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Noise and Bandwidth Consideration in Designing Op-Amp Based Transimpedance Amplifier for VLC

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ABSTRACT

In a visible light communication (VLC) system, there are many modules involved. One of the important modules is Transimpedance Amplifier (TIA) that resides in the analog front-end receiver (Rx-AFE). TIA is responsible for performing signal conversion from current signal, which is provided from the photodiode (PD) to voltage signal. It is the reason why the TIA should be operating in low noise condition and wide bandwidth of frequency. These will enable a flexible coverage of the VLC system in performing its signal processing. Hence, in this research, we provide considerations of the noise and frequency bandwidth analysis in designing TIA to cope with the required design specification of a VLC system.

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1.   INTRODUCTION

Visible Light Communication (VLC) is an alternative method for wireless communication besides radio frequency (RF) based communication. It uses visible light with the wavelength ranging from 380 nm – 780 nm as communication medium [1]. VLC also has several advantages compared to RF and infrared (IR), such as high-speed communication and robustness against electromagnetic interference [2]. Moreover, it is considered to be efficient and safe for daily implementation [3]. Nowadays, VLC becomes a popular topic to investigate because of its potential and future vision of applications. Many kinds of research have been conducted to enable this optical wireless communication technology. There are several interesting topics which are extensively discussed, such as:

a. Modulation scheme: Pulse Width Modulation [4]-[7], Pulse Position Modulation [8], Binary Phase-shift Keying [9-10], Quadrature Phase-shift Keying [11], Quadrature Amplitude Modulation [12] and etc;

b. Analog front-end (AFE) design: AFE circuit [13]-[14], analog filter circuits [15]-[16], automatic gain controller design [17]-[19], LED driver design [20]-[24], TIA [25], and etc.;

c. VLC's noise investigation: [26]-[28];

d. Digital signal processing (DSP): DSP prototyping [29], Viterbi encoder [30]-[31], system-on-chip (SoC) [32-33], and etc.;

e. Simulation model [34];

f. The applications: robotics [35], transportation [36], medical devices [37], audio transmission system [38-39], light fidelity [40-41] and etc.

g. Security issues [42];

Moreover, VLC technology rises with the support of Light Emitting Diode (LED) technology development because LED can be switched in high speed which is required for VLC implementation. The use of LED for VLC has other benefits that can be achieved as well, such as better efficiency and longer lifetime than standard neon or light bulb. Hence, VLC technology is very interesting topic to investigate.

In a VLC system, there are many modules involved. One of them is Transimpedance Amplifier (TIA) which resides in the receiver (Rx). TIA is used to convert current signal produced by a photodiode (PD), to voltage signal. In order to make it works properly, TIA should operate in low noise condition and wide bandwidth of frequency. These conditions enable a flexible coverage and functionalities of the following signal processing in VLC system. Hence, in this paper, we observe the considerations in designing TIA in terms of noise and frequency bandwidth analysis to full fill the specification of a VLC system. Hopefully, it can give a picture of what to consider in designing Operational Amplifier (Op-Amp) based TIA for VLC system in terms of noise and bandwidth issues.

This paper is presented in several sections. The first one is the introduction, the second one is general VLC system and the third one is related theories on noise and bandwidth analysis. The noise and bandwidth analysis are presented in the fourth section along with case study. It will be followed and enclosed by concluding remarks and references, respectively.

2.   RELATED THEORIES

The general circuit of Op-Amp based TIA is depicted in Figure 2. From literature, we can find that the noise analysis on Transimpedance Amplifier (TIA) is extensively studied. In summary, there are three main sources of noise in TIA, they are input current noise, input voltage noise and the feedback resistor thermal noise [43-44]. The main equations of the noise from input current, input voltage and feedback resistor thermal are presented in Equation 1, Equation 2 and Equation 3 respectively.
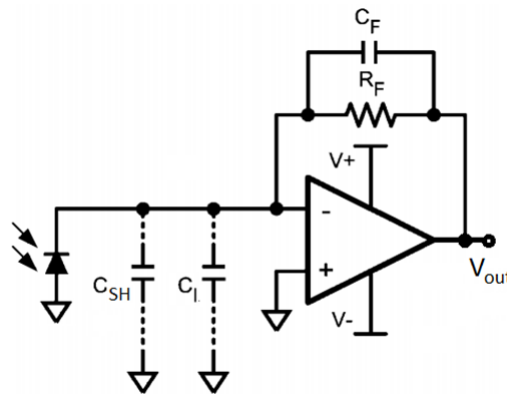

Figure 2. The general circuit of Op-Amp based TIA for VLC

$$N_{current} = I_n R_f \sqrt{\text{ENBW}}$$
(1)

$$N_{voltage} = N_2 \sqrt{\frac{\pi}{2} f_{p2}}$$
(2)

$$N_{R_f} = \sqrt{4kTR_f \text{ENBW}}$$
(3)

The noise from input current ($N_{current}$) is defined to be a result of multiplication among Op-Amp current noise density (I_n), feedback resistor (R_f) and the square root of equivalent noise bandwidth (ENBW). We can observe that $N_{current}$ is proportional with the value of all mentioned parameters. The definition of ENBW is given in Equation 4 and it is proportional to the -3dB frequency. The -3dB frequency itself is a function formed by gain bandwidth product frequency (f_{GBP}), feedback resistor (R_f) and total capacitor (C_T), which can be stated as Equation 5 for clear formulation. Here, the definition of the total capacitor is total capacitance emerged from photodiode (C_{sh}) and input of Op-Amp (C_i) as stated in Equation 6.

$$\text{ENBW} = f_{-3dB} \frac{\pi}{2} \tag{4}$$

$$f_{-3dB} = \sqrt{\frac{f_{GBP}}{2\pi R_f C_T}} \tag{5}$$

$$C_T = C_i + C_{sh} \tag{6}$$

The noise from input voltage ($N_{voltage}$) is defined to be a result of multiplication among plateau noise (N_2) and square root of second pole (f_{p2}) times $\pi/2$. With the assumptions that the first pole and zero of the output noise density is minimum a decade lower than the second pole, thus the output noise is equal to the plateau noise [43]. The equation of N_2 is presented in Equation 7. It includes the voltage noise density (e_n), Op-Amp input capacitance C_i, shunt capacitor from photodiode C_{sh} and the feedback capacitor C_f, as the function variables. In other hand, the f_{p2} is constructed by f_{GBP}, C_i, C_{sh} and C_f as presented in Equation 8.

The feedback capacitor C_f is placed across R_f to create a pole at f_p in noise gain function in order to maintain the stability [39] as illustrated in Figure 3. This placement definition of feedback capacitor C_f can be stated as Equation 9.

$$N_2 = e_n \left(\frac{C_i + C_{sh} + C_f}{C_f} \right) \tag{7}$$

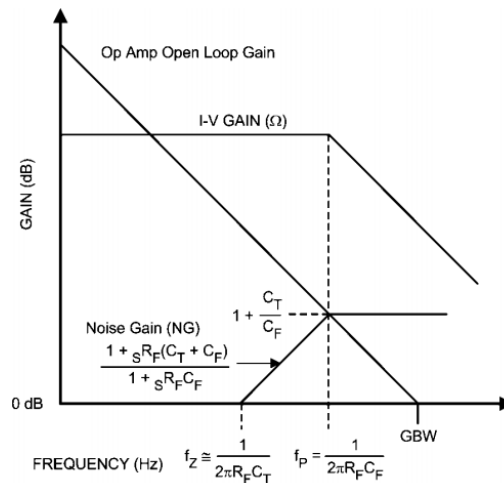$$f_{p2} = f_{GBP} \left(\frac{C_f}{C_i + C_{sh} + C_f} \right) \tag{8}$$

Figure 3. The bode plot graph of intersection between noise gain with Op-Amp open-loop gain [45]

$$C_f = \sqrt{\frac{C_T}{2\pi R_f f_{GBP}}} = \sqrt{\frac{C_i + C_{sh}}{2\pi R_f f_{GBP}}} \tag{9}$$

Last one is the noise from feedback resistor (N_{Rf}). It is defined by square root of multiplication among the Boltzmann constant (k), temperature in Kelvin (T), R_f, ENBW and value of 4. We have described

the definition ENBW, thus we can obtain the result faster using the previously calculated value of ENBW. All noise values from three noise sources have been obtained, thus we can calculate the total noise (N_{total}) occurred in the TIA circuit. Since, these three noise sources are independents, the total noise is the root-sum-square (RSS) from all of noise sources as stated in Equation 10. A low pass filter (LPF) on the output of TIA is beneficial to reduce the N_{total} if f_{p2} is much higher than the signal bandwidth f_{GBP} [45].

$$N_{total} = \sqrt{N_{current}^2 + N_{voltage}^2 + N_{R_f}^2} \tag{10}$$

3.   THE ANALYSIS AND CASE STUDY
3.1. Mathematical Analysis
From the third section, we see that there is a mathematical relation between noise and bandwidth frequency in designing TIA. Firstly, if we observe in input current noise $N_{current}$, we can derive Equation 11 from the existing equations. Noise of input current is mathematically proportional to the gain bandwidth product frequency (f_{GBP}). Hence, if we want to cover a wider bandwidth f_{GBP}, it could end up with the increasing of the input current noise $N_{current}$. Basically, the value of R_f and C_T can be chosen, so that the R_f is low and C_T is high to minimize the input current noise $N_{current}$. But of course, the selection of R_f and C_T depends on the capability of the chosen Op-Amp and its corresponding characteristics.

$$
\begin{aligned}
N_{current} &= I_n R_f \left(f_{-3dB} \frac{\pi}{2} \right)^{\frac{1}{2}} \\
&= I_n R_f \left(\left(\frac{f_{GBP}}{2\pi R_f C_T} \right)^{\frac{1}{2}} \frac{\pi}{2} \right)^{\frac{1}{2}} \\
&= I_n \left(\frac{\pi f_{GBP} R_f^3}{8(C_i + C_{sh})} \right)^{\frac{1}{4}}
\end{aligned}
\tag{11}
$$

Secondly, if we observe the input voltage noise $N_{voltage}$, we can derive Equation 12 from the existing equations. The input voltage noise $N_{voltage}$ is proportional to the gain bandwidth product frequency f_{GBP}. This manner is just like the $N_{current}$. Hence, if we want to cover wider bandwidth f_{GBP}, the input voltage noise $N_{voltage}$ could end up to be higher as well. The interesting part is that the total capacitance C_T is proportional to the input voltage noise $N_{voltage}$. This manner is different with $N_{current}$. Thus, these conditions need to be strategically compensated and could be a trade-off for Op-Amp devices selection.

$$N_{voltage} = e_n \left(\frac{C_i + C_{sh} + C_f}{C_f} \right) \left(\frac{\pi}{2} f_{GBP} \left(\frac{C_f}{C_i + C_{sh} + C_f} \right) \right)^{\frac{1}{2}}$$

$$= e_n \left(\frac{\pi}{2} f_{GBP} \left(\frac{C_i + C_{sh} + C_f}{C_f} \right) \right)^{\frac{1}{2}}$$

$$= e_n \left(\frac{\pi}{2} f_{GBP} \left(\frac{C_i + C_{sh} + \left(\frac{C_i + C_{sh}}{2\pi R_f f_{GBP}} \right)^{\frac{1}{2}}}{\left(\frac{C_i + C_{sh}}{2\pi R_f f_{GBP}} \right)^{\frac{1}{2}}} \right) \right)^{\frac{1}{2}} \tag{12}$$

$$= e_n \left(\frac{\pi}{2} f_{GBP} \left(\frac{C_i + C_{sh}}{\left(\frac{C_i + C_{sh}}{2\pi R_f f_{GBP}} \right)^{\frac{1}{2}}} + 1 \right) \right)^{\frac{1}{2}}$$

$$= e_n \left(\left[\frac{\pi^3}{2} R_f f_{GBP}^3 (C_i + C_{sh}) \right]^{\frac{1}{2}} + \frac{\pi}{2} f_{GBP} \right)^{\frac{1}{2}}$$

Lastly, if we observe the equation of feedback resistor noise N_{Rf}, we can extract this equation as presented in Equation 13. Position of the gain bandwidth product frequency (f_{GBP}) is proportional to the feedback resistor noise N_{Rf}. Basically, the value of R_f and C_T could be chosen, thus the R_f is low and C_T is high in order to minimize the N_{Rf}. It is similar with the idea in the $N_{current}$ section.

$$N_{R_f} = \left(4kTR_f f_{-3dB} \frac{\pi}{2} \right)^{\frac{1}{2}}$$

$$= \left(4kTR_f \left(\frac{f_{GBP}}{2\pi R_f C_T} \right)^{\frac{1}{2}} \frac{\pi}{2} \right)^{\frac{1}{2}}$$

$$= \left(4kTR_f \left(\frac{f_{GBP}}{2\pi R_f (C_i + C_{sh})} \right)^{\frac{1}{2}} \frac{\pi}{2} \right)^{\frac{1}{2}} \tag{13}$$

$$= \left(kT \left(\frac{2\pi f_{GBP} R_f}{C_i + C_{sh}} \right)^{\frac{1}{2}} \right)^{\frac{1}{2}}$$

These mathematical analysis lead to the main idea on low noise design of input current noise $N_{current}$, input voltage noise $N_{voltage}$ and feedback resistor N_{Rf}. In the first case, the $N_{current}$ is synchronous and convergent with N_{Rf}, because the R_f needs to be designed as low as possible and the C_T as high as possible for obtaining low noise design. Meanwhile in case of $N_{voltage}$, a bit contrary manner emerges, because both of the R_f and C_T need to be designed as low as possible. Besides, other important thing that we also need to consider is the selection of R_f and C_T depends on the operational characteristics of the Op-Amp device itself.

3.2. Case Study: Profiling Op-Amps for VLC TIA

In this sub-section, we investigate two kinds of Op-Amp for case study on designing TIA circuit for VLC system. Here, we use Op-Amp OPA656 and AD8011AN and give various condition of bandwidth as free variables in order to find the noise response. Other variables are designed to remain controlled in particular value as presented in Table I. The selection of values for these parameters depends on the datasheet for Op-Amp operational characteristics. Results of these experiments are presented in Figure 4 – Figure 7 as graphs.

Table 1. Op-Amps Parameters

Op-Amp	R_f (Ω)	C_{sh} (Farad)	C_i (Farad)	e_n (V/$\sqrt{\text{Hz}}$)	I_n (A/$\sqrt{\text{Hz}}$)
OPA-656	47×10^3	3.5×10^{-12}	3.4×10^{-12}	7×10^{-9}	1.3×10^{-15}
AD8011AN	47×10^3	3.5×10^{-12}	2.3×10^{-12}	2×10^{-9}	5.0×10^{-12}

Figure 4 is a graph of input current noise $N_{current}$ vs gain bandwidth product frequency f_{GBP}. We can see that noise performance for Op-Amp OPA656 is lower than AD8011AN. It shows that the current noise density I_n holds a dominant role in determining the $N_{current}$ here, R_f is proportional and C_T is disproportional. It is a bit contrary to the input voltage noise $N_{voltage}$ in Figure 5. In this case, value of $N_{voltage}$ is affected proportionally by the value of R_f, C_T and e_n. It is supported by Table I in which the capacitor and noise density values are higher in OPA656 than AD8011AN. Meanwhile, the feedback resistor noises N_{Rf} between these Op-Amps are close to each other as proven in Figure 6. If we trace the equations, we see that the difference between these two Op-Amps is only on capacitor value. A slight difference in capacitor values produce a slight difference in overall N_{Rf}.
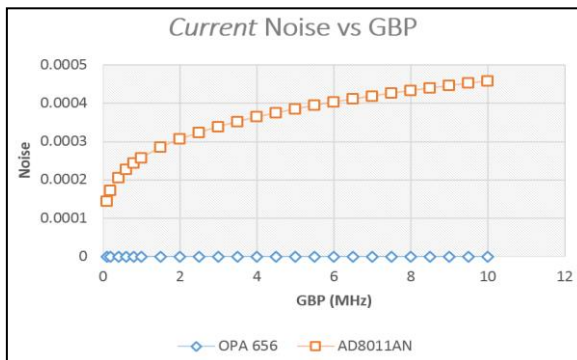

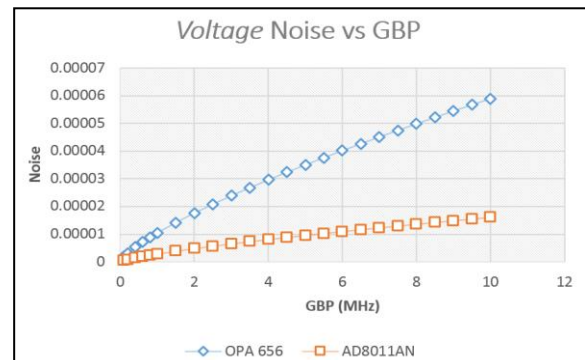Figure 4. Graph of $N_{current}$ vs f_{GBP}
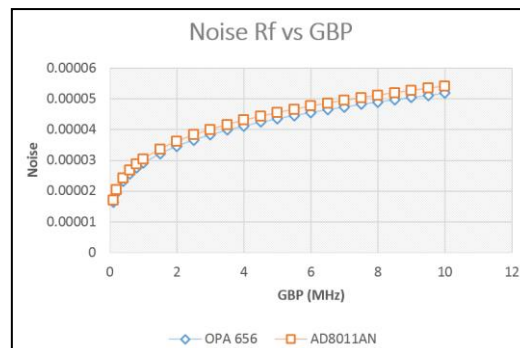

Figure 5. Graph of $N_{voltage}$ vs f_{GBP}

Figure 6. Graph of N_{Rf} vs f_{GBP}

In terms of the total noise N_{total}, Figure 7 shows that the N_{total} produced by OPA656 is lower than AD8011AN. Thanks to the huge gap on the current noise density I_n in two Op-Amps, which contribute a

huge gap in the total noise N_{total}. Hence, we can easily choose Op-Amp with the lower noise to use. It could be different if we use other kind of Op-Amp. Therefore, thorough design consideration are expected in selecting the best Op-Amp device for a particular designated VLC system.
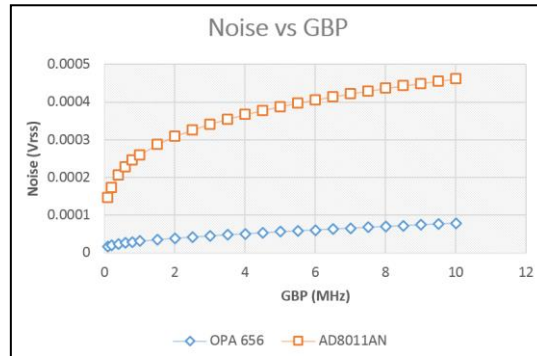

Figure 7. Graph of N_{total} vs f_{GBP}

4. CONCLUSION

The idea on designing a low $N_{current}$, $N_{voltage}$ and N_{Rf} for VLC TIA are not exactly the same for all of them. In case of $N_{current}$ and N_{Rf}, the R_f needs to be designed as low as possible and the C_T as high as possible for obtaining low noise design. Meanwhile in case of $N_{voltage}$, both of the R_f and C_T need to be designed as low as possible. Therefore, a thorough design consideration are expected, because we also need to consider the selection of R_f and C_T depends on the operational characteristics of the Op-Amp device itself for a particular designated VLC system.

NOTATIONS

The notation used throughout the paper are stated below,

Indexes:

$N_{current}$	Op-Amp input current noise [dB]
$N_{voltage}$	Op-Amp input voltage noise [dB]
N_{R_f}	Feedback resistor noise [dB]
N_{total}	Total transimpedance amplifier circuit noise [dB]
I_n	Op-Amp current noise density [A/√Hz]
R_f	Feedback resistor [Ω]
ENBW	Equivalent noise bandwidth [Hz]
N_2	Plateau noise [dB]
f_p	Pole frequency [Hz]
f_{p2}	Second-pole frequency [Hz]
f_{GBP}	Frequency of gain bandwidth product [Hz]
T	Temperature [K]
f_{-3dB}	Cut-off frequency or the –3dB frequency [Hz]
e_n	Voltage noise density [V/√Hz]
C_f	Feedback capacitance [F]
C_T	Total capacitance [F]

C_{sh} Photodiode's shunt capacitance [F]

C_i Op-Amp input capacitance [F]

Constants:

k Boltzmann's constant = $1.38 \times 10{-}23$ [J/K]

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