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High-Gain Transimpedance Amplifier (TIA) for Night Airglow Photometer

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Abstract

This paper describes a simple, inexpensive transimpedance amplifier (TIA) suitable to convert the fast current pulses delivered by photomultiplier tube of night airglow photometer into the corresponding voltage. Design criteria for the transimpedance amplifier are carefully selected to include low input bias current, offset voltage and noise. The operation of the transimpedance amplifier and the theoretical analysis of its gain are discussed. Theoretical and simulated results are compared with that of the developed high gain transimpedance amplifier. Correlations between photometer current readings and voltage output from the transimpedance amplifier are high and linear at both high and low airglow intensities. The test results and simulation involving class-leading FET operational amplifier are presented. A comparative analysis between two photomultiplier tube (PMT) amplifier circuits is carried out. One circuit is based on a conventional transimpedance amplifier connection and the other circuit is based on resistive-tee network connection. The results are satisfactory and show that the photometer amplifier performance can be improved by using resistive-tee network technique. These experimental results also underline the need for careful selection of electronic components, circuit layout and shielding if the capabilities of these devices are to be fully exploited.

Keywords: Photometer, Resistive tee-network, Transimpedance amplifier, Night airglow

Introduction

Night airglow photometers are regularly operational from a low latitude station, Kolhapur (16.4^{0}N, 74.15^{0}E; 10.6^{0}N dip lat.) in India by the Indian Institute of Geomagnetism, Navi Mumbai. Photometer is an instrument, used mainly for the measurement of light intensity of night airglow and it consists of an optical telescope, interference filter and a photomultiplier tube [1] as a detector. Photomultipliers are still the preferred light detectors for many applications, principally because they offer a unique combination of large detection area together with an internal amplifier of exceptional performance. The photomultiplier tube (PMT) is a current generator, which produces a current pulses. For encoding it requires conversion to an equivalent voltage. Even with the million fold gain of the PMT, the output current is very small, of the order of picoamperes for low airglow signal. This current has to be amplified sufficiently for the analog to digital converter to work properly without introducing gain instabilities or noise.

Transimpedance amplifier is an excellent device for converting current to voltage in most current-measurement applications. The current source feeds into the virtual ground of an op-amp, and the gain of transimpedance can be adjusted by changing the value of a single resistor. We developed a simple, inexpensive transimpedance amplifier that processes the current generated by a photomultiplier radiation sensor to a voltage range that is easily recordable by a computer, data loggers and can also used for voltage to frequency conversion.

In this paper we describe a simple linear amplifier circuit for converting the current generated in a photomultiplier tube to a voltage output of arbitrary range, however, Pearcy [2] describes a simple linear amplifier circuit for converting the current generated by a photodiode to a voltage output. Here we report the development and testing of a simple, inexpensive transimpedance amplifier, designed for the measurement of very small currents in the range of 10 nA to 100 nA of the night airglow photometer system using photomultiplier tube. The design takes advantage of low-leakage, low-power, low bias FET operational amplifiers.

The transimpedance amplifier is developed for photomultiplier tube with high switchable gain and low read out noise. The transimpedance amplifier uses a resistive-tee feedback network to achieve high sensitivity. We discuss the operation of the transimpedance amplifier, and present a theoretical analysis of its gain. Theoretical results are compared with the developed transimpedance amplifier results. In addition, simulated results are also presented and compared with theoretical and practical results.

The Photometer Circuits

Due to their excellent linearity, gain accuracy, high input resistance, high open-loop gain, low noise, low bias current, low offset and wide band width, among other characteristics, operational amplifiers are commonly used in monitoring small current pulses from a photomultiplier tubes (PMT) [3].

In addition, the energy transmitted by light to a photomultiplier tube can be measured either as a voltage or current output. However, according to [4], in spite of the fact that there are a variety of amplifier connections used for monitoring PMTs, most of them are based on the basic transimpedance amplifier (TIA) connection as shown in Fig.1, in which the PMT output is monitored as current. R_f is the negative feedback resistor used to convert the photocurrent into an output voltage as a linear function of light intensity.

According to [4], the circuit shown in Fig. 1 has both advantages and disadvantages. On the one hand, if the PMT exhibits very good conversion characteristics and the ambient temperature is held constant at the optimum value, this circuit provides a very reliable output voltage.

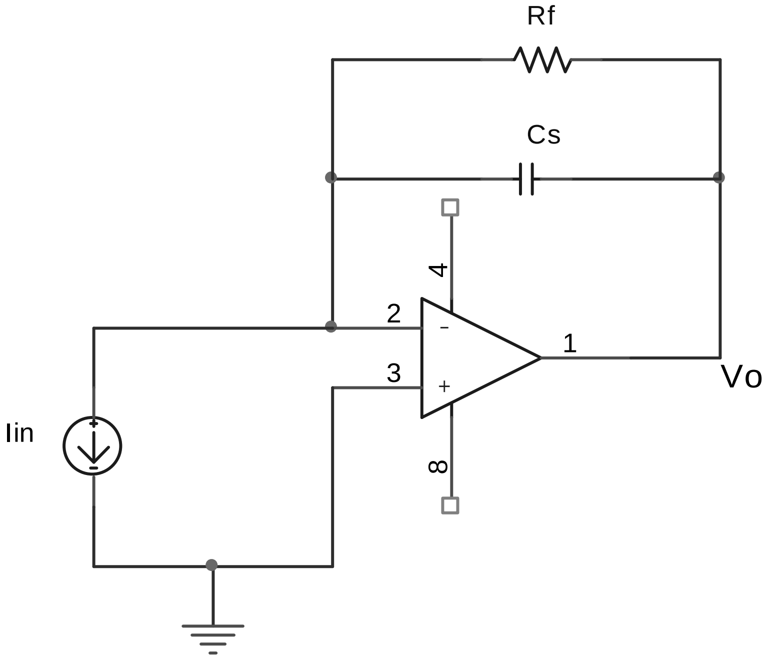


Figure 1: Circuit diagram of basic transimpedance amplifier.

On the other hand, in the field or in applications in other which the temperature is not constant, as the responsively, the shunt resistance, the junction capacitance and the dark current of the PMT are temperature dependent, and the noise is dependent upon the characteristics of the PMT and the operating conditions, the uncertainty of measurement of linear photometer circuits based on conventional TIA connections increases. Therefore, photometer circuits based on conventional TIA connections are not robust [5].

From the Control Engineering point of view, in Fig. 1, the sensor is placed in an open-loop system in which the feedback network cannot reject the negative effects of the disturbance and noise that corrupt the relevant information coming from the PMT. Therefore, changes in the ambient temperature, noise in the electrical components, noise coming from the power supply, etc. make the output of the system to deviate considerably from its true value [6].

Circuit Analysis

The classic transimpedance amplifier circuit is commonly used for high sensitivity (zero-bias) PMT monitoring. It consist of a single operational amplifier and feedback resistor, the latter occasionally shunted by a capacitor for bandwidth limitation or gain stabilization, the simplicity of this circuit belies its effectiveness. With high speed operational amplifier, the transimpedance gain will be rolled off by the combination of stray and supplemental capacitance Cs. The signal (transimpedance) gain, for an operational amplifier is then given by equation (1)

$$Asig = \frac{Vo}{Iin} \qquad \text{……………………. (1)}$$

In the circuit shown in Fig. 2, resistors R_1 and R_2 form a voltage divider that presents a fraction of the output voltage to R_f. Provided R_1 and R_2 are small compared to R_f, the effective feedback resistance, defining the transimpedance gain, is given by

$$K \approx R_f\left(1 + \frac{R1}{R2}\right) \qquad \text{……………………. (2)}$$

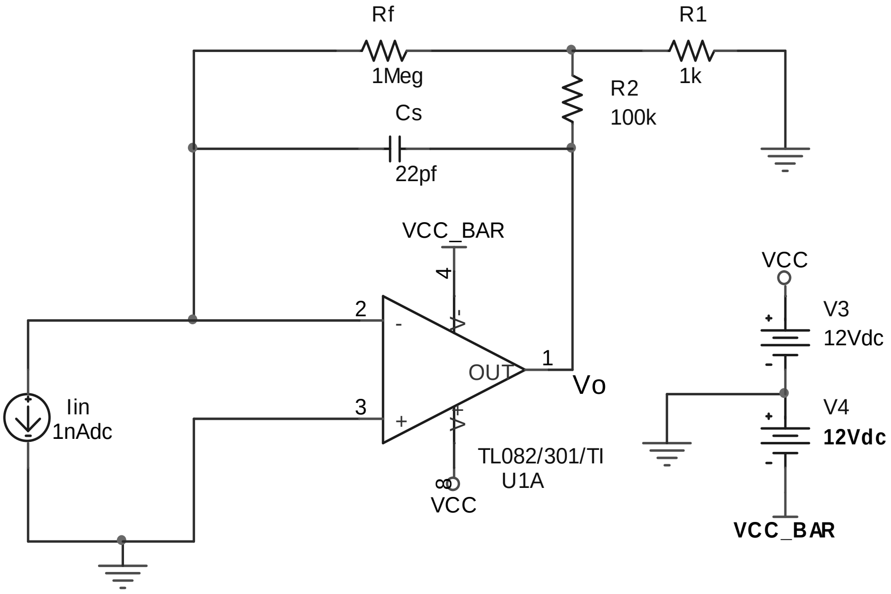


Figure 2: Circuit diagram of transimpedance amplifier using resistive tee-network.

This allows high effective feedback resistances to be realized using relatively small values of resistance. This is especially useful in high bandwidth, high gain, systems that would otherwise be limited by effect of stray capacitance on R_f. A further benefit of the resistive tee-network is a reduction in the output offset arising from the amplifier's bias current requirement by a factor of $\left(1 + \frac{R1}{R2}\right)$ albeit at the expense of a proportional increase in the output error resulting from amplifier offset voltage. [7]

A single very-high resistance will give better performance; the tee-network can overcome such problems as gain adjustment and avoids the need of a large value resistor. The resistive tee-network used in the circuit shows a trick for producing the effect of a large feedback resistor using smaller values. In this case the feedback network behaves like a single 100MΩ resistor in the standard inverting amplifier circuit giving a voltage gain of $100*10^6$. Resistor values above 100MΩ are not readily available. This present technique has the advantage of using resistors of convenient values without the problems of stray capacitance, which comes with very large resistor values.

The advantage of the resistive tee-network is that it can achieve sensitivity of the order for 0.1V/nA by small values of resisters and variable potentiometer, whereas the resultant feedback resistance value is very high of the order of 100MΩ. This is justified as follows.

The output voltage is given by equation (3),

$V_O = -K* R* .I_{in}$ ……………………. (3)

Where, $K = 1 + \frac{R2}{R1} + \frac{R2}{R}$

To achieve a sensitivity of 0.1V/nA,

KR = 0.1V/nA = $\frac{0.1}{10^{-9}}$

= 100MΩ

Suppose R = 1MΩ and multiplied by 100 to meet required specifications

∴ K = 100

Thus

$$1 + \frac{R2}{R1} + \frac{R2}{R} = 100$$

If R1 = 1KΩ,

Then $1 + \frac{R2}{10^3} + \frac{R2}{10^6} = 100$

∴ R2 = 99KΩ ≈ 100KΩ

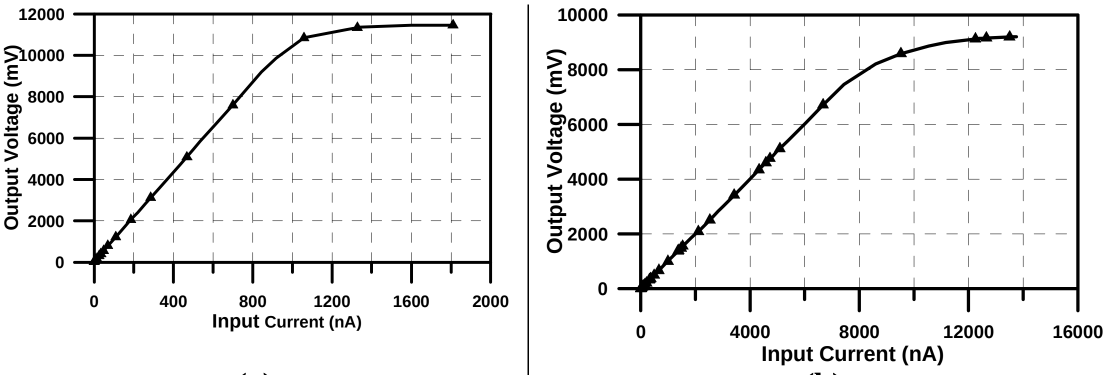
R2 can be a potentiometer for exact adjustment of KR value i.e. gains of the amplifier.

The output voltage for a single detected photon is of the order of 10mV at 50 Ω. This is much more than the noise of any reasonable electronic recording device. Thus, the PMT easily ‘sees’ the individual photons of the light signal. Further amplification cannot increase the number of signal photons and therefore does not improve the SNR. A photomultiplier tube converts an optical (weak airglow light intensities) input to current signal. For analytical purposes, the photo detector (PMT) is modeled by an ideal current source. To prevent high frequency oscillations due to the non-ideal open loop response of the operational amplifier a bypass capacitor C_s of 22pF is placed in parallel with R_f.

Experimental Results

The photometer circuit presented in this paper (Fig. 2) has been in operation at night airglow observatory with the photomultiplier tube EMI 9658B, the resisters given in circuit analysis section and the operational amplifier TL082. Fig. 2 shows the practical aspect of the transimpedance amplifier circuit. Furthermore, in order to test the current to voltage transfer performance of the circuit, the direct output current form the photomultiplier tube EMI 9658B is used as current input source through a Digital Nano Ammeter Model: DNM-121 and the current is adjusted by varying the exposure of the PMT to light.

Moreover, here two photometer circuits, one based on a IC TL082 using resistive tee-network in the feedback and another transimpedance amplifier A1 from Thorn EMI Electron Tubes, Ruislip, Middlesex, England based on a IC LH0032C using single high value resistor in its feedback, the input bias current of both the ICs are some of the order of 500pA. We have compared both the TIA circuits I-V characteristics as shown in Fig. 3. It is observed that the performance of photometer circuit using resistive tee-network in its feedback is much better than the performance of photometer circuit with a single high value feedback resistor.

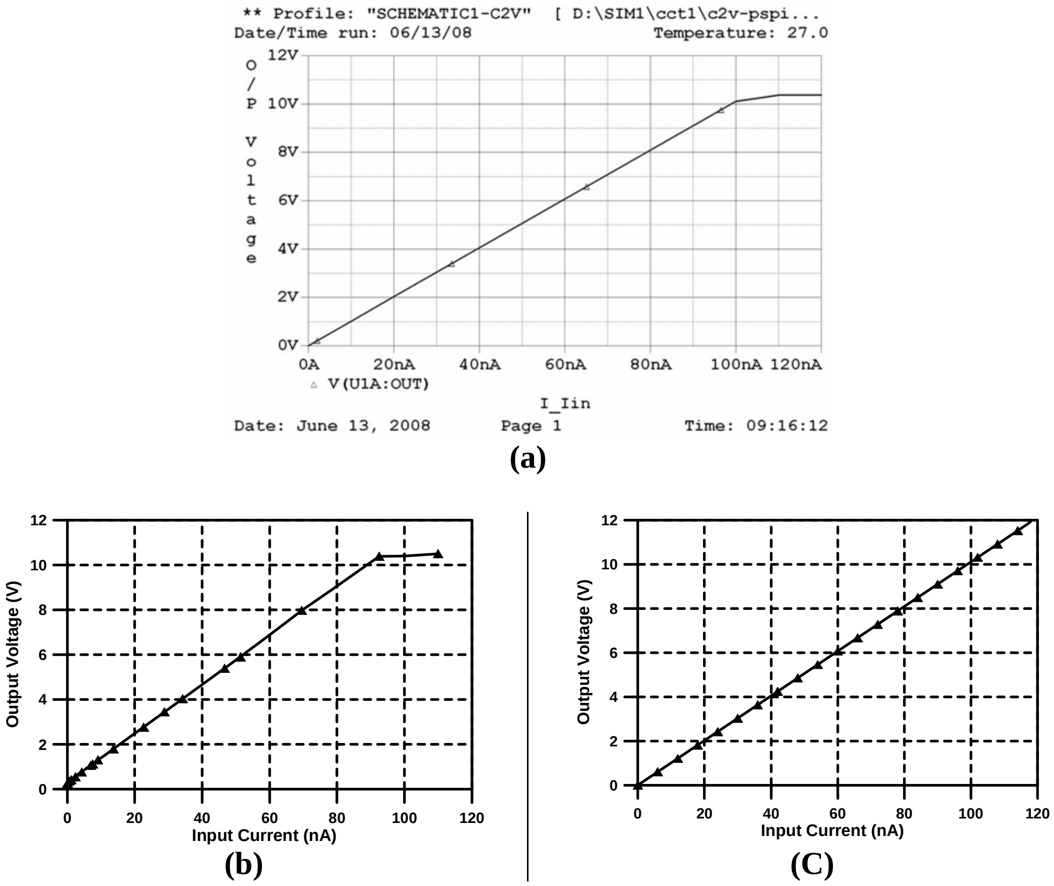


(a) **(b)**

Figure 3: Comparative I-V response of TIA - (a) using resistive tee-network (TL082) and (b) using single feedback resistor (LH0032C).

The experimental results show that the input current sensitivity of reported TIA is 10 times greater than the TIA from Thorn EMI Electron Tubes. For the op amp LH0032C the current sensitivity is equal to 0.01V/nA. However, for the op amp TL082 it is 0.1V/nA. This shows the importance of the application of resistive-tee feedback network using op amp TL082 to improve the performance of photometer circuits. It is apparent from the above data that, the TIA using TL082 performs better than the TIA using LH0032C. In practice, it is therefore necessary to consider the relative circuit configuration and its sensitivity when selecting an operational amplifier.

The simulated, practical and theoretical current to voltage transfer function of the circuit of Fig. 2, are shown in Fig. 4(a),(b) and (c) respectively. From the plots it can be seen that all the three graphs have a similar characteristics. The simulation of transimpedance amplifier is performed using Cadence OrCAD PSpice Release 10.0.



(a)

(b)

(C)

Figure 4: Comparative I-V response of TIA - (a) simulated (b) practical and (c) theoretical.

Conclusions

In this paper, an input and output transfer function of a photometer circuit based on an operational amplifier has been carried out. The analysis reveals the importance of the application of TIA with resistive-tee feedback network to improve the performance of photometer circuit.

The resistive-tee affords extra design flexibility, particularly when high transimpedance gain is required, and if used appropriately there will low circuit noise. The excellent performance of the TL082 in this test underlines the strength of the traditional FET-input amplifier in this application.

In conclusion, the circuit described in this paper provides undeniably useful building blocks for many photomultiplier tube monitoring applications.

The use of TIA with resistive-tee feedback network in designing complex photometer systems can bridge the gap between advanced signal conditioning techniques and the selection of different type of PMTs for a wide spectral range.

It is observed that there is good agreement between theory, simulation and practical measurement. We have developed a simple transimpedance amplifier to make photomultiplier tube sensor compatible with commercially available miniature data loggers or data acquisition systems. The transimpedance amplifier is inexpensive, precise, and able to withstand demanding outdoor field conditions. Transimpedance amplifier is a compact device that can be mounted close to the signal source such as a photomultiplier tube as possible to minimize input stray capacitance-always undesirable in fast electronics. By measuring the output voltage per current, high resolution current information can be obtained.

At the output of transimpedance amplifier a buffer can be used to provide additional current gain to drive the output sufficiently to interface with an external circuit. It is apparent from the forgoing discussion that the described transimpedance amplifier at present invention satisfies an immediate need for photometer amplifier with gain control having both a wide operating range with high stability without the need for additional circuitry to reduce the open loop gain.

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