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Analysis of Quenching Resistor Effect to Improve Stability of TIA Circuit for APD – A Secondary Publication

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Abstract: In this paper, since the Avalanche Photo Diode (APD) for Light-to-Voltage LTV conversion uses a high voltage in the operating range unlike other Photo Diodes (PD), the quenching resistor must be connected in series to prevent overcurrent when using the Transimpedance Amplifier (TIA). In such a case, quenching resistance may affect the transfer function of the TIA circuit, resulting in serious stability. Therefore, in this paper, by analyzing the effect of APD quenching resistance on the voltage and current loop transfer function of TIA, we proposed a loop analysis and a method for determining the quenching resistance value to improve stability. A TIA circuit with quenching resistance was designed by the proposed method and its operational stability was verified through simulation and chip fabrication.

Keywords: APD; TIA; Quenching resistor; Stability; Transfer function

1. Introduction

An Avalanche Photo Diode (APD) is a photonic device with high-speed and high-sensitivity performance that converts light into current. In the Light-to-Voltage (LTV) circuit for an APD, a Transimpedance Amplifier (TIA) is an important circuit that converts the output current of a Photo Diode (PD) into voltage.

Typically, a TIA can be simply implemented with an operational amplifier with a feedback resistor from the output to the inverting input [1], but this introduces polarization due to the parasitic capacitor of the PD, which leads to issues such as stability, bandwidth limitation, and oscillation of the output waveform [2]. Stability issues are usually analyzed as a closed-loop voltage loop transfer function where voltage noise is fed back by the TIA's feedback resistor [1-5], while issues such as settling time and bandwidth limitations are analyzed as a current loop transfer function where the PD's current follows the TIA's feedback resistor to the output in an open loop [6] and is compensated by a determined feedback capacitor. The compensated TIA must be accurately compensated for stability and settling time to avoid oscillations and under/over-shooting of the output waveform.

However, since the APD's operating point is formed at a high voltage, there is a possibility of overcurrent flow, so a quenching resistor is used outside the TIA circuit [7]. In this paper, we propose a direction for determining the value of the quenching resistor to improve stability through the analysis of the voltage and current loop of the TIA with such a quenching resistor. After that, it is verified by simulation and finally implemented into a chip to verify the actual behavior of the chip. This paper is organized as follows: In **Section 2**, the effect of quenching resistor on the stability and settling of TIA is analyzed by comparing the existing compensated TIA loop analysis with the TIA loop analysis including quenching resistor, and the method of determining the resistor value is discussed in **Section 3**.

2. Analyzing quenching resistance impact and determining resistance value

When using APD, the operating point is formed at high voltage, so there is a possibility of overcurrent flow. Therefore, a quenching resistor is used outside the TIA. We first analyzed the stability of the compensated TIA without a quenching resistor. This was done by performing a voltage loop analysis to analyze the effect of noise, and a current loop analysis was performed to analyze the bandwidth and settling effect on the input current. Then, the voltage and current loops of the compensated TIA with a quenching resistor were analyzed to determine the stability and bandwidth. Lastly, the method for determining the quenching resistor value is presented.

2.1. Analyzing compensated TIA loops without quenching resistors

Figure 1 shows the compensated TIA without quenching resistors, while **Figure 2** is a block diagram of the voltage/current loop analysis used to analyze the stability and bandwidth of a compensated TIA without quenching resistors. The noise is modeled as a voltage source V_n, and the APD is modeled as an equivalent circuit with a current source I_{in}, a capacitor C_{PD}, and a resistor R_{PD}. Drawing a block diagram to interpret the voltage and current loops of the TIA using **Figure 2** yields **Figures 3 and 4**.

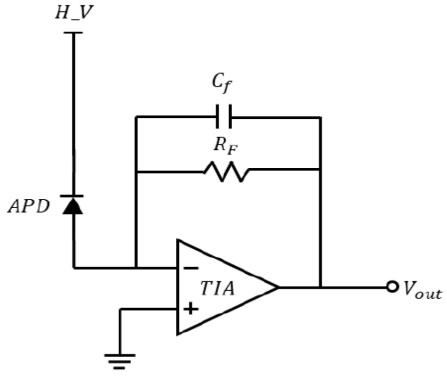

Figure 1. Compensated TIA without quenching resistor

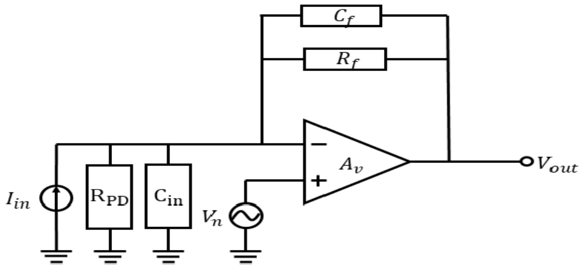

Figure 2. Compensated TIA voltage/current loop analysis block diagram without quenching resistor

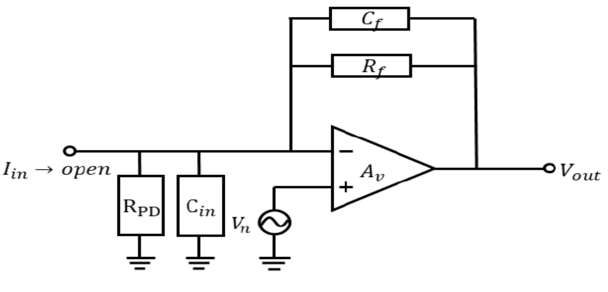

Figure 3. Compensated voltage loop analysis block diagram without quenching resistor

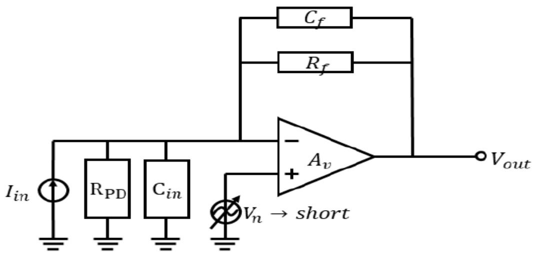

Figure 4. Compensated current loop analysis block diagram without quenching resistor

The loop gain for the voltage loop in Figure 3 is shown in Equation (1), and the poles and zeros are calculated as in Equation (2).

$$A_v \bullet \beta = \frac{\frac{R_{PD}}{R_{PD}+R_f}(1+sC_fR_f)}{1+s(R_{PD}\parallel R_f)(C_f+C_{in})} \bullet \frac{A_0}{1+\frac{s}{p1}} \tag{1}$$

$$f_{p1} = \frac{p1}{2\pi}, f_{p2} = \frac{1}{2\pi(R_{PD}\parallel R_f)(C_f+C_{in})} \tag{2}$$

$$f_{z1} = \frac{1}{2\pi R_f C_f}$$

Where C_{in} refers to all capacitors visible at the input, including the APD's capacitor (C_{PD}), and R_{PD} refers to the APD's resistance. In addition, A_0 represents the DC gain of the amplifier and P_1 represents the pole point of the amplifier.

Analyzing the current loop in **Figure 4**, the open-loop gain is shown in Equation (3), and the center frequency w_o and Q factor are shown in Equation (4).

$$\frac{V_{out}}{I_{in}} = -R_f \bullet \frac{\frac{A_0\,p1}{C_{in}R_f}}{s^2+sp1\left(1+\frac{C_f A_0}{C_{in}}\right)+\frac{A_0\,p1}{C_{in}R_f}} \tag{3}$$

$$\omega_0 = \sqrt{\frac{A_0\,p1}{C_{in}R_f}}, Q = \frac{1}{1+\frac{C_f A_0}{C_{in}}}\sqrt{\frac{A_0}{C_{in}R_f p1}} \tag{4}$$

2.2. Loop analysis of TIAs with quenching resistors

Since the APD used at high voltage is likely to overcurrent during LTV conversion, a TIA is constructed using an external quenching resistor (R_Q) as shown in **Figure 5**. To analyze the voltage/current loop in **Figure 5**, the noise is modeled as a voltage source Vn, and the APD is modeled as an equivalent circuit with a current source I_{in}, a capacitor C_{PD}, and a resistor R_{PD}, and the block diagram can be shown in **Figure 6**. The quenching resistor in **Figure 5**, like the C_{PD} of the APD, affects the stability and settling of the TIA.

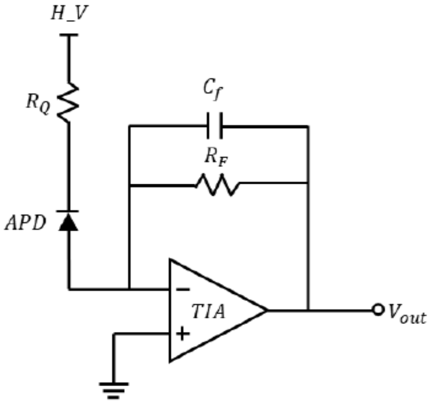

Figure 5. TIA with quenching resistor

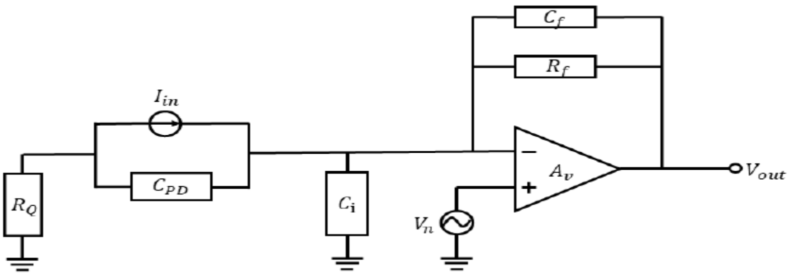

Figure 6. TIA voltage/current loop analysis block diagram with quenching resistor

The effect of quenching resistance was analyzed by studying the voltage and current loops of the TIA's transfer function. The block diagrams are shown in **Figures 7 and 8.**

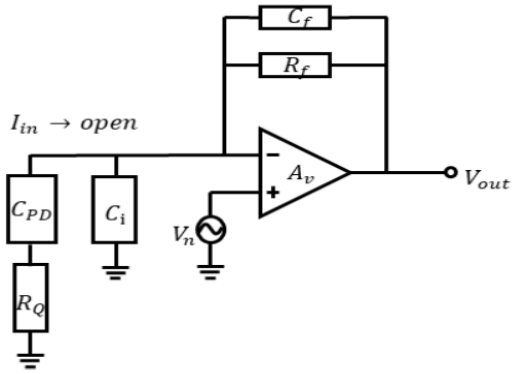

Figure 7. Voltage loop analysis block diagram with quenching resistors

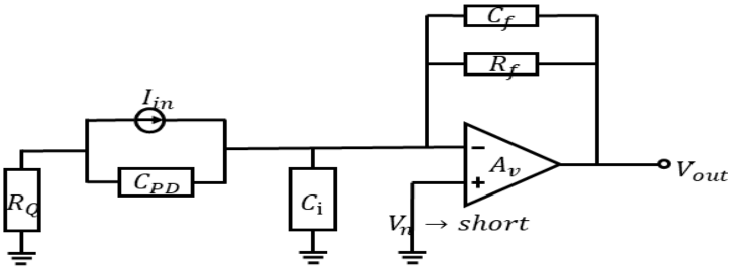

Figure 8. Current loop analysis block diagram with quenching resistor

In **Figure 7**, the loop gain is obtained from the voltage loop and through Equation (5).

$$A_v \cdot \beta \approx \frac{(1+sR_f C_f)(1+sR_Q C_{PD})}{1+sR_f(C_f+C_i)(1+sR_Q C_{PD})} \cdot \frac{A_V}{1+\frac{s}{p1}} \qquad (5)$$

In Equation (5), the value of C_i is equal to the total capacitor (C_{in}) at the input end of the TIA minus the capacitor (C_{PD}) of the APD. The zero and pole points are given by Equation (5).

From Equation (6), it can be seen that the poles and zeros caused by the quenching resistor meet and cancel each other, and can be analyzed as a quadratic system.

$$\begin{aligned} &f_{p1} = \frac{p1}{2\pi}, f_{p2} = \frac{1}{2\pi\, R_f\, (C_f + C_i)}, f_{p3} = \frac{1}{2\pi\, R_Q\, C_{PD}} \\ &f_{z1} = \frac{1}{2\pi\, R_f\, C_f}, f_{z2} = \frac{1}{2\pi\, R_Q\, C_{PD}} \end{aligned} \qquad (6)$$

In addition, if the loop analysis is performed for the current loop as shown in **Figure 8**, the open-loop gain is as shown in Equation (7).

$$\frac{V_{out}}{I_{in}} = \frac{-R_f \cdot \frac{A_V p1}{C_{in}\, R_f} \cdot \frac{1}{R_Q(C_i \parallel C_{PD})}}{[s + \frac{1}{R_Q(C_i \parallel C_{PD})}][s^2 + sp1(1 + \frac{C_f A_V}{C_{in}}) + \frac{A_V p1}{C_{in}\, R_f}]} \qquad (7)$$

From Equation (7), it can be seen that the quenching resistance is affected by R_Q by adding a pole point f_{p3} as shown in Equation (8) to the second-order system response, Equation (4).

$$f_{p3} = \frac{1}{2\pi\, R_Q(C_i \parallel C_{PD})} \qquad (8)$$

In short, based on Equation (1) and Equation (6), we can see that the quenching resistor does not affect the stability of the voltage feedback loop, i.e., the phase margin.

On the other hand, based on Equation (3) and Equation (7), the quenching resistor can limit the bandwidth by adding one more pole in the current open loop, making it a third-order system, and affecting the Q factor or

ω_o, causing overdamping in the output waveform of the TIA, which slows down the signal processing speed of the APD sensor.

2.3. Determining the value of the quenching resistor R_Q

Since the secondary system becomes a tertiary system due to the quenching resistance, the value of R_Q should be set so that the poles in Equation (3) become the dominant poles and the tertiary system is approximated like a secondary system as shown in Equation (9) below.

$$H(s)=\frac{\alpha\bullet\omega_0^2}{(s+\alpha)(s^2+\frac{\omega_0}{Q}s+\omega_0^2)}\approx\frac{\omega_0^2}{s^2+\frac{\omega_0}{Q}s+\omega_0^2} \qquad (9)$$

In order for a cubic system with one real root and a pair of complex number pair roots to be approximated as a quadratic system with a pair of complex number pair roots as shown in Equation (9), the real root must be at least 10 times larger than the real part of the pair roots. Therefore, the R_Q value can be set using an expression such as the following Equation (10). For Q factor, the value of Critical Damping is 0.5.

$$\frac{\omega_0}{2Q}=10\alpha,\quad R_Q=\frac{10}{\omega_0(C_i\parallel C_{PD})}\quad (Q=0.5) \qquad (10)$$

If the R_Q value is determined by the above equation, the existing complex number pole will become the dominant pole over the pole created by the R_Q, and the Q factor and ω_o of the existing TIA will not be affected. However, since the quenching resistance is for current limiting purposes, the current characteristics of the APD should also be considered, and care should be taken not to set a value that is too small.

3. Simulation and chip test results

Figures 9 and 10 are simulations of the voltage loop gain and current loop gain as a function of the quenching resistor. As mentioned in **Section 2**, the voltage loop gain was not affected by the quenching resistor, and for the current loop, the polarization points as shown in Equation (8) caused by the quenching resistor limited the bandwidth of the TIA. Therefore, it is confirmed that the external quenching resistor affects the stability of the TIA.

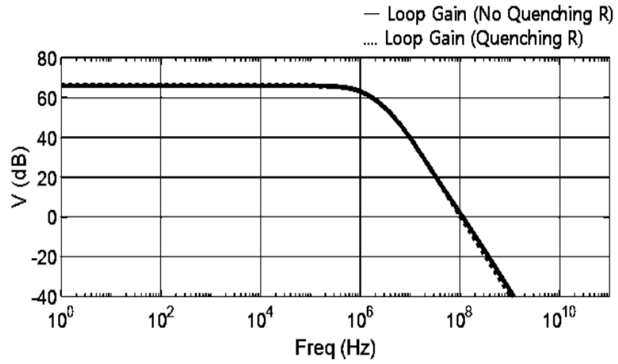

Figure 9. Voltage loop gain according to quenching resistor

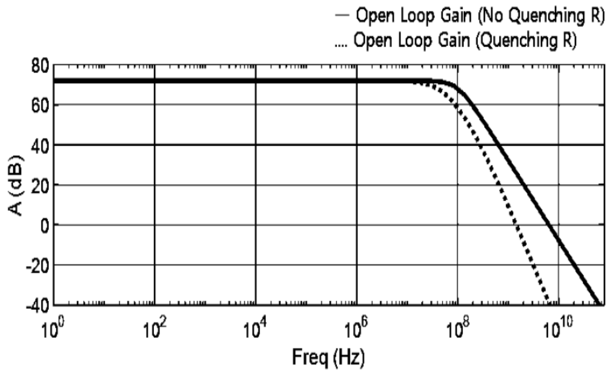

Figure 10. Current loop gain according to quenching resistor

It can also be seen that the polarization of Equation (8) affects the Q factor or ω_0, causing the output waveform of the TIA to overdamp as shown in **Figure 11**.

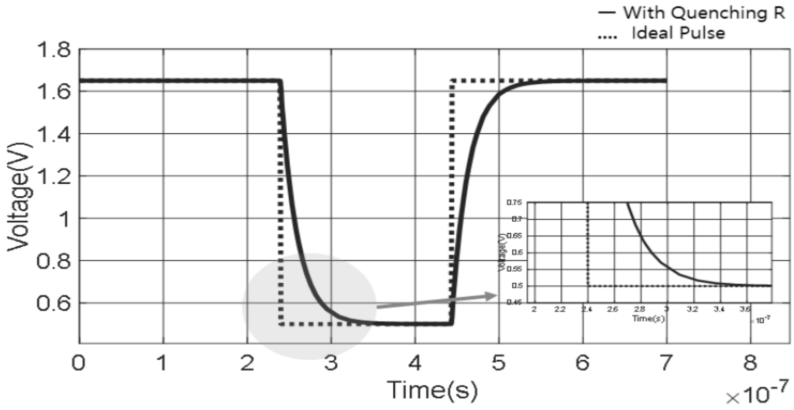

Figure 11. Overdamping of output waveform due to quenching resistor

To avoid overdamping as shown in **Figure 11**, the pole-zero map of the cascaded system was drawn, as shown in **Figure 12**.

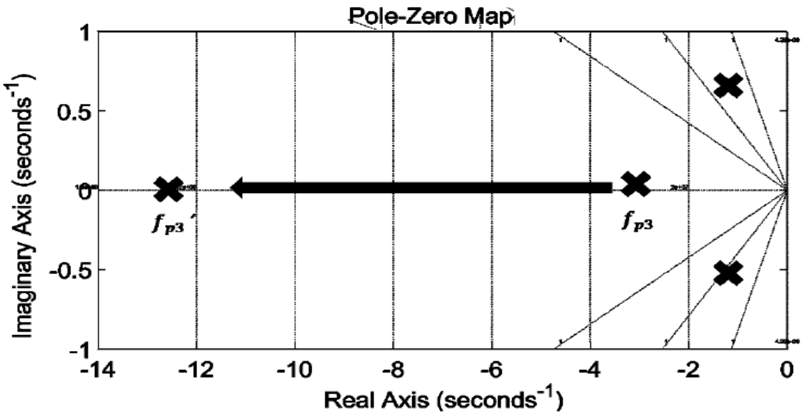

Figure 11. Pole-zero map of TIA with quenching resistor

If the value of the quenching resistor is set as shown in Equation (10) to move the real part of the pole point f_{p3} caused by the existing R_Q about 10 times larger than the real part of the complex number pair root as shown in **Figure 12**, the actual step response of the tertiary system is approximated as the step response of the secondary system without the quenching resistor, ignoring the step response caused by the quenching resistor, as shown in **Figure 13**.

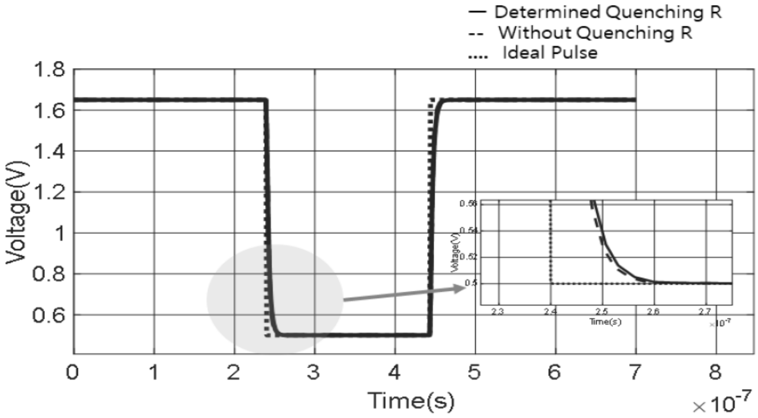

Figure 13. TIA's step response according to quenching resistor

Therefore, the TIA with the quenching resistor determined by Equation (10) has the same Q factor value of 0.5 as the conventional TIA without the quenching resistor and has a step response of critical damping, as shown in **Figure 13**.

This TIA was designed in CMOS 0.18 um process using Virtuoso tool, and the die chip drawing and layout drawing of the designed TIA are shown in **Figure 14**.

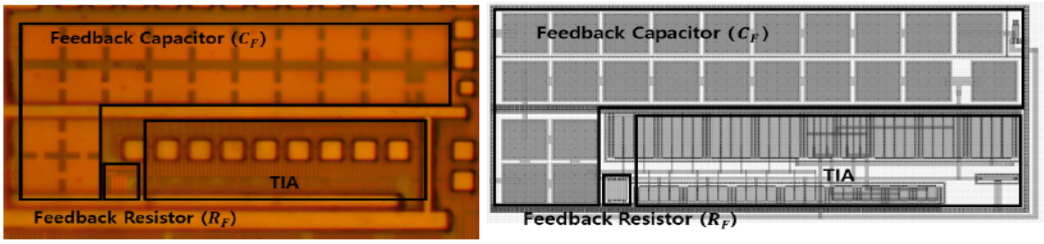

Figure 14. COS TIA die chip and layout

If the chip is fixed according to **Figure 14**, with the quenching resistor placed outside, overdamping would occur, as illustrated in **Figure 15**.

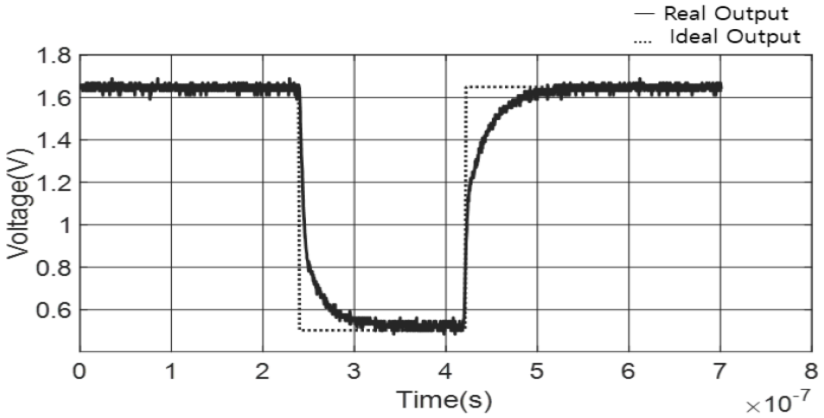

Figure 15. Overdamping of actual output waveform due to quenching resistor

If the R_Q value is set based on Equation (10) so that the quenching resistor does not affect the transfer function, a stable actual output waveform can be obtained, as shown in **Figure 16**.

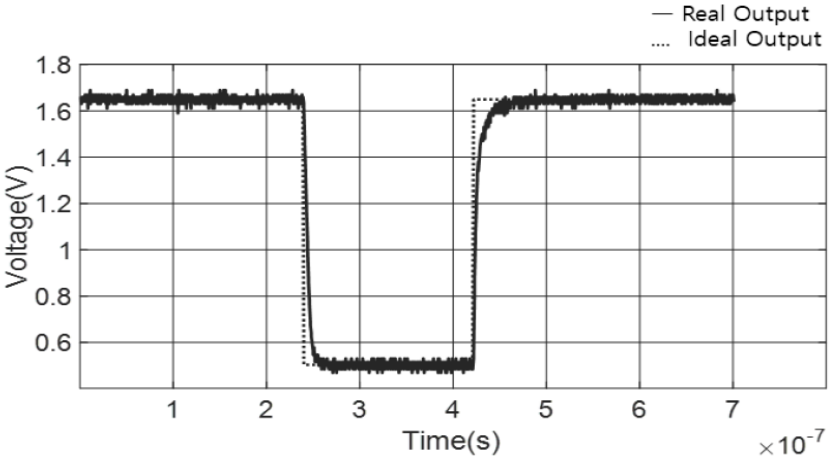

Figure 16. Stable actual output waveform

4. Conclusion

In order to improve the stability and settling time of the LTV circuit for APD, this paper analyzes the effect of the quenching resistor on the transfer function of each loop and proposes a method for determining the resistance value. Based on the proposed theoretical background, a TIA was designed by setting the quenching resistor value, and simulation and chip test results showed that the quenching resistor used to prevent overcurrent in the APD light sensor does not affect the stability of the voltage feedback loop, but has the same effect as bandwidth limitation in the current loop, proving the direction for determining the quenching resistor value.

This paper aims to contribute to the improvement of analog front-end performance of APDs by improving the bandwidth and stability of TIAs according to APD device characteristics by enabling the selection of an appropriate value of R_Q.

Disclosure statement

The authors declare no conflict of interest.

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