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Monitoring DC anode current of a grounded-cathode photomultiplier tube

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Abstract

The Pierre Auger Observatories (PAO) for the highest energy cosmic rays will make use of both the Cherenkov and Air Fluorescence techniques. Surface Detectors (SD) and Fluorescence Detectors (FD) will have to operate in a desert-type environment during at least 15 years. In order to avoid dust deposition, due to electrostatics, and other practical inconveniences derived from biasing the cathode with a negative potential, the 15 000 PMTs of the FD will operate in the grounded cathode configuration. Despite the fact that the anodes will remain at high voltage with respect to ground, the DC anode current, which varies with background light, will have to be recorded. We have developed a current monitoring system based on a novel optocoupled feedback circuit that allows sensitive, linear, and temperature-independent measurements of the DC anode current. A distinctive feature of this circuit is that it uses optical coupling between passive components at high voltage and active components near the ground potential. This represents a substantial improvement over classical solutions which require the supply of power to an active circuit at high voltage. We report on the first tests performed with both active and passive biasing networks which demonstrate the validity of this new method.

1. Introduction

Measuring the DC anode current of a photomultiplier tube (PMT) operating in the anode-grounded connection is straightforward. A current meter connected in series with the load resistor does the job. But in those cases in which the cathode should be grounded, leaving the anode at high potential with respect to ground, direct measurement of the anode current is not simple at all. To our knowledge no solution to this problem has been found besides indirect methods like pulse rate counting or measuring the baseline fluctuations. PMT manufacturers suggest the anode-grounded connection as the only way to measure DC anode current [1,2].

In the Auger experiment [3–6] an optical detector (FD) will measure the fluorescence light of showers initiated by cosmic rays of energies above 10^{19} eV. The experiment will be conducted in two sites located in desert areas in the Northern and Southern hemispheres. About 15 000 PMTs will be used in each site to pixelize half of the sky in slices of 1.5×1.5 deg^2. To reduce the risk of dust deposition at the cathode due to electrostatics, it is convenient that the tubes will operate with the cathodes grounded. In addition, PMTs manufacturers recommend, whenever possible, biasing with positive

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polarity to avoid the need to insulate the tube from its surroundings or applying conductive coating to neutralize potential gradient in the glass, and other inconveniencies [1,2]. So far, there was no other way but to accept such inconveniencies when the DC anode current had to be measured.

The FD will take data mostly during dark nights, although operation under higher background illumination, as due to the presence of some backscattered Moon light, for example, is not excluded. Under these circumstances, a variation of the anode DC current by a factor 30 or more is expected. To avoid the consequent increase of pulse-gain with high background current, an active-biasing network has been proposed [7].

Monitoring DC anode current will give information on the actual background light seen by every pixel. Integration of the current will give the actual charge accumulated during the PMT's life. A correlation of the tube gain with the charge accumulated at the anode in the large set of tubes during 15 years will give valuable statistics of tube performance. Also, an even wearing-out of PMTs could be assured by tube swapping every one or two years. In addition, permanent recording of the DC anode current will allow to perform protective actions like switching-off HV supply, or eventually to interact with the pixel trigger system to keep trigger rate constant.

To measure the DC anode current of a grounded-cathode PMT, we have developed a current-monitoring system which has a passive, two-terminal input at high voltage optically coupled to an active circuit near ground potential. The passive input is connected directly in series with the last element of the biasing network. A voltage in the range of 0–10 V referred to ground, proportional to the DC anode current, is developed at a terminal located at the PMT base.

We will present the results obtained with a circuit optimized for the operating conditions of Auger PMTs for which the gain will be $\sim 5 \times 10^4$, the bias voltage ~ 1000 V and the DC anode-current will vary from 200 nA to more than 10 μA depending on the background light seen at the particular PMT. Nevertheless, the circuit is flexible enough to accommodate many other operating conditions. In Section 2 we describe the principle of operation of the system. In Section 3 we present an optically coupled current-mirror circuit which is the key element in the implementation of the current monitor system. In Section 4 we present the results obtained with a PMT tube emulating the operating conditions of the Auger FD.

2. Configuration of the current monitor

The principle of operation of the current monitor is illustrated in Fig. 1. A resistive biasing network for an 8 dynode PMT is assumed as an example. The balance of currents at the different nodes for a DC cathode current I_k is indicated.

I_0 represents the current at the divider for $I_k = 0$; when $I_k \neq 0$, the current through the divider can be calculated by superposition and expressed as $I'_0 = I_0 + I_k/(N+1)\sum_{i=0}^{N} g^i$ [2], where N is the number of dynodes, and g is the current gain between two consecutive dynodes.

Above a threshold I_{TH}, the current through R9 is mirrored and inverted by an optocoupled circuit (optically coupled current mirror, OCM) which has a passive, two-terminal low impedance input. The total voltage developed at the OCM input is ~ 1 V. By inspection, it becomes evident that the voltage V_0 at the op-amp output will be proportional to the anode current.

3. The optically coupled current mirror

This circuit consists of a current-sensitive feedback amplifier in which both the open-loop amplifier and the feedback are optically isolated. In fact, the open-loop amplifier consists of an optocoupler chip followed by a current post-amplifier which is used to further increase the current gain. The current post-amplifier could simply be a bipolar transistor or an operational amplifier with a proper feedback network. A Toshiba's TLP523 was used as optocoupler in this first prototype, because of its large current-gain at low input current. The feedback is provided by a linear optocoupler chip, a Siemens IL300, in which a LED illuminates evenly two isolated photodiodes, PD1 and PD2. The circuit is schematically illustrated in Fig. 2.

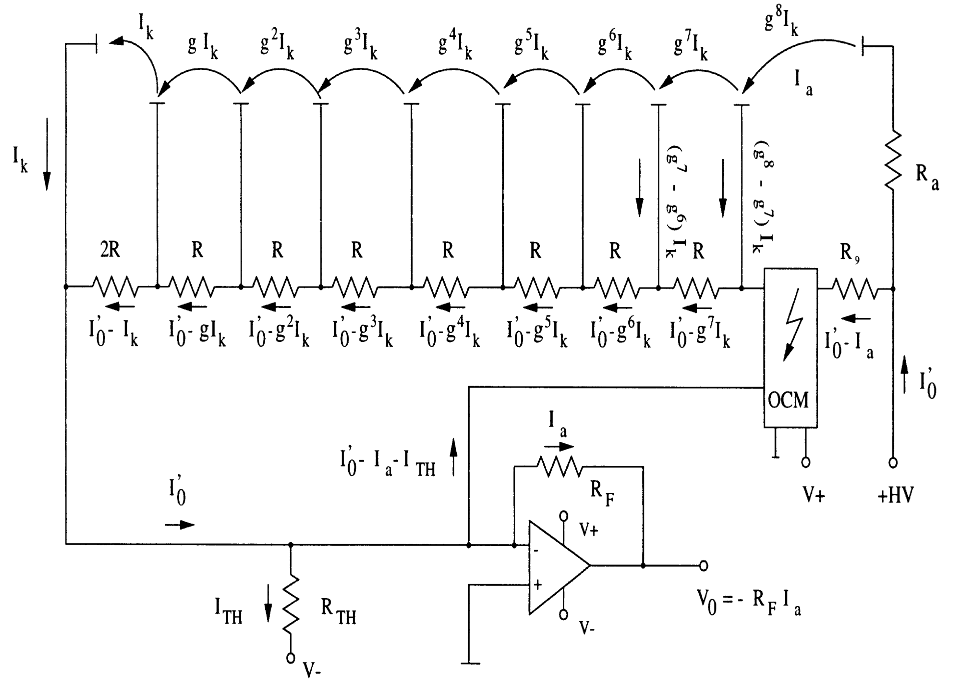

Fig. 1. An optically coupled current mirror is interposed in series with the last element of the PMT biasing network. The op-amp delivers a voltage proportional to the DC anode current.

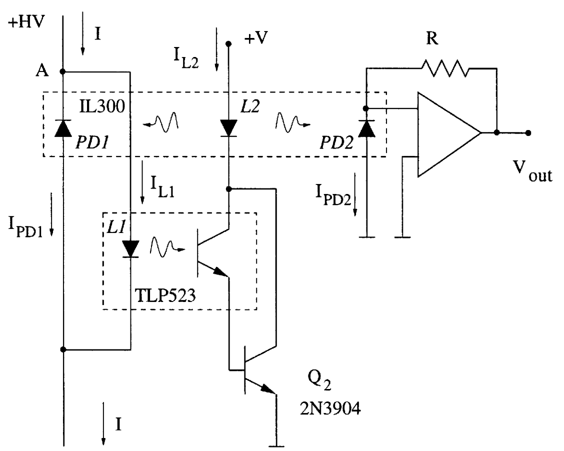

Fig. 2. The current mirror is based on a current-sensitive feedback loop which determines a LED current I_{L2} such that $I_{PD1} \sim I$.

As it is shown in Fig. 2, the current I to be measured enters the circuit through node A and splits into I_{L1} and I_{PD1}. In order to establish a current through the photodiode PD1, the LED L2 must pass a current I_{PD1}/K_1, where K_1 is the coupling factor of the IL300 ($K_1 \sim 7 \times 10^{-3}$). The LED current is supplied by the open-loop amplifier, and as it has a very large current gain, $A_I \sim 10^4$, the current $I_{L1} = I_{L2}/A_I$ is very small. As a consequence, $I_{PD1} \sim I$ and the current through the second photodiode, I_{PD2}, is linearly related to I_{PD1}. In fact, $I_{PD2} = K_2 \cdot I_{L2} = I_{PD1} \cdot (K_2/K_1)$. The IL300 chip has a transfer gain $K_3 = (K_2/K_1) = (I_{PD2}/I_{PD1})$ which is constant for a very large current range, largely exceeding the needs of the present application. In addition, K_3 is not far from unity and, what is more important, it is virtually independent of temperature: it is specified to have a maximum change of 1.5% in a temperature range from 0°C to 75°C.

The set of equations describing the optically coupled current mirror are those of a current-sensitive feedback amplifier, whose scheme is indicated in Fig. 3. The loop is closed above a minimum

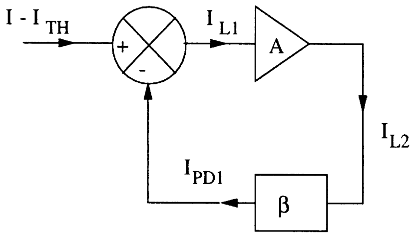

Fig. 3. Both the open-loop amplifier and the feedback network are optically coupled. Photodiode PD2, passes a current linearly related to that of PD1, which is close to I.

current I_{TH}, necessary for the passive input to operate.

- Open loop gain $A_I = I_{L2}/I_{L1}$; A_I is close to 10^4
- Feedback return ratio $\beta = I_{PD1}/I_{L2} = K_1$
- Error signal $= I_{L1}$
- Closed-loop gain: $A_{CL} = I_{L2}/(I - I_{TH}) = A_I/(1 + A_I K_1) = (\frac{1}{A_I} + K_1)^{-1} \sim K_1^{-1}$; then, $(I - I_{TH}) \sim I_{PD1}$.

The voltage at the operational amplifier output is

$$V_0 = R\cdot(I - I_{TH})\cdot\frac{K_2}{K_1}\left(\frac{1}{1 + (1/A_I K_1)}\right) \sim R_{eq}\cdot(I - I_{TH}), \quad R_{eq} = K_3 R. \qquad (1)$$

Prior to its application with a PMT, the optical current-mirror circuit was tested to check its linearity and temperature stability. A 2N3904 bipolar transistor was used as a current post-amplifier. A semi-automatic system, shown in Fig. 4,was used for these tests. A HP 3631A provided the DC current whose value was measured by a HP 34401A meter. The output voltage was measured by a Rhode & Schwartz URE3 DMM. The circuit under test was installed in a Vötsch VT 7004 climatic chamber which allowed to take data between $-10°C$ and $+50°C$.

The results of these measurements are indicated in Fig. 5. A threshold I_{TH} at an input current of about 80 μA is noticeable. For the application of interest the circuit mirrors a current $I'_0 - I_A - I_{TH}$ circulating in the last element of the biasing chain. The standing current I_0 for a typical bias network is ~ 300 μA. The maximum deviation from the quiescent point before reaching the non-linear region of the characteristics is 220 μA, very much in

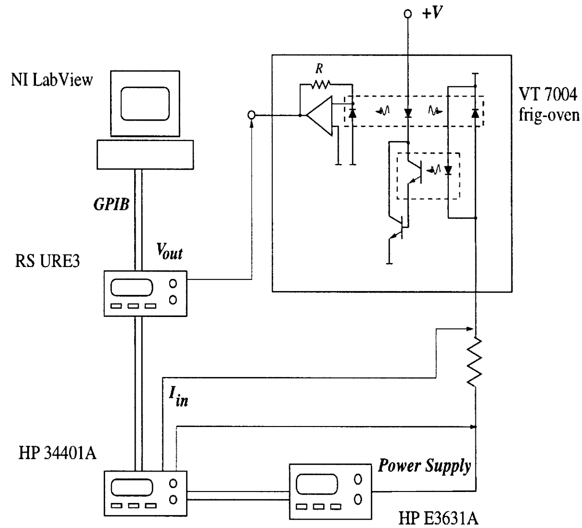

Fig. 4. Schematics of the test set-up used to record the input–output characteristics of the optically coupled current-mirror at different temperatures.

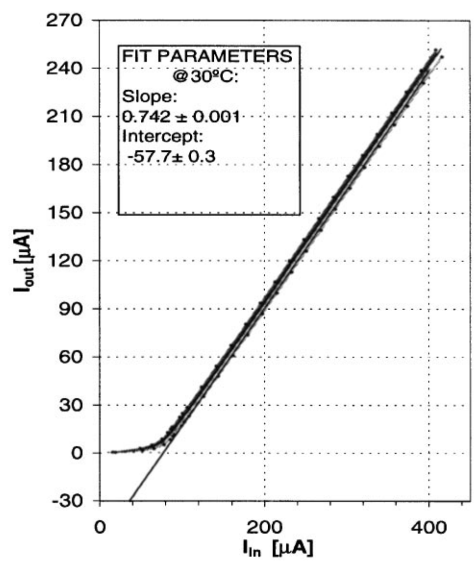

Fig. 5. Transfer characteristics of the optical current mirror taken from $-10°C$ to $+50°C$. Total dispersion in sensitivity is within 1.5%.

excess of the expected maximum anode current. The transfer characteristic in the linear region is given as $V_0 = RK_3\cdot(I - I_{TH})$. The sensitivity to the input current $G = (\Delta V_0/\Delta I) = RK_3$ is quite high; in

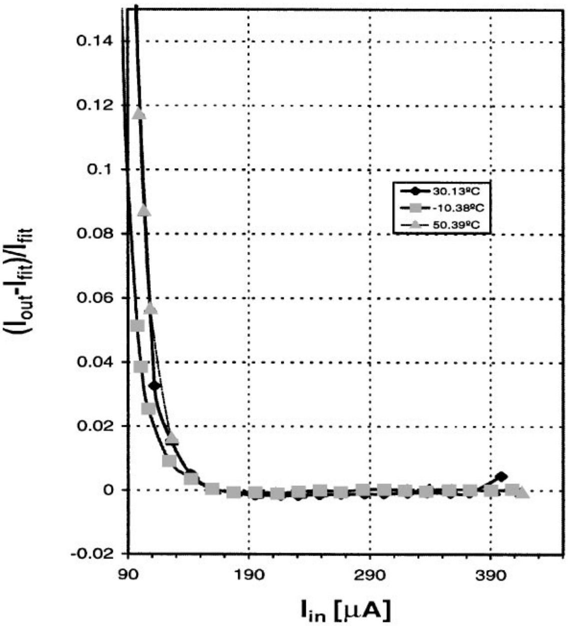

Fig. 6. Deviation from linearity as a function of I_{in} at 30°C, at − 10°C, and at 50°C using same data as in Fig. 5.

fact, for $R = 1\ \mathrm{M}\Omega$ and $K_3 = 0.7$ it is 700 mV/μA. In order to assure accurate current mirroring we decided at the beginning to bias the photodiode PD2 at the same reverse voltage of PD1, which sees the LED L1 voltage of ~ 1V. This was done by biasing one discrete LED with a resistor to the negative supply and connecting the PD2 anode to the LED's cathode. PD2 was biased also to ~ 1V. The result shows only a ~ 3% increase in sensitivity and no noticeable change in linearity. For this reason, this kind of biasing was abandoned and all measurements were done with ~ 0V across PD2. Fig. 6 shows deviations from linearity smaller than 0.2% in a large input current region. The biasing point of 300 μA and deviations due to the background anode current are far from the non-linear region.

4. Current monitor operation under Auger FD conditions

As mentioned above, the FD PMTs will be able to operate with either active or passive biasing networks. We have tested the current monitor for both options. In Fig. 7 we show the simplified scheme of an active network used for the test which included three anode current sweeps, from low to high values. Fig. 8 shows the absence of hysteresis

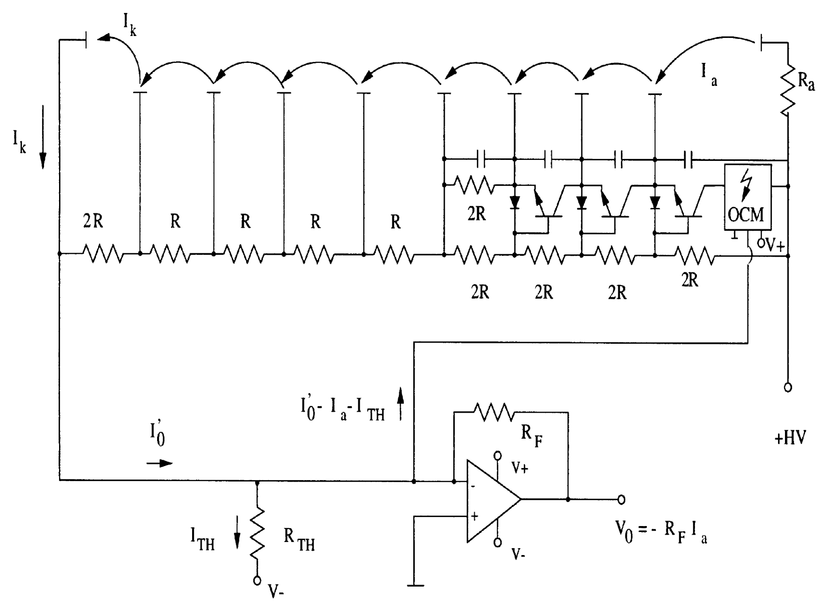

Fig. 7. The current monitoring system applied to an active biasing network.

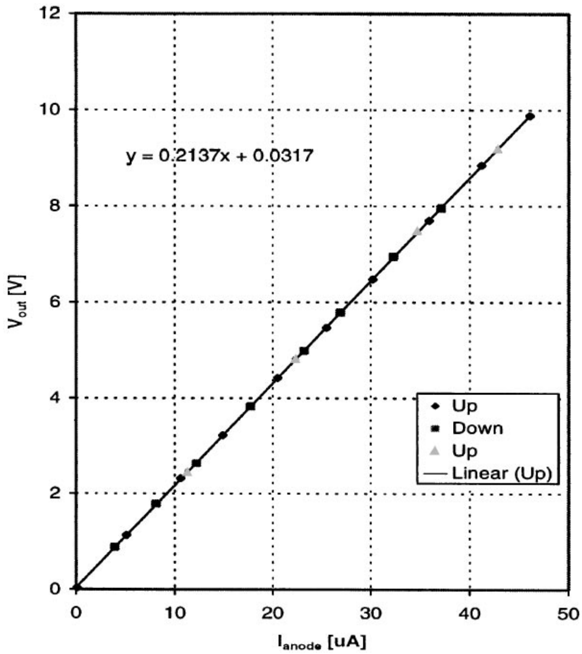

Fig. 8. The output voltage of the current monitor as a function of the DC anode current in an active base.

and a sensitivity of 214 mV/μA. The passive network shows similar results.

5. Conclusions

We have developed a monitor system to measure the DC anode current of PMTs operated with grounded cathode. A current mirror with optical isolation, interposed in series with the last element of the PMT biasing network, is the key element in the design. The current mirror is based on a feedback loop in which the open-loop amplifier and the feedback are both optically isolated. A large open-loop gain is obtained by using an optocoupler with large sensitivity for low input current, followed by a bipolar transistor. The feedback element is a linear optocoupler chip in which a LED evenly illuminates two isolated photodiodes. The current mirror has shown variations in sensitivity of the order of 1% for a temperature change between $-10°C$ and $+50°C$, a 2% variation in threshold current between 20°C and 35°C (12.9% between $-10°C$ and $+50°C$), and deviations from linearity smaller than 0.2% between 150 and 400 μA. For the present PMT application the current mirror passes a nominal divider current minus the anode current minus the threshold current. An operational amplifier performs the difference between the mirrored current and the nominal divider current minus a current equal to the threshold. Eventually, errors determine a small pedestal for $I_A = 0$. An output voltage proportional to the anode current is delivered at the op-amp output. A sensitivity of more that 200 mV/μA with an extremely linear characteristics was obtained.

References

[1] See for instance the Hamamatsu Photomultiplier manual.
[2] Philips Photonics, Photomultiplier Tubes: Principles and Applications, manual.
[3] A.A. Watson, Nucl. Phys. B (Proc. Suppl.) 22B (1991) 116.
[4] J.W. Cronin, Nucl. Phys. B (Proc. Suppl.) 28B (1992) 213.
[5] P. Sommers, Astropart. Phys. 3 (1995) 349.
[6] B.R. Dawson et al., Astropart. Phys. 5 (1996) 239. For detailed information see: Design Report, http://www.auger.org/admin (1997) or US Proposal (at same http address).
[7] S. Argirò, D.V. Camin, M. Destro, C.K. Guérard, GAP-98-063, http://www.auger.org/admin, 1998.