A SUB-NANOAMPERE CURRENT DIFFERENTIATOR

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Abstract

A novel current differentiator capable of differentiating a step current with step size as low as 50pA is described. It requires only four MOSFETs and consumes less than 10^{-8} W power. This makes the novel current differentiator, called the Current-Mirror (CM) differentiator, a suitable building blocks for the implementation of motion-detecting imagers with medium pixel density (≈ 60 pixels / mm^2).

1. Introduction

The visual systems in most animals have image-motion detection capabilities. An animal cannot be in its most alert state constantly in order to guard itself against predators. To conserve energy and to prevent fatigue, nature has given most animals specialized motion-detecting neurons. Whenever triggered by a moving image, these motion-detecting neuron will send an alerting signal to the central nervous system. In this way, the animal will be excited into its highest state of awareness only when a moving object is approaching.

The vast majority of artificial vision systems do not have an integrated motion-detecting capability. This makes vision systems, such as those used in security surveillance, less than ideally cost effective. Thus, in most cases, the amount of redundant information generated by these systems is far too large to be stored in memory devices.

Image-motion detection can be done either by a digital or analog processor. Using a digital processor requires that analog signals generated by the pixels of an imager be digitized by an A/D converter. Random Access Memory (RAM) is used to store one or more previous image frame and intermediate data generated by the processor. Thus, using a digital approach to image-motion detection requires the A/D converter, the digital processor and the RAM to be operated at full capacity constantly with correspondingly large consumption of power. Moreover, the practical difficulty of integrating an A/D converter with each pixel results in the sequential digitization of the image. Thus, parallel processing is severely limited.

Alternatively, image-motion detection can be done by a temporal differentiator integrated with each pixel [1] as illustrated in Fig. 1. Current differentiation can be performed directly using an inductor. However, on a VLSI chip, inductors cannot be implemented easily or economically. Discrete-time current differentiation can be performed using current-copier cells [2]. But unfortunately, switching noise limits the usefulness of the current-copiers in low-current applications [3,4,5].

2. Current-mirror (CM) differentiator

In this paper, a novel approach to current differentiation based on the current mirror shown in Fig. 2 will be described. A transconductance amplifier with its output driving a capacitor is added in the feedback loop of the mirror to convert it into a current differentiator. The input current is injected into node A and the output voltage is observed at the same node. Analysis of the circuit shows that

$$\frac{V_o}{i_{in}} = \frac{\dfrac{s\,C}{G_{mc}\,(g_{m1}\,//\,g_{m3})}}{1+\dfrac{s\,C}{r_{o2}\,G_{mc}\,(g_{m1}\,//\,g_{m3})}} \qquad (1)$$

where G_{mc} is the gain of the transconductance amplifier, g_m is the transconductance of the individual transistor and r_{o2} is the output resistance of transistor n_2.

If $s \ll r_{o2}\,G_{mc}\,(g_{m1}\,//\,g_{m3})\,/\,C$ then

$$\frac{V_o}{i_{in}} \approx \frac{s\,C}{G_{mc}\,(g_{m1}\,//\,g_{m3})} \qquad (2)$$

Thus, the output voltage is the time derivative of the input current.

When a step current, is injected into node A, the gate voltage of n_1 cannot rise instantly to increase the drain current of n_2 due to delay in charging C. This leads to a large overshoot of the output voltage as shown in Fig. 3. If the input-current step size is large enough, the output voltage saturates at its maximum value, V_{omax}, as shown in Fig. 4. If at t_1 and t_2, the output voltage is $1/\sqrt{2}\,V_{omax}$, the response time of the CM differentiator, T_R, can be defined as

$$T_R = t_2 - t_1 \qquad (3)$$

If at $t=\infty$, $V_o = V_F$, the output response of the CM differentiator, O_R, can be defined as

$$O_R = \frac{V_{omax} - V_F}{V_{omax}} \qquad (4)$$

Neglecting the rise time of the output voltage, the response time of the CM differentiator can be expressed as

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$$T_R = \frac{C}{i_{cmax}\,(g_{m1} \,//\, g_{m3})} \left[\Delta i - \frac{V_{omax}}{\sqrt{2}\, r_{o2}} \right] \qquad (5)$$

where i_{cmax} is the maximum output current of the transconductance amplifier, and Δi is the step size of the input current. Ideally, the value of O_R should be as close to one as possible, and the response time should be in the milisecond range.

3. Design considerations

To achieve analog VLSI density, a very simple transconductance-amplifier configuration must be used. This leads to a large input-offset voltage. However, in the present design, the transconductance amplifier is part of the negative feedback loop which greatly reduces potential current mismatch due to the input-offset voltage of the transconductance amplifier. For example, using an input-offset voltage of 1V and an input current of 10 nA, the mismatch of the drain currents of n_2 and n_3 can be shown to be less than 10%. The simplest available transconductance amplifier is the MOSFET itself, in which case the basic CM differentiator is as shown in Fig. 5. Note that the sourcing current of the transconductance amplifier is limited by I_{bias}. However, the sinking current of the transconductance amplifier is much larger. This makes the CM differentiator much more sensitive to positive than to negative steps of input current. Equal sensitivity to positive and negative steps can be achieved by adding a current source ($2\,I_{bias}$) in series with the drain of p_1 to the CM differentiator.

If the series resistance of the capacitor is zero, the conventional voltage differentiator using an R-C network and an opamp will differentiate an infinitely small step voltage to produce an output voltage proportional to the rate of change of the input voltage. As a result, high frequency noise can cause the differentiator output to be useless. However, in the CM differentiator this problem is under control: The sensitivity of the CM differentiator is a function of the dc input current which controls the output impedance of n_2 in Fig. 2. In a noisy environment, the dc input current (produced by an independent current source) should be increased to reduce r_{o2}, and thus the sensitivity of the CM differentiator. As long as the input current is much larger than the noise current, the CM differentiator can be biased in such a way that its response will be dominated by the step input current.

The CM differentiator will not oscillate unless the parasitic capacitance, C_{in}, at node A is infinitely large. However, to avoid excessive ringing, the following conditions must be met,

$$C > 4\, r_{o2}^2\, G_{mc}\,(g_{m1} \,//\, g_{m3})\, C_{in} \,. \qquad (6)$$

Note that condition (6) is easily met by the CM differentiator with very small I_{bias}.

4. CMOS implementation

The CM differentiator shown in Fig. 6 has been implemented using 3µm CMOS technology. Note that a voltage-to-current conversion circuit has been added to the output of the CM differentiator. This allows the output signals of all pixels to be summed and thus to implement a wired-OR function, used to generate an interrupt signal for the A/D converter and the associated microprocessor whenever a moving image is detected. A photodiode is used to supply the input current. The layout and the micrograph of the CM differentiator are shown in Fig. 7. The micrograph shows only the photodiode and the second-layer metal which shields the majority of the CM differentiator from light. The output current i_{d4} which mirrors the input current, provides a means for measuring the input current indirectly. To avoid loading node A while the output voltage is measured, a p-MOSFET connected in the common-drain configuration with an uncommitted source is used to buffer that node. Fig. 8 shows the output voltage of the CM differentiator (lower trace) and the voltage across a LED (upper trace) illuminating the photodiode. The measured output voltages for input currents with step sizes of 20 pA to 1.2 nA are shown in Fig. 9.

The experimentally obtained O_R and T_R as functions of $I_F \,/\, I_S$ and the slew rate of the input current, are shown in Figs 10 and 11. The value of I_S for all cases is 80 pA. The experimental results clearly show that the CM differentiator is well-suited for applications where the input current is in the nanoampere range, such as motion detection.

5. Conclusion

A novel current differentiator, called the Current-Mirror (CM) differentiator, has been presented. The CM differentiator can differentiate an input current with a step size in the range of a few nanoamperes. The small area (0.022 mm^2 - including the capacitor and the photosensors) occupied by the CM differentiator makes it very suitable for VLSI applications in the area of motion detection.

Acknowledgements: This work was supported by the Natural Science and Engineering Research Council of Canada, and Micronet.

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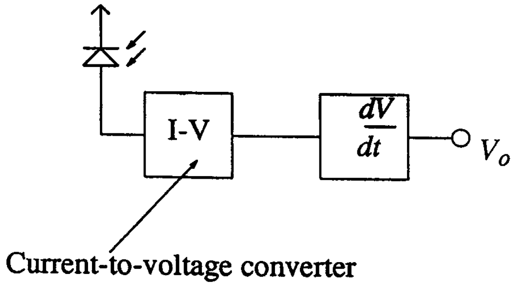

Fig. 1: Motion detection using temporal differentiation of the output of the pixel.

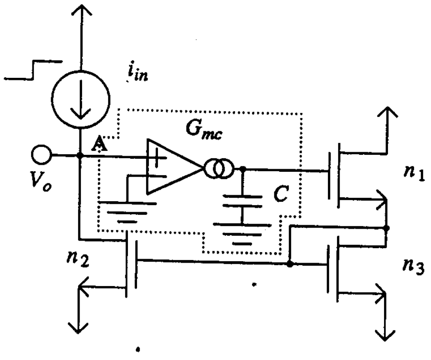

Fig. 2: The CM differentiator.

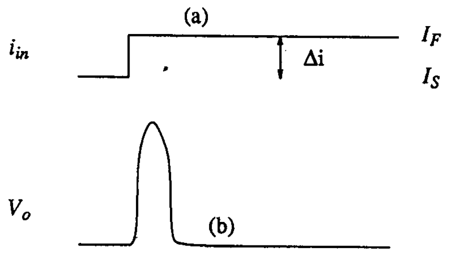

Fig. 3: The waveforms of (a) the input current and (b) the output voltage.

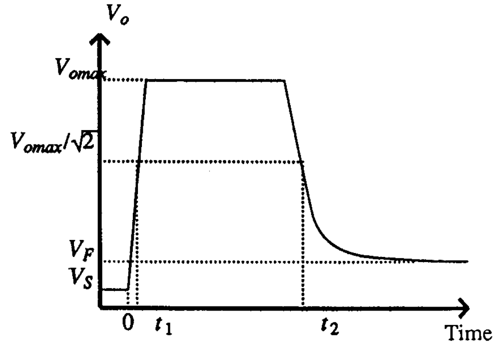

Fig. 4: The output voltage of the overdriven CM differentiator.

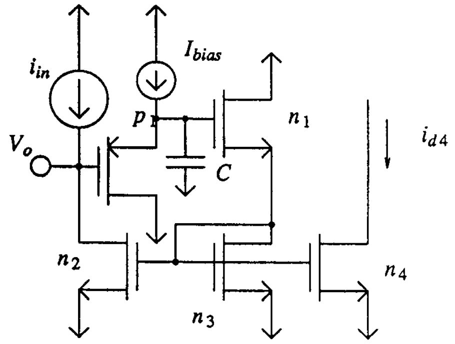

Fig. 5: The basic CM differentiator.

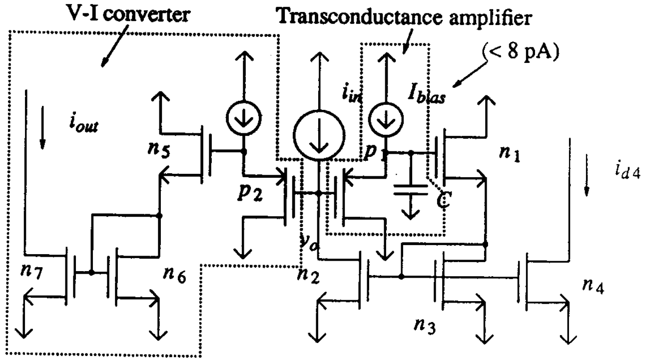

Fig. 6: The experimental CM differentiator.

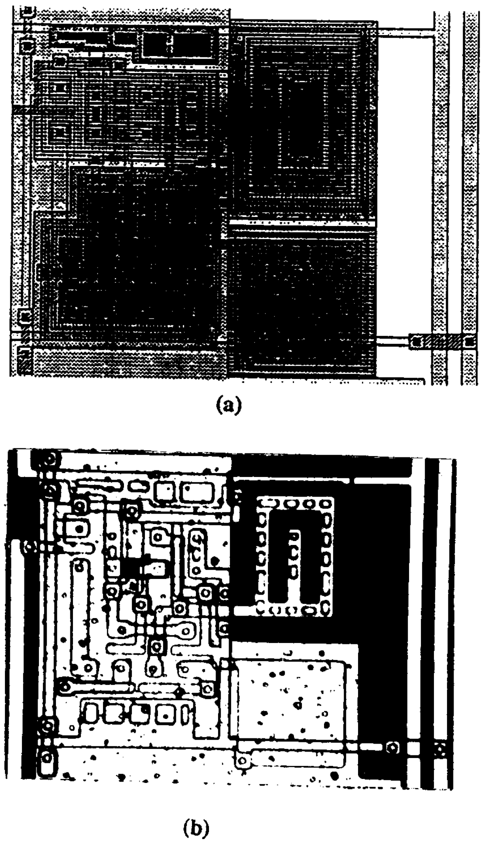

Fig. 7: (a)The layout and (b) the micrograph of the CM differentiator.

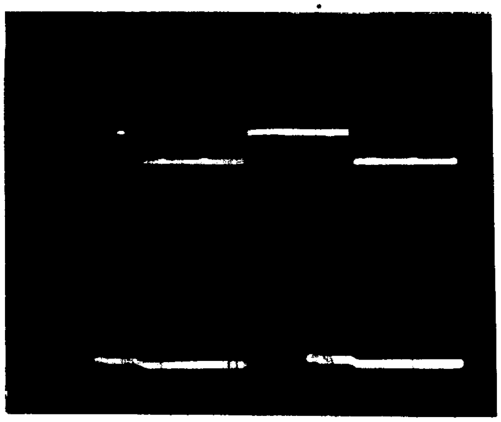

Fig. 8: The output voltage of the CM differentiator (lower trace). The upper trace is the voltage across an illuminating LED. The step size of the input current is less than 10 nA. The vertical scales are 5V/div (upper trace) and 2V/div (lower trace). The horizontal scale is 2ms/div.

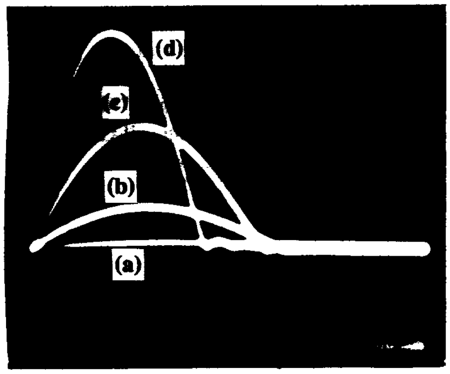

Fig. 9: The output voltage of the CM differentiator. The step sizes of the input current are (a) 20 pA, (b) 45 pA, (c) 106 pA and (d) 1.2 nA. The vertical scale is 1V/div and the horizontal scale is 2ms/div.

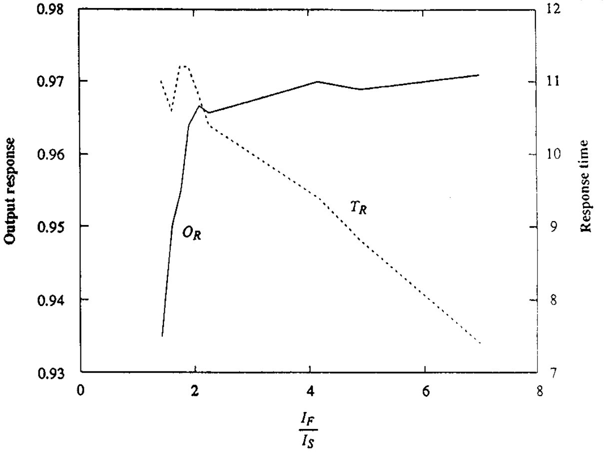

Fig. 10: The measured Output response (O_R) and Response time (T_R) as functions of I_F / I_S.

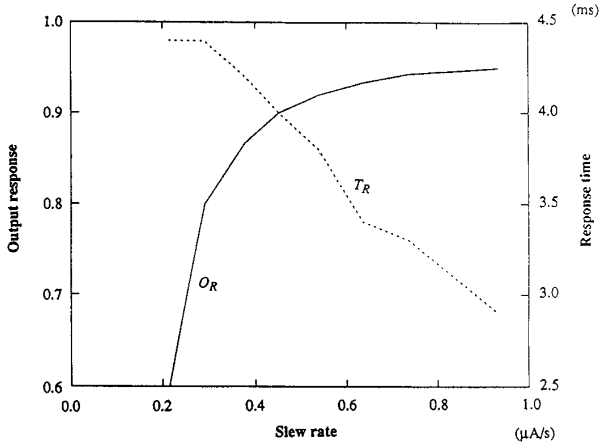

Fig. 11: The measured Output response (O_R) and Response time (T_R) as functions of the slew rate of the input current.