On-Chip Current-Mode Focal Plane Signal Processing for a CMD Image Sensor

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Abstract On-chip current-mode signal processing for a Charge Modulation Device (CMD) image sensor is under investigation. The design of current-mode circuits including a fixed pattern noise suppression circuit and a current-mode second-order incremental Σ-Δ analog-to-digital converter is described. Preliminary experimental results will be presented at the workshop.

I. INTRODUCTION

A Charge Modulation device (CMD) image sensor[1]-[3] is a type of active pixel image sensor [4]. It features one phototransistor per pixel, high speed operation, low power consumption and flexibility in implementing various readout schemes. Also, since its driving and readout circuits are implemented with CMOS, further integration of signal processing function can be easily achieved.

Current-mode signal processing, instead of the conventional voltage-mode signal processing, seems natural and appropriate for the CMD image sensors since the output of the CMD is in the current domain. Switched current (SI) circuits have gained considerable interest for analog sampled-data processing. Advantages of the SI technique over the voltage-mode technique include low power consumption, low supply voltage, potential for high speed operation, compatibility with standard CMOS process, and less real-estate.

Current-mode signal processing for the CMD image sensor is under investigation. An image sensor with on-chip fixed pattern noise (FPN) suppression and on-chip analog-to-digital conversion (ADC) is expected to increase sensor system performance, while reducing sensor system size, weight and cost [5]. In Section II, FPN suppression using a current copier cell is described. In Section III, building blocks for a current-mode over-sampling Σ-Δ ADC which is expected to achieve high resolution (≥10 bit) are described.

II. FPN SUPPRESSION WITH A CURRENT COPIER CELL

a. Current Copier Cell [6]-[7]

The principle of a current copier cell, also called a dynamic current mirror, is shown in Fig. 1. A single transistor \( M_M \) is combined with 3 switches \( S_X, S_Y, S_Z \) that are implemented by means of additional transistors, and a capacitor \( C \). In the first phase (phase 0), \( M_M \) operates as the input device of a mirror, with its gate and drain connected to the input current source. When equilibrium is reached, capacitor \( C \) at the gate is charged to the gate voltage \( V \) required to obtain \( I_D = I_0 \). The value of \( I_0 \) is thus stored as a voltage across \( C \). In the second phase (phase 1), \( M_M \) operates as the output device of a mirror, with its drain disconnected from the gate and connected to the output node. It sinks an output current \( I_I \), that is controlled by the same gate voltage \( V \) and thus is equal to \( I_0 \).

b. FPN Suppression with a Current Copier Cell

FPN in a CMD image sensor is mainly caused by the offset current mismatch of the pixel CMD phototransistor. In order to suppress the FPN within an imager chip, the current copier cell was used [8]. Two current copier cells are assigned to each column. Current \( I_{RD} \) from a selected CMD pixel,

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which consists of the light dependent current $I_{\text{sig}}$ and the offset current $I_{\text{off}}$ ($I_{\text{RD}} = I_{\text{sig}} + I_{\text{off}}$), and current $I_{\text{RS}}$ which is equal to $I_{\text{off}}$ ($I_{\text{RS}} = I_{\text{off}}$) are memorized on the two current copier cells during the horizontal blanking period. The currents are readout in parallel during the succeeding horizontal period. An external analog circuit produces a subtracted signal, which should be FPN free.

Resulting FPN level of 0.5 % p-p for the saturation signal was reported[8]. This residual FPN is seen as vertical stripes.

A newly developed circuit configuration and pulse timing for FPN suppression is shown in Fig. 2. During $\phi_1$ phase, current $I_{\text{RD}}$ is memorized on the first copier. During $\phi_2$ phase, current $I_{\text{RS}}$ flows into the circuit while the first copier is in the copying phase ($I_{\text{RD}}$ is output) and the additional current sink $I_0$ is connected to the common node of the both copiers. The current, $I_{\text{RD}} - I_{\text{RS}} + I_0 = I_{\text{sig}} + I_0$, is thus memorized on the second copier. $I_0$ prevents settling time degradation for small $I_{\text{sig}}$. During $\phi_3$ phase, the second copier outputs the memorized current, $I_{\text{sig}} + I_0$, with $I_0$ flowing. The output current flowing into the load is $I_{\text{sig}}$. Thus, FPN can be suppressed. Note that the variation in $I_0$ does not generate FPN. A cascode transistor is used to reduce the output conductance effect.

III. CURRENT-MODE $\Sigma$-$\Delta$ ANALOG-TO-DIGITAL CONVERTER

a. Rationale for $\Sigma$-$\Delta$ ADC

Typical pixel data rate in scientific applications is around 100kHz and resolutions greater than 12 bits are required. High resolution with medium conversion speed is possible using oversampling technique [9].

Oversampling methods have recently become popular because they avoid many of the difficulties with conventional methods for A/D and D/A conversion. Conventional converters require high precision analog circuits. Oversampling converters, on the other hand, can use simple and relatively high-tolerance analog components. Though they require fast and complex digital signal processing stages, their robustness is suited for fast growing VLSI technology.

b. A current-mode second-order incremental $\Sigma$-$\Delta$ ADC [10][11]

Compared to the conventional voltage-mode approach which is usually a switched capacitor approach, the current-mode approach is expected to be faster and less sensitive to component variations. The critical elements in switched capacitor approach include the MOS op amp, which is the slowest analog component and the one most vital to conversion accuracy, and linear capacitors. Our current-mode approach uses no MOS op amps or linear capacitors. The main building block is a current copier cell which is described above.

A first-order $\Sigma$-$\Delta$ ADC requires $2^n$ cycles to perform a n-bit A/D conversion. A higher order $\Sigma$-$\Delta$, built by incorporating additional error loops, can speed up the conversion. However, the addition of more than one integrator in the feedback tends to cause stability problems. This problem can be overcome by cascading two first-order stages resulting in an incremental $\Sigma$-$\Delta$ ADC topology [11]. Since it consists only of cascaded first-order stages, it is immune to loop instabilities. At the same time, compared to a first-order topology, it vastly improves the conversion speed. The number of cycles (m) needed for a k-th order $\Sigma$-$\Delta$ ADC to achieve n-bit resolution is given by

$$m = (k!2^n)^{\frac{1}{k}}$$

A block diagram of the current-mode second-order incremental $\Sigma$-$\Delta$ modulator is illustrated in Fig. 3. The algorithm for the second-order incremental ADC (for an integrator gain of unity) is given by
\[ I_1(p) = pI_{in} - \sum_{i=1}^{p} a_i I_R \]

\[ I_2(p+1) = p(p+1)I_{in}/2 - \sum_{i=1}^{p} a_i (p+1-i)I_R - \sum_{i=2}^{p+1} b_i I_R \]

where \( p \) denotes p-th integration period, \( I_{in} \) the input current, \( I_R \) the reference current, \( I_1 \), \( I_2 \) the first (second) integrator's output, \( a_i \) (\( b_i \)) the first (second) comparator's output ("1" or "0"), respectively.

c. Building Blocks

- **c-1. Constant Feedthrough Current Copier Cell**

  One of the limitations in the current copier cell is the charge injection due to switching. Figure 4 shows a current copier cell in which the feedthrough is expected to be independent of the input current levels. Constant feedthrough levels yield just an offset in the resulting digital data.

  During the period when the pulses \( \phi_1 \) and \( \phi_3 \) are ON, the value \( I_{in} + I_0 \) is memorized on \( C_M \). When the pulse \( \phi_2 \) is OFF, the clock feedthrough corresponding to \( \delta I_M \), which depends on \( I_{in} \), is added on \( C_M \). Thus, \( I_{in} + I_0 + \delta I_M \) is stored on \( C_M \). During the period when the pulse \( \phi_2 \) is ON with \( \phi_1 \) remaining ON, the value \( I_0 + \delta I_M \) is memorized on \( C_C \). When \( \phi_1 \) is OFF, the clock feedthrough corresponding to \( \delta I_C \), which is constant under the condition of \( I_0 \gg \delta I_M \) because of the constant \( I_0 \), is added on \( C_C \). Thus, \( I_0 + \delta I_M + \delta I_C \) is stored on \( C_C \). During the period when the pulse \( \phi_2 \) is ON, the output current with constant feedthrough \( I_{out} \) given by

\[ I_{out} = (I_{in} + I_0 + \delta I_M) - (I_0 + \delta I_M + \delta I_C) = I_{in} - \delta I_C \]

is obtained.

- **c-2. Integrator**

  An integrator consists of an n-channel and a p-channel CFT CCC. The n-channel copier acts as an accumulator and a p-channel copier acts as a memory, denoted \( \Sigma \) and \( M \) in Fig. 3, respectively. In the first phase, input current is memorized on an n-channel copier. In the second phase, the memorized current is copied on a p-channel copier. In the third phase, new input current and the copied current on the p-channel copier are added on the n-channel copier.

- **c-3. Comparator**

  Each comparator follows an integrating stage. A basic result of this is that the comparator's offset and noise are not as important as in other A/D configurations where comparators directly measure the analog input.

  Fig. 5 shows a current comparator[12]. The first inverter operates as an integrating current-to-voltage converter.

**ACKNOWLEDGMENT**

One of the authors (J. N.) would like to express his appreciation to Dr. M. Chahine and Dr. Eric R. Fossum of JPL for arranging participation in the JPL Distinguished Visiting Scientist Program. The authors of Olympus wish to thank Dr. S. Nagai and Dr. A. Yusa of Olympus Optical Co., Ltd. for their continuous encouragement.
The research described in this paper was carried out at the Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the National Aeronautics and Space Administration, Office of Advanced Concepts and Technology, and Olympus Optical Co. Ltd.

References


Fig. 1 Principle of current copier cell.
Fig. 2  Circuit configuration (a) and pulse timing diagram (b) for FPN suppression.

Fig. 3  Block diagram of the current-mode second-order incremental Σ-Δ modulator.

Fig. 4  New current copier cell.

Fig. 5  Current comparator.