESIGN OF A PROGRAMMABLE OTA WITH MULTI–DECADE TRANSCONDUCTANCE ADJUSTMENT

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Abstract A programmable operational transconductance amplifier (OTA) structure is presented which permits a g_m adjustment by greater than two decades without severe degradation in linearity. This is achieved by including a programmable current mirror structure in the OTA output stage for coarse g_m adjustment in addition to a fine g_m adjustment via control of a bias current in the OTA differential input stage. Experimental results indicate that less than 1% nonlinearity in the transconductance characteristic is achieved throughout the g_m adjustment range for input signals less than $1V_{p-p}$.

I. Introduction

In both discrete and monolithic applications of MOS operational transconductance amplifiers (OTAs), it is often assumed that the transconductance (g_m) of the OTA is programmable over a wide range by either a dc current or voltage [1–3]. This allows precise values of g_m to be obtained in spite of IC process variations, transistor mismatch effects, etc., as well as allowing OTA–based circuits with wide adjustment ranges, such as OTA–C filters with wide frequency and bandwidth adjustment ranges.

Unfortunately, the linearity and, correspondingly, the input signal swing of most existing MOS OTA structures degrades significantly with the dc programming variable. This degradation is generally attributable to the inherent relationship between dc bias current and transconductance gain in the source–coupled differential pair which often serves as the input stage to the OTA [3, 4]. Although much effort has been devoted to improving the linearity of the input stage [5], in many OTA structures it remains the input stage which limits the overall linearity of the device. It follows that the input stage also limits the g_m adjustment range in many cases.

In the design to be presented, the limitation in the g_m adjustment range due to linearity degradation in the input stage is largely overcome by including an adjustable current mirror structure in the OTA output stage. This results in two types of g_m adjustment: a fine adjustment corresponding to adjustment of the bias current in a differential pair; and a coarse adjustment corresponding to the changing of the gain of a current mirror. The fine adjustment range is intentionally restricted to minimize the linearity degradation inherent with g_m adjustment in the differential pair. Minimal linearity degradation is associated with the coarse g_m adjustment.

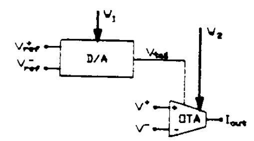

Fig. 1: Basic architecture of programmable OTA

The basic architecture of the programmable OTA is illustrated in Fig. 1. Digital control word W_1 corresponds to the fine adjustment of the OTA while digital control word W_2 corresponds to the coarse adjustment.

The design which will be described is such that g_m is programmable in uniform increments on a logarithmic [6,7] rather than a linear axis. The logarithmic spacing is particularly attractive for circuits which operate over a wide adjustment range. Logarithmic fine adjustment is readily obtainable by using a nonlinear DAC to establish the bias current for the OTA input stage. A unique current mirror sizing strategy in the output stage is used to obtain the logarithmic coarse adjustment in an area efficient manner.

II. Input Stage Linearity and Limitations on g_m Adjustment Range

A common OTA structure consisting of a differential input stage and three current mirrors is shown in the block diagram of Fig. 2. Assuming that the current mirror gains are set such that $M_1 = M_2M_3 = A_M$, the transfer characteristic of the OTA is ideally given by

$$I_o = g_{md}A_MV_d \quad (1)$$

where g_{md} is the transconductance gain of the differential input stage, defined in (3) below.

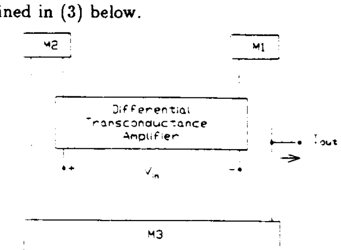

Fig. 2: Block diagram of 3-current-mirror OTA

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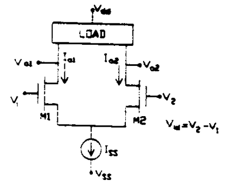

Fig. 3: Source coupled differential amplifier

In MOS implementations, the differential transconductance stage is often based upon the source coupled pair shown in Fig. 3. Using the standard square–law saturation region model for the transistors and assuming λ effects are negligible, one obtains the following transconductance characteristic for this stage:

$$\frac{I_{o2}-I_{o1}}{V_{id}} = -\sqrt{\frac{2K'WI_{SS}}{L}}\sqrt{1-V_{id}^2\left(\frac{K'W}{2LI_{SS}}\right)} \quad (2)$$

For small V_{id}, this reduces to

$$g_{md} = \frac{I_{o2}-I_{o1}}{V_{id}} = -\sqrt{\frac{2K'WI_{SS}}{L}} \quad (3)$$

It is seen from (3) that a two–decade change in tail current is required for a single–decade change in g_{md}. Unfortunately, the linearity of the source coupled pair is strongly a function of the tail current. It follows from (2) that for a given fractional deviation, x, from linear the maximum differential input voltage is

$$V_{id_{MAX}} = \sqrt{\frac{2I_{SS}L}{K'W}}\sqrt{x(2-x)} \quad (4)$$

A two–decade decrease in tail current thus corresponds to a decade degradation in signal swing.

The impact of the linearity degradation inherent with tail current adjustment of g_m is apparent from (3) and (4). If a given nonlinearity is to be maintained, then the g_m adjustment range is restricted by the amount of input signal swing degradation which can be tolerated. For example, a g_m adjustment by a factor of 2 is possible if the corresponding 6 dB change in signal handling capability is acceptable.

III. Output Stage Programmable Mirror Structure

The fact that nonlinearity considerations place severe restrictions on the adjustment range of the differential input stage provides the incentive for including a programmable current mirror structure in the OTA output stage in cases where a large g_m adjustment range is desired. In general, for the basic 3–mirror OTA structure, the nonlinearity due to the current mirror stages is much less than that due to the differential input stage; hence, a large g_m adjustment range is possible in the programmable current mirror stage without severe degradation in the overall linearity of the OTA.

The programmable feature of the OTA creates the desire for efficient assignment of digital states to g_m values. Where the goal is to maximize the g_m adjustment range for a given number of digital states and a given resolution, it is advantageous to assign g_m values to uniformly spaced points on a logarithmic rather than linear scale.

Consider a parallel combination of N current mirrors as shown in Fig. 4. The N mirrors share a common input and output, and can be individually enabled or disabled by the digital inputs D_0 through D_{N-1}, controlling the smallest through the largest mirrors, respectively. Let a_i be the gain of the ith individual mirror, and let A_j be the overall gain of the structure corresponding to the jth state of the control word $D_{N-1}D_{N-2}...D_0$. A_j is then given by the sum of the gains of all enabled individual mirrors, i.e.,

$$A_j = \sum_{i=0}^{N-1} d_{j,i}a_i \qquad \begin{matrix} d_{j,i}\epsilon\{0,1\} \\ j=0,1,...,2^N-1 \end{matrix} \quad (5)$$

where $d_{j,i}$ assumes the value of the enable input to the ith individual mirror during the jth state. The overall gain $A_0 = 0$, corresponding to the state in which all individual mirrors are disabled, is of little concern in the following discussion.

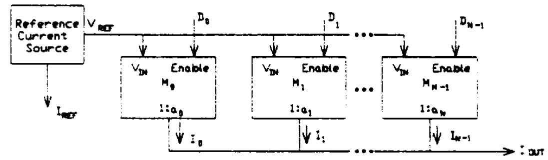

Fig. 4: Block diagram of programmable-gain current mirror structure

A given resolution in the overall gain,

$$r_A = \max_j\left[\frac{A_{j+1}-A_j}{A_j}\right] \qquad j=1,2,...,2^N-2 \quad (6)$$

may be simply obtained by choosing individual mirror gains a_i such that

$$a_{i+1} = (1+r_A)a_i \quad (7)$$

This results in N of the possible 2^N values of A_j being uniformly spaced on a logarithmic scale, corresponding to the N states in which only one of the individual mirrors is enabled. Considering only these N values, it follows that the overall gain can be adjusted by a factor of

$$\frac{A_{2^{(N-1)}}}{A_1} = (1+r_A)^{N-1} \quad (8)$$

Including the 2^N-N values of A_j which are not uniform logarithmically–spaced, the overall adjustment range is bounded by

$$(1+r_A)^{N-1} < \frac{A_{2^N-1}}{A_1} < (1+r_A)^N \quad (9)$$

For a given number, N, of individual mirrors, considerable improvement in the adjustment range can be obtained if the designer is free to choose the resolution r_A. The improvement is a result of a more efficient assignment of digital states to overall gains of the structure for certain values of r_A; this assignment will now be described.

Assume the gain of the first mirror in Fig. 4 is $a_0 = \theta$, and the gain of the second mirror is $a_1 = \theta x$. If only these mirrors are enabled, the resulting overall gain is

$$A_3 = \theta(1+x) \quad (10)$$

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If x is chosen to be a solution of the equation

$$x^2 = x + 1 \tag{11}$$

then the *two* mirrors provide *three* uniform logarithmically-spaced overall gain values, i.e., θ,θx, and θx^2. Successive individual mirror gains may be chosen as θx^3, θx^5, θx^7, etc., while the overall gains θx^4, θx^6, θx^8, etc., may be synthesized according to the equation

$$\theta x^j = \theta x^{j-1} + \theta x^{j-2} \qquad j = 2, 4, 6, ..., N \tag{12}$$

A solution of (11) is $x = 1.618$; hence, this method may be applied if the corresponding resolution of $r_A = 0.618$ is acceptable. In general, with this choice of r_A, the scheme outlined above can be used to obtain $2N - 1$ uniform logarithmically-spaced overall gains using N individual mirror stages. The corresponding adjustment range is

$$\frac{A_{2^N-1}}{A_1} = (1 + r_A)^{2N-2} \tag{13}$$

which can be a considerable improvement over the case described by (9).

A few additional comments are in order. Most importantly, since it is desired that the overall resolution of the OTA be determined by the adjustment of the differential input stage transconductance rather than the adjustment of the output mirror gain, the fine adjustment must allow an adjustment of g_{md} by a factor greater than $1 + r_A$. This will ensure that there are no undesirable gaps in the obtainable values of the overall g_m. Recalling the limitations on the g_{md} adjustment range due to nonlinearity considerations, it is clear that the choice of r_A is also limited by these same considerations, i.e., r_A must be chosen such that

$$\frac{g_{md_{MAX}}}{g_{md_{MIN}}} > 1 + r_A \tag{14}$$

The method described for obtaining $2N-1$ uniform logarithmically spaced overall gains is not strictly limited to the case where $r_A = 0.618$. For example, a resolution $r_A = 0.466$ results when the individual mirrors in Fig. 4 are designed to realize gains of θ, θx^1, θx^2, θx^5, θx^6, θx^9, θx^{10}, etc. and x is chosen to be a solution of the equation

$$x^3 = x^2 + 1 \tag{15}$$

The overall gains θx^3, θx^4, θx^7, θx^8, etc. are readily synthesized from the individual mirror gains. N individual mirror stages will again yield $2N - 1$ uniform logarithmically spaced overall gains.

A number of other possibilities exist for the choice of r_A when this technique is used to obtain more than N uniform logarithmically-spaced gains using N gain stages. All that is required is that $x = 1 + r_A$ be a solution of a design equation of the form

$$x^n = \sum_{k=0}^{n-1} c(k)x^k \tag{16}$$

where $c(k)$ may assume the value 0 or 1.

It is noted here that the usefulness of choosing $1 + r_A$ to be a solution of a design equation of the form of (16) may not be limited to programmable current mirror structures alone. For example, this concept may prove useful in such structures as programmable capacitor arrays. The advantage here would be a greater capacitance range for a given number of capacitors and a fixed resolution in the attainable capacitance.

IV. Implementation in a 3μ CMOS Process

Fig. 5 shows a schematic of the complete OTA. The circuit contains a linearized differential input stage in which a square-law compensating current is used to counter the inherent nonlinearities of the source-coupled differential pair [5]. Also included are programmable mirrors M1 and M3 and fixed mirror M2.

The control voltage V_{tail} sets the bias currents and determines the transconductance gain, g_{md} of the input stage. Fine adjustment of g_m is accomplished by the adjustment of the control voltage. The design of this input stage is such that adjustment of g_{md} by a factor of approximately 1.8 (i.e., $\frac{g_{md_{MAX}}}{g_{md_{MIN}}} \simeq 1.8$) is possible while maintaining less than 1% nonlinearity throughout the adjustment range.

The six stages of programmable mirrors are designed such that the resolution in the mirror gain is $r_A = 0.618$. As explained in Section III, this results in the six mirror stages yielding eleven uniform logarithmically-spaced values of gain. The permissible fine adjustment by a factor of 1.8 is deemed adequate for overlap of the coarse adjustment ranges.

The circuit was fabricated in a 3μ CMOS process through the MOSIS program. Circuit area excluding pads is 0.225mm^2.

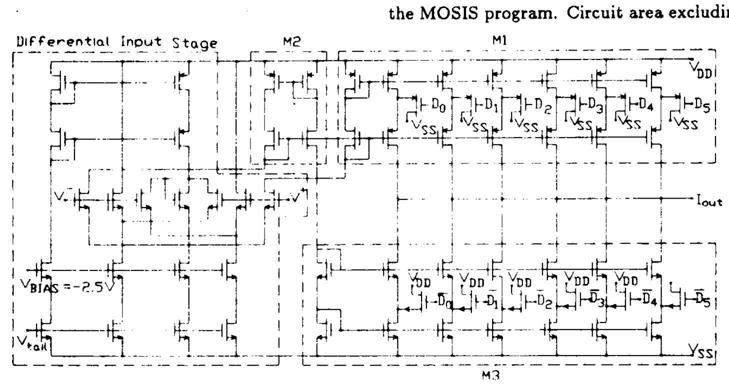

Fig. 5: Schematic diagram of OTA

V. Experimental Results

The measured transconductance characteristic for $V_{tail} = -3.5V$ and the maximum mirror gain A_{63} is shown in Fig. 6. The DC input voltage was applied to the non-inverting terminal, while the inverting input terminal was shorted to ground. The circuit demonstrated less than 1% nonlinearity for inputs up to $4V_{p-p}$. Throughout the entire g_m adjustment range, the maximum input signal swing for 1% nonlinearity remained above $1V_{p-p}$.

The measured g_m adjustment range is shown in Fig. 7. In these measurements, the fine adjustment was made by adjusting V_{tail} directly to show the relationship between g_m and V_{tail} throughout the entire V_{tail} adjustment range; in a completely programmable OTA, this fine adjustment would be made by changing the input to a DAC. It is seen that the g_m adjustment range is greater than two decades. It is further noted that there are no gaps in the attainable values of g_m due to the switching of the output mirror stages; this ensures that the overall resolution of the OTA is determined by the fine adjustment of V_{tail}.

The frequency response was measured with $V_{tail} = -3.5V$. The short circuit transconductance gain had a 3dB bandwidth slightly above 11 MHz. This is in good agreement with SPICE simulations. Changing of the output stage mirror gain was found to have a negligible effect on the 3dB bandwidth, which is also in agreement with simulations.

A programmable OTA-C filter containing a preliminary 2-output stage version of this OTA was reported in [8]. A 6^{th}-order, 3-decade programmable and reconfigurable filter structure using this OTA has been fabricated and is reported in [9].

VI. Conclusion

A method has been presented for the design of a programmable OTA with a wide g_m adjustment range. By including a programmable mirror structure in the OTA output stage and restricting the adjustment range of the differential input stage, the wide g_m adjustment range is obtained without severe degradation in the overall linearity of the OTA.

A technique has been described for realizing greater than N uniform logarithmically-spaced current mirror gains using only N current mirror stages. In logarithmically-programmable structures, including applications other than current mirrors, this technique may considerably reduce circuit complexity.

The focus of this paper has been on increasing the g_m adjustment range of the OTA, which is certainly of interest in applications where wide parameter tuning ranges are desired. However, the method of including a programmable current mirror structure in the OTA output stage may prove useful in applications requiring only one precise value of g_m, e.g., in cases where adjustment of a bias current in a differential input stage is, by itself, inadequate in overcoming the effects of IC process variations.

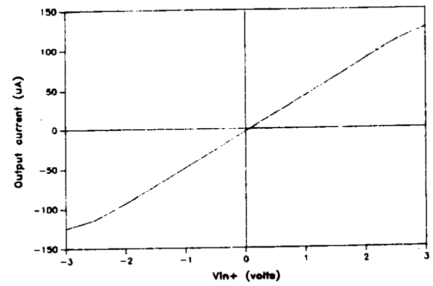

Fig. 6: Experimental DC transfer characteristic for maximum output stage mirror gain

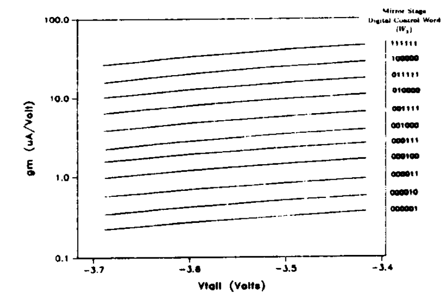

Fig. 7: Experimental g_m adjustment range

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