# Current-Mirror Based Ambient Light Rejection Technique for VLC Receiver

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***Abstract*—Ambient light interference is a significant hurdle as it creates unwanted DC current in optical receivers used for visible light communication, infrared communication, etc., that face solar irradiance in the daytime or unwanted light sources such as bulbs at night. This paper presents a current mirror-based receiver topology. By introducing a current-to-voltage converter module, the receiver can handily remove the background interference. A prototype receiver is designed using a 180 nm CMOS process operating at a speed of 160 MHz. It can cancel up to 100 $\mu$A of DC background interference while maintaining a low power dissipation of 7 mW from a 1.8 V supply. Additionally, it achieves a transimpedance gain of 120 dB$\Omega$ and an input referred noise of 10 pA/$\sqrt{Hz}$.**

***Index Terms*—Ambient light interference, visible light communication, optical receiver, transimpedance amplifier, TIA**

## I. Introduction

Optical communication systems [1], which utilize light as the medium for transmitting information, have revolutionized the way data is shared over distances. At the core of these systems is converting electronic data into light signals, which are then transmitted through mediums such as optical fibers or free space. This method of communication offers numerous advantages, including ultra-high data transmission speeds, vast bandwidth capacities, and immunity to electromagnetic interference, making it a cornerstone of modern telecommunications infrastructure. Data are transmitted in such a system by modulating light intensity, typically from a light-emitting diode (LED) or a laser diode. The modulated light is then received by a photodetector, such as a photodiode, which converts the light back into an electrical signal. A critical component in an optical communication system on the receiver front is the transimpedance amplifier (TIA) [2] as the current generated by the photodetector is usually very weak, and amplification is needed for the signal to be further processed. The TIA plays a crucial role in this process, converting the small photo-current into a usable voltage signal with minimal noise, thus preserving the integrity of the transmitted data.

However, several design challenges exist in designing a high-performance TIA, particularly due to ambient light interference, which can introduce significant offset into the system. As a result, this overwhelms the weak signal generated by the photodetector, making it difficult for the TIA to accurately amplify the desired data signal without amplifying the unwanted noise. This issue is especially pronounced in environments with strong and varying light conditions, which can cause fluctuations in the signal-to-noise ratio (SNR), leading to errors in data transmission.

In biomedical applications, the optical interfaces that also utilize TIAs typically do not have stringent ambient light cancellation requirements, as their signal amplitudes only range from pA to nA [3], [4]. High-speed optical receivers deployed in data centers that utilize NRZ (non-return to zero) [5] or PAM4 (pulse amplitude modulation) [6] modulation schemes are also unaffected by ambient light because of the closed environment in which they are deployed. However, optical receivers used in visible-light communication (VLC) [7], infrared communication systems are severely affected by solar irradiance in the daytime or light sources such as bulbs at night, which introduces unwanted DC signals at the input of the receiver and must be canceled to achieve a high SNR.

One way to cancel the ambient light interference is by adding an active feedback loop (an error amplifier with an N-type (negative) [7]–[9] or a P-type (positive) [10] transistor around the TIA as shown in Fig. 1 (a)(b). Using this method, [7] reported a 5 $\mu$A of unwanted DC current cancellation, and [10] canceled out 3500 lx of ambient light interference. Another way to cancel the unwanted current is using active inductor-based topology [11], [12]. However, such design is best suited for low-speed applications (20 MHz), and a maximum of 50 $\mu$A [12] of cancellation is reported in such topologies [Fig. 1 (c)(d)].

In this work, we proposed an active feedback loop with a current-mirror-based topology to cancel the unwanted current. This topology employs a current-to-voltage block added between the error amplifier and the TIA. As a result, the system can handle unwanted DC currents with a much higher magnitude. The entire receiver is designed in a 180 nm CMOS technology and can cancel any ambient light interference up to 100 $\mu$A with TIA operating at 160 MHz.

## II. Proposed System Architecture and Principle of Operation

The main challenge in VLC communication systems is the range/distance at which the VLC receiver can receive signals without sacrificing the signal integrity. Ambient light interference is the main reason which affects this range due to the presence of natural sunlight in outdoor conditions and fluctuating light conditions in indoor environments [13]. Hence, it is essential to include the cancellation mechanism in the receiver system to eliminate ambient light interference.

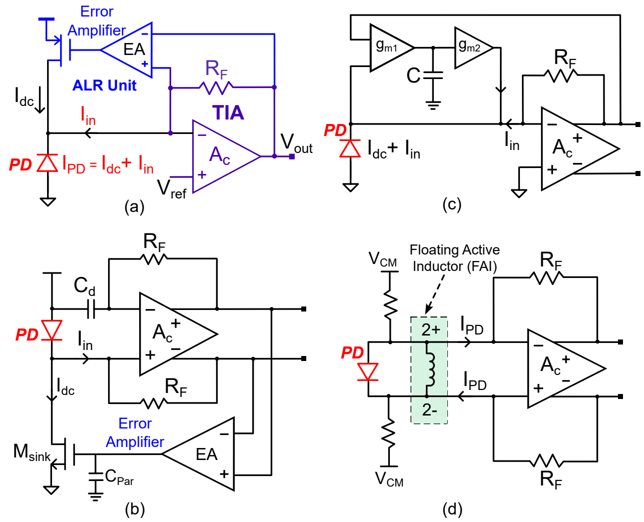


Fig. 1. Various ambient light cancellation techniques (a) and (b) employing single NMOS/PMOS device to sink ambient Dc; (c) and (d) utilizing active inductor.

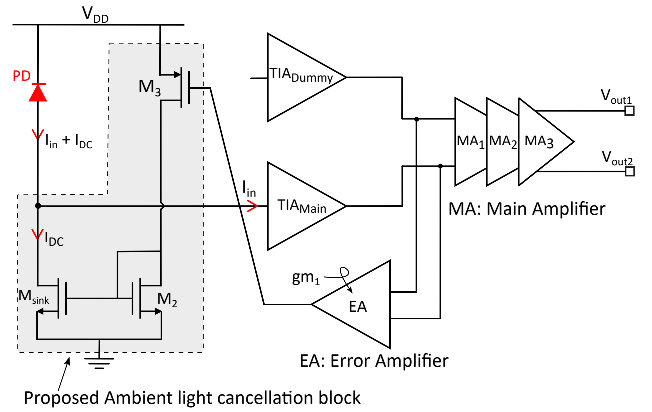


Fig. 2. TIA design employing proposed current-mirror based ambient light rejection scheme.

The proposed design, as seen in Fig. 2, has a TIA acting as a current-to-voltage converter, followed by a differential amplifier (including a common-mode-feedback mechanism) to provide gain and minimize offset voltage. To cancel the DC ambient photo-current a current mirror based topology with an error amplifier is implemented in the design as it helps in, a) reducing the noise, b) stability of the system and c) and in mitigating greater magnitude of unwanted DC current. Analysis demonstrating how this topology helps in mitigating higher magnitude of ambient interference is shown below:

The transfer function of ambient DC photo-current cancellation block shown in Fig. 1 (a,b). can be expressed as:

$$\frac{V_{\mathrm{o}}}{I_{\mathrm{ac}}}(s) = \frac{R_{\mathrm{f}}}{(1 + L(s))} \tag{1}$$

where $V_{\mathrm{o}}$ is the output voltage, $I_{\mathrm{ac}}$ is the input modulated current and $L(s)$ is the closed loop gain which is further expressed by

$$L(s) = R_{\mathrm{f}} \cdot \mathrm{Av}_{\mathrm{erroramp}} \cdot \mathrm{gm}_{\mathrm{sink}} \tag{2}$$

where $R_{\mathrm{f}}$ is the gain of TIA, $\mathrm{Av}_{\mathrm{erroramp}}$ represents the transfer function of an error amplifier and $\mathrm{gm}_{\mathrm{sink}}$ is the transconductance of $M_{\mathrm{sink}}$ in the feedback loop. The transfer function of the error amplifier is given by

$$\mathrm{Av}_{\mathrm{erroramp}} = \frac{A_{\mathrm{DC}}}{(1 + s/\omega_{\mathrm{p1}})} \tag{3}$$

where $\omega_{\mathrm{p1}} = 1/R_{\mathrm{out}}C_{\mathrm{par}}$ is the dominant pole, (1) can be further rewritten as

$$\frac{V_{\mathrm{o}}}{I_{\mathrm{ac}}}(s) = \frac{R_{\mathrm{f}}}{(1 + \frac{R_{\mathrm{f}} \cdot A_{\mathrm{DC}}}{(1+s/\omega_{\mathrm{p1}})} \cdot \mathrm{gm}_{\mathrm{sink}})} \tag{4}$$

By simplifying, we get

$$\frac{V_{\mathrm{o}}}{I_{\mathrm{ac}}}(s) = \frac{1 + s/\omega_{\mathrm{p1}}}{A_{\mathrm{DC}} \cdot \mathrm{gm}_{\mathrm{sink}}(\frac{1+s}{R_{\mathrm{f}} \cdot A_{\mathrm{DC}} \cdot \omega_{\mathrm{p1}} \cdot \mathrm{gm}_{\mathrm{sink}}})} \tag{5}$$

Assuming $R_{\mathrm{f}}A_{\mathrm{DC}}\omega_{\mathrm{p1}}\mathrm{gm}_{\mathrm{sink}} \gg 1$, the high pass response of the overall TIA is

$$\omega_{\mathrm{p}} = R_{\mathrm{f}} \cdot A_{\mathrm{DC}} \cdot \omega_{\mathrm{p1}} \cdot \mathrm{gm}_{\mathrm{sink}} = \frac{R_{\mathrm{f}} \cdot A_{\mathrm{DC}} \cdot \mathrm{gm}_{\mathrm{sink}}}{R_{\mathrm{out}} \cdot C_{\mathrm{par}}} \tag{6}$$

Based on (6), the major limitation of employing a single transistor is that the magnitude of slow varying ambient interference DC current that can be sunk/diminished at a frequency below 50 Hz is less. In order to increase the ability of the design to sink in higher value of DC current there is a need to minimize $\omega_{\mathrm{p}}$. Therefore, to minimize $\omega_{\mathrm{p}}$ with a moderately small $\mathrm{gm}_{\mathrm{sink}}$, we need a very large $C_{\mathrm{par}}$ at the output of the error amplifier. In the proposed design (Fig. 2), a transconductance block $\mathrm{gm}_1$ and a current-to-voltage block $1/\mathrm{gm}_2$ are inserted between the error amplifier and the DC sink transistor $M_{\mathrm{sink}}$ to control the current to be sunk. Hence, the new passband response of the proposed TIA can be expressed as:

$$\omega_{\mathrm{p}} = \frac{R_{\mathrm{f}} \cdot A_{\mathrm{DC}} \cdot \mathrm{gm}_{\mathrm{sink}} \cdot \frac{\mathrm{gm}_1}{\mathrm{gm}_2}}{R_{\mathrm{out}}C_{\mathrm{par}}} \tag{7}$$

By making $\mathrm{gm}_1/\mathrm{gm}_2 \ll 1$, we can minimize $\omega_{\mathrm{p}}$ to a very low frequency, As demonstrated in eq (7), $\omega_{\mathrm{p}}$ can be reduced by maintaining small $\mathrm{gm}_1$, without the necessity of very small $\mathrm{gm}_{\mathrm{sink}}$ to decrease $\omega_{\mathrm{p}}$. Subsequently, $R_{\mathrm{out}}$ and $C_{\mathrm{par}}$ need to be maximized for the lower $\omega_{\mathrm{p}}$.

## III. Results and Discussions

To simulate the design, we have used a silicon pin photodiode (PD) (VISHAY BPV 10), which has a high sensitivity within the visible light region [14] and has an 11 pF input capacitance. For TIA we have selected regulated gate cascode (RGC) based design as it provides low input impedance nullifying the effect of high PD capacitance [15]. Emulating the real time conditions, a 200 ps of rms jitter is introduced in the pseudo-random bit sequence (PRBS) $2^7 - 1$ signal, which is assumed to be deriving from a LED transmitter source having a bit error rate (BER) of 1E-9 (IEEE 802.15.7 standard) [16]. Ambient light interference is introduced into the system through a DC current source at the input of TIA. To understand the magnitude of ambient light interference, sunlight in a room with multiple artificial lights produces an illuminance of $\leq$ 1000 lux [17], a fluorescent bulb having a surfce area of 64 mm$^2$ would produce an illuminance of $\simeq$ 1500 lux; however, there is no definitive way for it to convert this value into current. Hence we have simulated the design upto 100 $\mu$A of ambient light DC current, assuming to compensate the disturbances in various surroundings.

Comparative analysis shows the functionality of single transistor based topology and current-mirror based topology through eye diagrams at different DC current mirroring the ambient light interference. Fig. 3 shows the eye diagram of single transistor based topology at 70 $\mu$A and 80 $\mu$A. Offset voltage in terms of zero-voltage-crossing is visible even at a magnitude of 70 $\mu$A and the eye is completely closed at 80 $\mu$A through which it can be deduced that such a system is not functionally viable for such high DC current modeling the ambient light interference. Simulations were done with

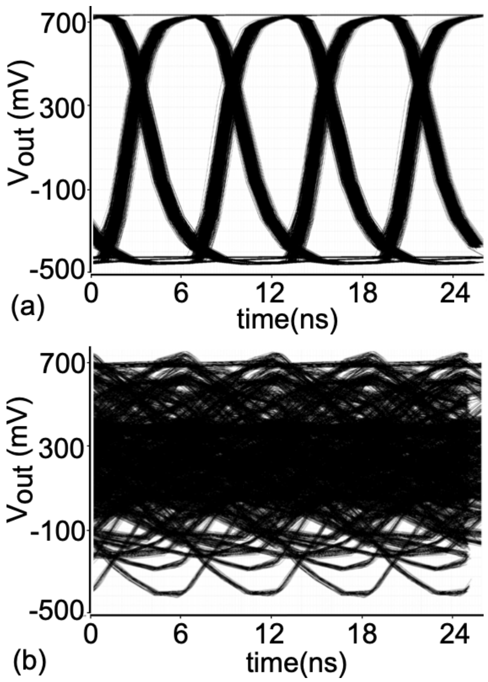


Fig. 3. Eye diagram for single transistor based topology for (a) 70 $\mu$A and (b) 80 $\mu$A.

the same settings for current mirror based topology and eye diagrams were captured as seen in Fig. 4 to have a better understanding of comparative functionality between the two designs. As can be seen, Fig. 4 current-mirror based proposed design is able to cancel the ambient light interference as large as 100 $\mu$A as it introduces a current-to-voltage block $1/\mathrm{gm}_2$ in order to control the amount of current that needed to be sunk effectively without increasing the noise.

Further simulations were done to check the ability of current-mirror based design in cancelling the ambient light interference. From Fig. 4(c) a visible offset is seen from the zero-voltage-crossing at 110 $\mu$A which could further be improved but there is a trade-off in terms of power consumption,

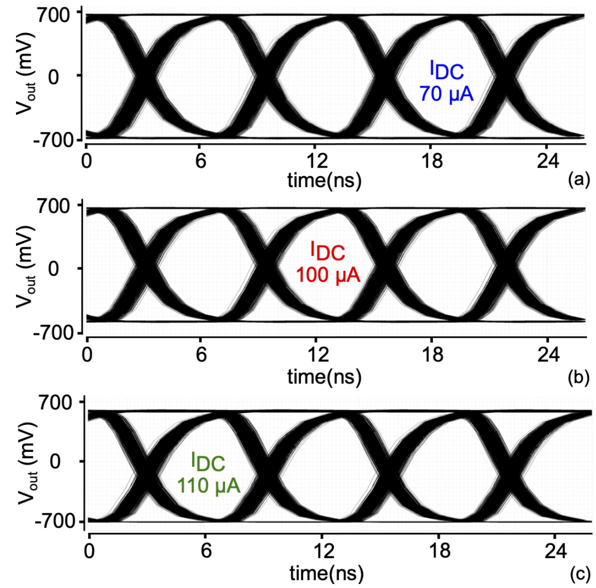


Fig. 4. Eye diagram at the output of the TIA for current mirror based topology at the input current of (a) 70 $\mu$A; (b) 100 $\mu$A and; (c) 110 $\mu$A to validate the maximum amount of ambient light interference cancellation

noise and stability of the system. Fig. 5 depicts the gain of both the designs and it can be seen that the current-mirror based design has a better band-pass response which helps in reduction of noise in the system. Fig. 6 depicts the graph for

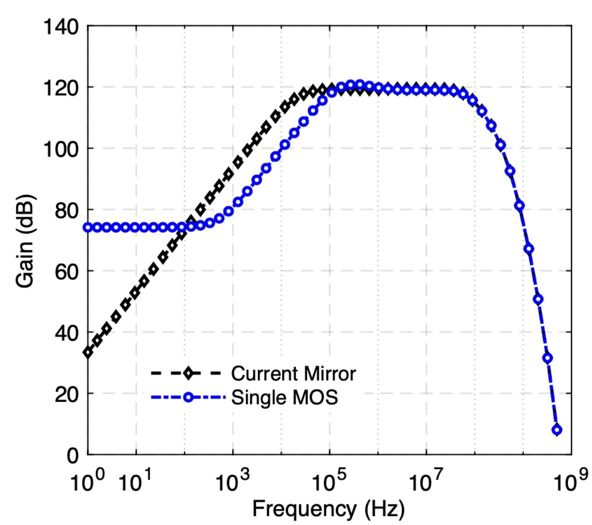


Fig. 5. Transfer function of both the system

input-referred noise for both the system, which is 80 $pA/\sqrt{Hz}$ and 10 $pA/\sqrt{Hz}$ for current-mirror based topology.

Table I presents the performance comparison with other VLC receiver designs. It can be deduced that the proposed current-mirror architecture can cancel a larger magnitude of ambient interference current (110 $\mu$A) while having a similar or higher transimpedance gain (120 dB), larger input capacitance (11 pF), a higher data rate using same technology node

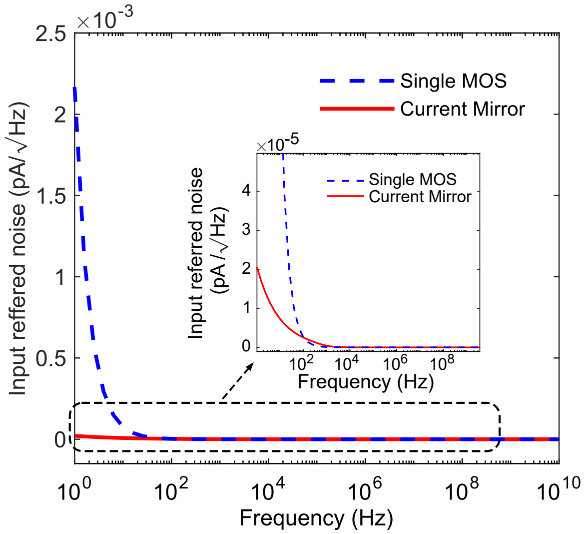


Fig. 6. Input-referred noise of both the system

TABLE I
PERFORMANCE COMPARISON WITH EXISTING VLC RECEIVER DESIGNS.

| | [9] | [14] | [11] | [7] | This work |
|---|---|---|---|---|---|
| Data Rate (MHz) | 25 | 25 | 2.5 | 80 | 160 |
| Technology (nm) | 180 | 180 | 180 | 180 | 180 |
| Power Dissipation (mW) | 2.2 | 2.2 | 0.5 | 3.2 | 7 |
| Ambient current DC ($\mu$A) | n/a | 50 | na | 70 | **100** |
| Gain (dB$\Omega$) | 128 | 124 | 98 | 94 | 120 |
| Input Capacitance (pF) | 7 | 7 | na | 7 | **11** |

(160 MHz @ 180 nm), with higher power consumption (7 mW) partially due to the requirement of canceling the effect of higher input capacitance.

## IV. CONCLUSION

Optical receivers used in visible-light communication, infrared, etc. communication systems continuously face solar irradiance in the daytime and light sources such as bulbs at night creating unwanted DC signals at the input of the receiver, which must be canceled to achieve a high SNR. In this paper, a current-mirror-based technique is used to cancel the unwanted ambient light interference. This technique introduces a current to the voltage converter block, enhancing the system's ability to sink the unwanted DC. The proposed system operates at 160 MHz designed in a 180 nm CMOS technology. It achieves an ambient light interference cancellation up to 100 $\mu$A while maintaining lower power consumption ($\sim$ 7 mW), which is higher but is needed to cancel the effect of higher input capacitance ($\sim$ 11 pF) of the photodiode.

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