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10.1109/ISCAS.2002.1010386
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A CMOS IMAGER WITH PFM/PWM BASED ANALOG-TO-DIGITAL CONVERTER

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ABSTRACT

An On-pixel Analog-to-Digital Converter based on both PFM and PWM schemes is reported. The proposed architecture uses a limited number of transistors that can be implemented in a small silicon area resulting in a 23% fill-factor. The digital sensor can be externally configured in order to operate under either the PFM or PWM scheme. At high-light intensities, the PFM scheme is replaced by the PWM scheme which proves to be much more efficient in terms of power consumption and clock frequency requirements. An in-built light adaptation mechanism has also been implemented which allows the sensor to better adapt to low-light intensity or to adjust the sensor saturation level. As a consequence, the sensor features a programmable dynamic range. Image lag is reduced in both schemes since a reset of the photodetector is performed after the conversion period. The pixel based ADC has been designed and fabricated using CMOS 0.25µm technology.

1. INTRODUCTION

Digital vision sensors are very important components of future multi-media and intelligent systems. In order to meet the requirement of such systems in terms of low cost and low power consumption, it is very important to integrate the Analogue-to-Digital Converter (ADC) on the chip. This provides the possibility of integrating on-chip digital processing together with the image acquisition circuitry allowing the designers to greatly benefit from the on-going advancement of CMOS technology. In order to fully benefit from these advantages, one must consider very carefully the trade-offs involved in such a VLSI implementation.

In digital vision applications, ADCs can be integrated at the array level [1,2], at the column level [3,4], or at the pixel level [5]-[7]. The array level approach is at present the most widely used. In this approach, a single ADC is used for the entire array, which reduces the total silicon area and allows the realization of high fill-factor vision sensor since most of the pixel area would be dedicated to the photodetector. However, by using an array level ADC, the signal-to-noise ratio is reduced since the weak pixel output would drive the entire column bus. In addition, for video applications, very high speed ADC, operating at about 10Msamples/s, is required for the array level ADC, which tend to increase the power consumption. To lower the ADC operating speed, the column-level approach has been used [3,4]. In this approach, a battery of ADCs, each dedicated to one or more columns of the array, is used. The ADCs are operated in parallel, and therefore, low-to-medium-speed ADC architectures can be used. To lower ADC speeds even further the pixel-level approach has been recently introduced. In this approach, an ADC is dedicated to each pixel and the array is operated in parallel. Consequently very high frame rates can be obtained with ADCs operating at only tens of samples per second [6]. In addition, when ADCs are integrated at the pixel level the load capacitance seen at the pixel's output is negligible as compared to the one that is associated with the array based ADC which results in SNR improvements. Unfortunately, the main drawback of an on-pixel ADC is a reduced fill-factor of the image sensor since a significant part of the pixel area will be dedicated to the ADC circuitry. As a consequence, implementing high fill-factor On-pixel ADC is a real challenge that faces researchers and CMOS imager designers.

This paper presents two efficient Analog-to-Digital conversion schemes based on Pulse Frequency Modulation (PFM) and Pulse Width Modulation (PWM) principles. The digital sensor can be externally configured in order to operate under both schemes. In addition the circuit can be integrated with very limited number of transistors leading to a high fill-factor on-pixel ADC. Section 2 presents the principle of the PFM and PWM based ADC together with the sensor in-built light adaptation mechanism. Section 3 describes the VLSI design and presents the simulation results of the on-pixel ADC. Section 4 presents a conclusion.
2. PFM/PWM-BASED ADC

The main advantage of our proposed on-pixel architecture is that it uses the same hardware resources to produce either a PFM or a PWM coding at the sensor’s output. The circuit, as shown in the block diagram of Figure 1, is composed of a photosensitive device (photodiode $P_d$) with its internal capacitance $C_d$, a reset circuit, a feedback circuit, and a clocked comparator.

![Block diagram of the proposed pixel based ADC. Dashed lines corresponds to the circuit parts related to PWM scheme.](image)

**Fig. 1.** Block diagram of the proposed pixel based ADC. Dashed lines corresponds to the circuit parts related to PWM scheme.

The reset circuit can be either controlled by the feedback of the comparator in the case of the PFM mode or externally, using the reset signal, in the case of a PWM mode. For this last case, a PMOS transistor is also added in order to reset the voltage $V_d$ across the node of the photodiode. For both modes, the light falling onto the photodiode $P_d$ is responsible for discharging the internal capacitor of the photodiode $C_d$. This results in a linearly decreasing voltage $V_d$ across the node of the photodiode. This voltage $V_d$ is compared to a reference voltage $V_{ref}$ using a voltage comparator triggered by a clock signal $Clk$. When the voltage $V_d$ reaches the reference voltage $V_{ref}$, the output of the comparator $V_{out}$ switches and a feedback circuit is used to reset the photodiode node to either $V_{dd}$ or $V_{ss}$ in the PFM mode or PWM mode respectively. At the next cycle, the same procedure is repeated again for the PFM mode while a stand-by is applied to the circuit, until an external reset signal is received, in the case of the PWM mode. A pulse is generated at the output of the comparator whenever the voltage $V_d$ reaches $V_{ref}$. Figures 2.A and 2.B show the voltage across the photodiode $V_d$ and the output of the comparator $V_{out}$ for the PFM and PWM modes respectively. It can be seen that only one pulse is needed for the PWM mode while a train of pulses is required for the PFM based conversion. On both Figures (2.A and 2.B), $T_d$ represents the discharge time of the capacitor from $V_{reset}$ to $V_{ref}$ which can be expressed by:

$$T_d = \frac{(V_{reset} - V_{ref}) \times C_d}{i_d}$$

where $i_d$ and $C_d$ are the photocurrent and the photodiode capacitor, respectively. The frequency $f$ of the voltage across the photodiode $V_d$, for the PFM mode, is inversely proportional to $T_d$ and therefore can be expressed as:

$$f \approx \frac{1}{T_d} = \frac{i_d}{(V_{reset} - V_{ref}) \times C_d}$$

The pulse width for the PWM scheme represented on Figure 2.B can also be expressed by:

$$P_w = T_d = \frac{(V_{reset} - V_{ref}) \times C_d}{i_d}$$

The switching frequency $f$ (and the pulse width $P_w$) of the comparator output $V_{out}$ for the PFM mode (and the PWM mode) is directly proportional (inversely proportional) to the capacitor discharge current $i_d$. Therefore, a conversion from photocurrent to pulse frequency (and pulse width) is obtained. In order to obtain the digital output from the two previous coding schemes, the output of the comparator is directly connected to the input of a digital configurable counter/decounter. The output of the comparator is either connected to the counter input in the case of PFM scheme or to the Enable signal of the clocked decounter in the case of the PWM scheme.
In the case of the PFM scheme, the enable signal (En) is provided externally allowing the counter to be operational only during a counting period \( T_{cnt} \). The number of impulses detected by the counter is therefore given by:

\[
N_{imp} = \frac{T_{cnt}}{T_d} \approx \frac{T_{cnt} \times i_d}{(V_{dd} - V_{ref}) \times C_d}
\]  

(4)

Global adaptation to the mean light intensity of the digital sensor can be simply implemented by modulating the \( T_{cnt} \) signal according to the mean light intensity. If the sensor is being used in a given scene where illumination levels result in a photocurrent varying from 0 to \( i_{dm} \), then \( T_{cnt} \) will be modulated such that \( 2^n \) impulses resulting from the PFM scheme are counted for the highest photocurrent \( i_{dm} \), where \( n \) is the number of bits. By substituting \( N_{imp} = 2^n \) and \( i_d = i_{dm} \) in Eq.(4) we deduce the optimum \( T_{cnt} \) as follow:

\[
T_{cnt} = 2^n \times \frac{(V_{dd} - V_{ref})}{i_{dm}} \times C_d
\]  

(5)

In our digital sensor, the Enable signal of the counter, which is high during \( T_{cnt} \), is therefore used to adapt the ADC to different illumination levels so that the brightest pixel would always generate \( 2^n \) pulses and hence would correspond to the full range of the ADC. According to this adaptation mechanism, for each environment where the photocurrent varies from 0 to \( i_{dm} \), a corresponding optimum \( T_{cnt} \) can be obtained using Eq.(5). This \( T_{cnt} \) will correspond to the minimum counting time that allows the use of the ADC’s full range. In other words, \( T_{cnt} \) will optimise the dynamic range as well as the conversion speed of the ADC. Table 1 illustrates a typical example in which we consider the use of the ADC for three different environments: (i) a typical bright office; (ii) a typical outdoor light, and (iii) a typical sunlight. In this example \( T_{cnt} \) is obtained from Eq.(5), with \( V_{dd} = 2.5V, V_{ref} = 1V, C_d = 1F \) and \( n = 8 \)-bits. For the three cases, the ADC operates within its full dynamic range (digital output: 00-FF).

### Table 1. Conversion results for an 8-bit accuracy using Optimal \( T_{cnt} \) values (Eq. 5) for three different environments.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Photocurrent ( &quot;i_d&quot; )</th>
<th>Optimal ( &quot;T_{cnt}&quot; )</th>
<th>Digital Output (Hex)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bright office</td>
<td>0 - 2 nA</td>
<td>192 ( \mu s )</td>
<td>00 - FF</td>
</tr>
<tr>
<td>Outdoor light</td>
<td>0 - 4 nA</td>
<td>96 ( \mu s )</td>
<td>00 - FF</td>
</tr>
<tr>
<td>Sunlight</td>
<td>0 - 8 nA</td>
<td>48 ( \mu s )</td>
<td>00 - FF</td>
</tr>
</tbody>
</table>

The previous example shows that the Enable signal provides the possibility to adapt the sensor to any illumination level and allows the ADC to operate within its full range providing a programmable dynamic range of the photosensor. This last feature is usually obtained through a complex gain control amplifier integrated within the photodetectors array. In our case, this is simply realized by using a digital enable signal of a conventional digital counter. It must be noticed that for high level of illumination it is required to maintain the clock frequency of the comparator very high in order to reduce offset errors. Figure 3 shows the required clock frequency of the PFM scheme, for different illumination levels and for different precisions.

![Fig. 3. Required clock frequency of the comparator as function of the illumination level for different precisions.](image)

From this figure one can deduce that for higher level of illuminations the power consumption of the PFM scheme is dramatically increased which makes the PWM approach more suitable.

3. VLSI DESIGN

Both the PFM and the PWM based converters operate in two different phases: (i) counting phase and (ii) shift-out phase. During the counting phase, all the pixels are operated in parallel resulting in full parallelism. Once the conversion is achieved, the shift-out mode is set and the digital values of the pixels stored in the internal registers are read-out. In this scheme, no read-out circuit is needed and hence the silicon area is fully dedicated to the photodetector array.

Additional gating circuitry has been included within each pixel in order to switch all the analog circuitry part to a stand-by mode during the shift-out phase. The circuit is also placed at a stand-by mode once the pulse is obtained for the PWM scheme. This has resulted in a significant reduction in power consumption during the shift-out phase. The average power consumption per pixel at a frequency of 200KHz is estimated at 85\( \mu W \) and 10\( \mu W \) for PFM and PWM respectively. More than 95% of this power is dissipated during the counting phase.
Figure 4 shows the layout of the pixel based ADC. It has been implemented using CMOS 0.25μm technology and occupies an area of $45 \times 45 \mu m^2$ with a fill-factor of 23%. Careful attention has been paid to the layout of the pixel by separating the analog and digital parts and using guard rings and grounded shields.

A prototype including an array of $32 \times 32$ pixels has been designed and fabricated using CMOS 0.25μm technology. The circuit occupies an area of $10mm^2$. The average power consumption per pixel at a frequency of 200KHz is estimated at 85μW and 10μW for PFM and PWM respectively.

Acknowledgement

This research is supported by a large Australian Research Grant. The author would like to thank Dr. F. Boussaid and Dr. A. Bouzerdoum for helpful discussions.

5. REFERENCES