A Photodiode Sensor Readout Circuit Utilizing a Differential Current Mirror for Dark Current Cancellation

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***Abstract* - This paper proposes a differential current mirror circuit with built-in dark current cancellation for photodiode applications. The photodiode sensor, modeled with a diode and a parasitic capacitor, generates a current signal that is directed through two current mirrors. The signals from each current mirror are then differentially outputted. Thanks to the proposed differential current mirrors, the only high frequency signal current can be transferred to output port effectively. The proposed sensor interface ICs were implemented using the PDK of the DB Hitek process and achieved a dark current cancellation ratio of 40 dB at a reconfigurable frequency.**

***Keywords*—Photodiode sensor interface ICs, Dark current cancellation, Current mirrors**

I. INTRODUCTION

Photodiodes are among the most widely used sensors, capable of detecting various factors such as light intensity and radiation to generate charge-based current signals [1]. However, photodiodes generate current not only in response to incident photons but also in the absence of light, leading to a current that can degrade the accuracy of signal processing circuits. This phenomenon is known as dark current [2]. Eliminating dark current enhances sensor accuracy, simplifies signal processing, reduces power consumption, and extends the operational lifetime of the sensor signal processing system [3–4].

Traditional photodiode sensor signal processing systems typically consist of a photodiode, a transimpedance amplifier (TIA), and an analog-to-digital converter (ADC), as shown in Fig. 1 [5–7]. The photodiode converts incident photon particles into charge, which the TIA integrates to produce a voltage signal suitable for conversion by the ADC. Due to their operational characteristics, signals generated by photodiodes inherently include dark current. Since the TIA cannot distinguish between dark current and signal current, it must output peak voltage values for every event where current is generated.

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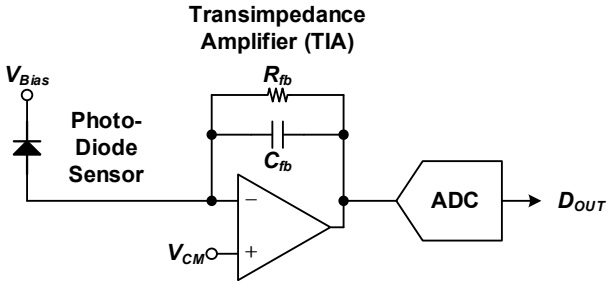

Fig. 1. Conventional Photodiode Sensor Interface Circuits.

II. DESIGN METHODOLOGY

A. System Configuration

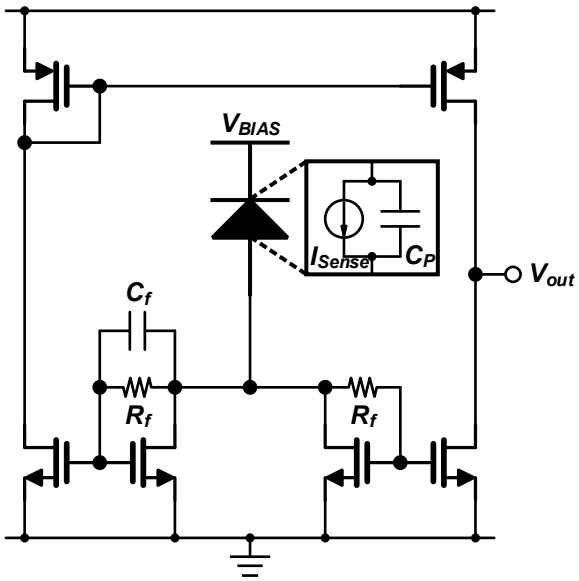

Fig. 2. Proposed Photodiode Dark Current Cancellation Circuit.

Fig. 2 illustrates the configuration of the proposed photodiode dark current cancellation circuit. The current signal generated by the photodiode is split between two current mirrors. Unlike conventional connections where the gate and drain of the MOS transistors are directly connected with a wire, each current mirror in this design utilizes a pair of resistors R_f . Additionally, the left current mirror has a capacitor C_f connected in parallel with R_f . The photodiode generates the current signal, while the two current mirrors receive and convey the current signal to the output port V_{out}.

B. Key Concepts

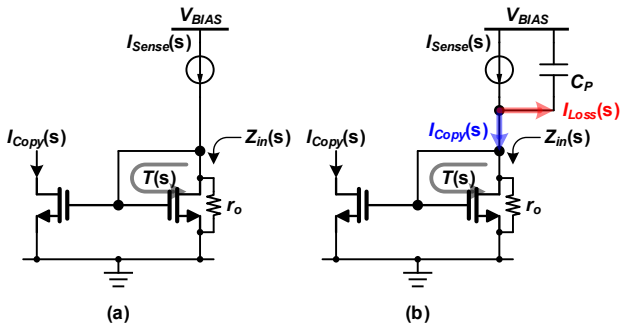

Fig. 3 (a) Schematic of the traditional current mirror circuit, (b) Schematic of the traditional current mirror circuit with the parasitic capacitance of the photodiode added.

The current mirror that receives the current signal generated by the photodiode should have low input impedance (Z_{in}(s)) to minimize the loss of current signal transmission. The Z_{in}(s) of the current mirror described in Fig. 3(a) can be expressed as follows:

$$Z_{in} = \frac{r_o}{1 + g_m r_o} \approx \frac{1}{g_m} \tag{1}$$

The principle behind deriving the formula in (1) involves utilizing the fact that the gate and drain are connected by a feedback loop. The impedance of a circuit with feedback can be calculated by dividing the impedance of the circuit without feedback (r_o) by the loop gain ($1+T = 1+g_m r_o$). However, the Z_{in} can be relatively increased due to the parasitic capacitance C_P. C_P can be modelled as a parasitic capacitance of sensor. In this work, C_P is determined by a type of radiation sensor, the SiPM, with several nano Farad. As shown in Fig. 3(b), the increased high-frequency impedance reduces the signal current entering the current mirror, resulting in greater signal loss.

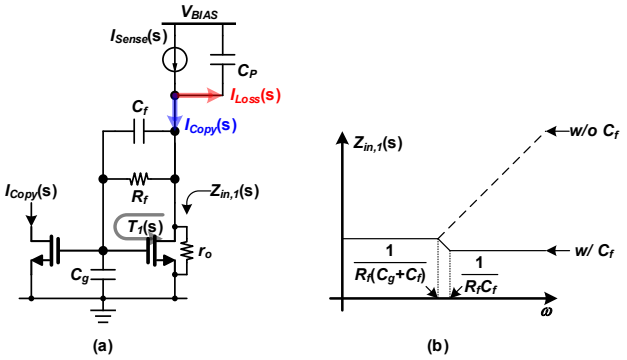

Fig. 4. Proposed low-loss current mirror (a) Detailed schematic, (b) Bode plot of the input impedance.

To overcome the high-frequency impedance issue of the traditional current mirror in Fig. 3, we propose a low-Z_{in}(s) at high-frequency current mirror as shown in Fig. 4(a). By connecting an R_f and a capacitor C_f between the gate and drain of the MOS transistor, the Z_{in}(s) can be changed as follows:

$$Z_{in,1} = \frac{1}{g_m} \cdot \frac{1 + sR_fC_f}{1 + sR_f(C_f + C_g)} \tag{2}$$

Fig. 4(b) shows a comparison of impedances (1) and (2) in the frequency domain using a Bode plot. The new pole created by the addition of R_f and C_f prevents impedance rise, minimizing the leakage of high-frequency current signals that could be absorbed by C_P. To utilize the proposed current mirror in photodiode sensor signal processing circuits in Fig. 2, we additionally use a current mirror with only the resistor R_f connected, without C_f. The Z_{in}(s) of the current mirror without C_f can be rederived as follows:

$$Z_{in,2} = \frac{1}{g_m} \cdot \frac{1}{1 + sR_fC_g} \tag{3}$$

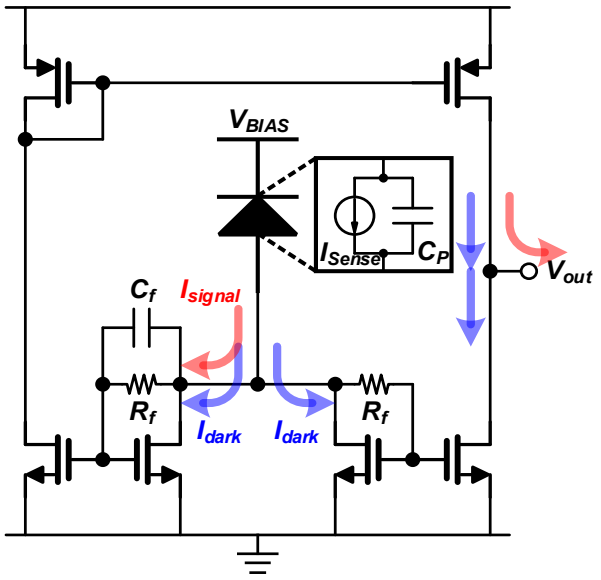

Fig. 5. Conceptual diagram of the differential current mirror for removing photodiode dark current.

Thus, the current signals generated by the photodiode sensor are injected into two different current mirrors and pass through an active load circuit composed of the PMOS transistors to output a single voltage signal. The current mirror with only R_f connected blocks high-frequency current signals and only passes low-frequency current signals. The low-frequency current signal, specifically the dark current, is removed at the output stage. Fig. 5 explains the principle of dark current removal. The final transfer function of the output voltage (V_{out}) for input current (I_{Sense}) can be calculated as follows:

$$\frac{V_{out}}{I_{Sense}} = \left(\frac{Z_{in,2}}{Z_{in,1} + Z_{in,2}} - \frac{Z_{in,1}}{Z_{in,1} + Z_{in,2}} \right) Z_{out} \tag{4}$$

Z_{out} is the output impedance of the output node V_{out}.

III. RESULTS AND DISCUSSIONS

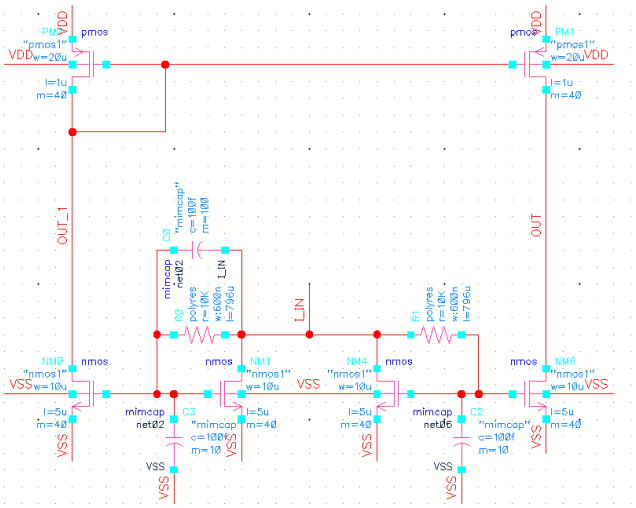

Fig. 6. Schematic of proposed photodiode sensor interface ICs.

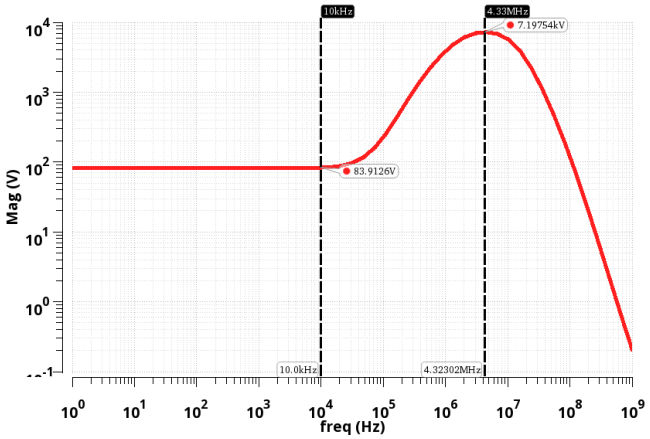

Fig. 7. Bode plot of output voltage from input current source (V_{out} /I_{Sense}).

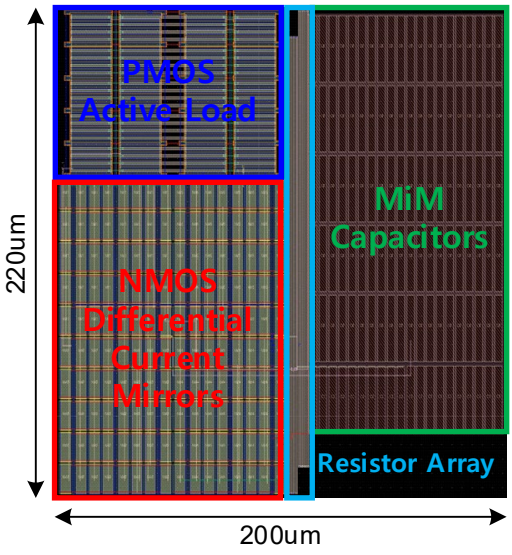

Fig. 8. Layout of proposed photo-diode sensor interface ICs.

Fig. 6. displays the schematic design results of the circuit as described above. As the values of each component in Fig. 6, 10 pF of C_f, 1 pF of C_g and 10 kΩ are used. All of the transistors are sized to satisfy the condition of 0.2 V $V_{d,sat}$. As shown in Fig. 7, the signal transfer function reaches a peak in the MHz range. If some current signal of photodiode is distributed over MHz, the gain of signal can be maximized. On the other hand, the low-frequency dark current signal can be filtered by the low gain over low frequency. The maximum ratio between dark current and signal current is simulated as 40 dB. The layout design of the proposed concept is shown in Fig. 8. The implemented circuit occupies an area of 0.13 mm^2, but it can be changed for each application.

IV. CONCLUSION

This paper proposes an integrated circuit for photodiode sensor interface utilizing differential current mirrors. Thanks to the differential current mirrors, the dark current from the photodiode can be cancelled effectively. In addition, this design methodology can be applied to other applications that are sensitive to dark current.

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