State-of-the-Art Logarithmic Transimpedance Amplifier With Automatic Gain Control and Ambient Light Rejection for fNIRS

Ehsan Kamrani*[a,b], S. H. Andy Yun[b], Frederic Lesage [a], Mohamad Sawan[a]
[a]Dept. of Electrical Engineering, Ecole Polytechnique, Montreal, QC, H3T1J4 Canada;
[b]Wellman Centre for Photomedicine, Harvard Medical School, Boston, MA, 02139 USA

BIOGRAPHY

Ehsan Kamrani: Ehsan received his B.Sc. degree in Biomedical engineering from SBMU, Iran, in 2002 and his Masters degree in Electrical and Control Engineering from TMU, Iran, in 2005. He has been with the Institute of Medical Engineering, Salamat-Pajooh-Bartar (05-09), MetaCo. (03-04), Ferdowsray (00,04), Saadat Co. (98-04) and Imen-Ijaz Inc. (99-00) working on design and development of biomedical imaging and real-time monitoring systems. From 2005 to 2009 he has been an Academic Member-Instructor in the Department of Electrical and Electronics Engineering, University of Lorestan, Iran. His expertises are on Analog integrated circuits, smart CMOS image sensors, wireless networked sensors, web-based control systems and biomedical signal/image processing. He published more than 30 papers in peer reviewed journals and conference proceedings. Since 2009 he has been doing his PhD on Biomedical Engineering at Polystim neurotechnologies Laboratory, Ecole Polytechnique, Montreal, Canada. He is working on design and implementation of an fNIRS photo receiver for real-time brain monitoring. From March 2012 he has joined Harvard Medical School and Wellman Center for Photomedicine, Massachusetts General Hospital in Boston, MA, USA working in an active bio-optics project for developing novel innovative technologies by integration of photonics and biological system aiming at developing a novel diagnostic optical instrument for medical applications.

TECHNICAL ABSTRACT

Logarithmic transimpedance amplifier (LogTIA) is practically useful in systems that need scale-invariant and wide dynamic range operation. Its sensitivity to the contrast (ac/dc) of the input and its scale-invariant fractional amplification is beneficial in several applications where percentage changes rather than absolute changes carry information. This photoreceptor was inspired by the operation of biological photoreceptors in turtle cones and bears many of its properties including higher ac gain than dc gain, a contrast-sensitive response, and a relatively wide dynamic range of operation. Unfortunately, the merit characteristics of this amplifier specially for biomedical imaging and optoelectronics circuits and systems are not introduced well and only a limited application of LogTIA in photodetectors implementation are reported.

In this paper we have introduced the unique characteristics of LogTIA as a state-of-the-art front-end circuit for photodetection especially in near infra-red region of light spectrum. Here we have designed and implemented a new LogTIA to be applied in functional near infra-red spectroscopy (fNIRS) photodetector front end. This is the first proposed and successfully designed and implemented application of LogTIA in a near infra-red photodetector front-end and in fNIRS application. In this circuit (Fig. 1), M1 act as the logarithmic amplifier transistor, M6-M7 provides the feedback resistor. M9 acts as a feedback transistor placed directly across the input and output terminals of the current mirror. Using this direct feedback topology, decrease the input impedance seen by the photodiode and improve the speed of the circuit by the cost of the lower output swing. Using logarithmic amplifier makes also the response to a fixed image contrast invariant to absolute light intensity and improves the dynamic range of the photodetector. The N1 transistor at the output of TIA, cause the circuit acts as a cascade current mirror, reduce the output voltage variation by boosting the output impedance and reduce the v_{DS} -mismatch effect. Using an automatic gain control and DC rejection feedback we have increased the sensitivity and BW. The transimpedance gain of the linear TIA increases the sensing speed by decreasing the time constant such that the rapid changes in the input are not filtered at the output. The input voltage (V_{in}) is kept at a virtual reference value (V_{ref}) by the feedback loop such hat it doesn't change by the variation of the input current, thus the current variations due to the Vin variation (e.g. due to early effects and other sensor effects), are

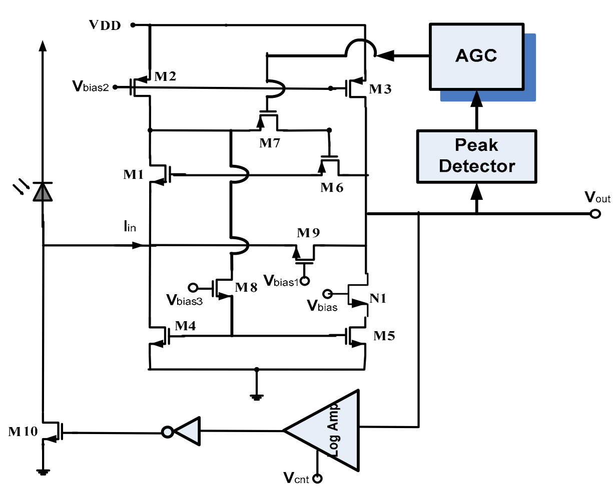
minimized. By increasing the power supply, the dynamic range of the output voltage can be maximized while maintaining the avalanche photodiode (APD) breakdown voltage at the input. In contrast, the logarithmic TIA shown in Fig. 1, uses a sub-threshold transistor as the feedback element with an exponential parameter of κ_s (the sub-threshold exponential coefficient of M_f) and a pre-exponential constant of I_{os}. The key motivation for using the logarithmic instead of linear sensing is that it is inherently sensitive to the contrast (ac/dc) of the input photocurrent signal. By assuming V_{ref} and considering that the i_{in} and v_{out} are the small changes in the operating-point current (I_{IN}) and voltage (V_{out}) respectively, the output voltage of the LogTIA is equal to:

$$v_{out}(s) = \frac{KT}{q}\left(\frac{i_{in}}{I_{IN}}\right)\left(\frac{A/(1+A)}{1+\frac{s(C_{in}/g_f)}{1+A}}\right) = \frac{KT}{q}\left(\frac{\Delta I_{IN}}{I_{IN}}\right)\left(\frac{A/(1+A)}{1+\frac{s(C_{in}/g_f)}{1+A}}\right) = V_{ref} + \frac{KT}{q\kappa_s} ln\left(\frac{I_{in}}{I_{Ios}}\right)$$

$$v_{out} = \left(\frac{dV_{out}}{dI_{in}}\right) i_{in} = \left(\frac{KT}{q\kappa_s} \times \frac{1/I_{Ios}}{I_{in}/I_{Ios}}\right) i_{in} = \left(\frac{KT}{q\kappa_s}\right) \times \left(\frac{i_{in}}{I_{in}}\right) = \left(\frac{KT}{q\kappa_s}\right) \times \left(\frac{i_{ac,in}}{I_{DC,in}}\right)$$

So in LogTIA, the output voltage is proportional to the ac/dc of the input current as expected. It converts the small fractional changes in input ($\frac{\Delta I_{IN}}{I_{IN}}$) into an output voltage while increasing the speed of the input time constant by the factor of (1+A). Contras to the linear TIA, The time constant of LogTIA depends on the operating point and varies linearly with I_{IN} (g_f depends on I_{IN}). The LogTIA provides a wide dynamic range operation with a moderate power supply voltage. The minimum detectable contrast in a LogTIA is not depends on the input current intensity because the BW and therefore integration interval of the system scales with input current so that a constant number of the electrons is always gathered during the sensing period. In linear TIA, the BW and subsequently the integration intervals of the system are fixed such that the minimum detectable contrast is worsened at low input intensities due to the gathering of the more electrons. The LogTIA can be considered as a linear TIA with a built-in gain controller, such that the feedback resistance (R_f) varies with I_{in} to keep the $I_{in}R_f$ fixed. In order to keep the photodetector gain stable under temperature and ambient light variations we develop an automatic gain monitoring and control (AGC) mechanism and an ambient light rejection circuit (include Log Amp, buffer and M10) on our proposed TIA circuit that also increase the input dynamic range.

Keywords: near infra-red spectroscopy, transimpedance amplifier, analog integrated circuit, logarithmic amplifier, ambient light noise rejection, automatic gain control, brain imaging



Parameter	Value	
	LogTIA	LogTIA+AGC and Noise Rejection
Fabrication technology	CMOS 0.18µm	CMOS 0.18µm
Supply voltage (V)	1.8	1.8
Max. Swing (V)	1.8	1.8
Max Gain	220 M	300 M
Power diss. (mW)	0.04	0.5
BW (MHz)	0.1-1000	0.001-5000
Input Noise at 1kHz (A/√Hz)	100 f	< 10 f
GBW/Power dis. (GHzΩ/mW)	5.5 M	3 G
Sensitivity (dBm)	-32	-42
Data rate (Gb/s)	3.04	3.4
Bit Error Rate (BER)	10^{-11}	10^{-13}
PRBS	$2^{31}-1$	$2^{33}-1$

Figure 1. Proposed logarithmic TIA with ambient light rejection and AGC loops (left), and its characteristics (right)