Linear transmission of analogue current-signals via fibre optics using the Optically-Coupled Current-Mirror (OCCM) architecture.

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Abstract

The Optically-Coupled Current-Mirror (OCCM) is a circuit architecture based on a novel optical feedback loop, that allows mirroring a current flowing in an isolated, or high voltage biased conductor, to ground potential. The OCCM has a simple but powerful structure: its input stage is a passive dipole consisting on an LED and a photodiode connected back-to-back. When the dipole is interposed in series with the conductor where a current signal flows, the signal is mirrored to ground potential while keeping full Galvanic isolation with the conductor itself. The OCCM has been used with success to mirror the quasi-DC signals left by stars in the first two Fluorescence Detector (FD) telescopes of the ultra-high-energy cosmic ray experiment Pierre Auger. In each telescope, star signals were recorded by an array of 440 photomultiplier tubes (PMTs) biased with cathode grounded. After the good results obtained with slow signals we have started an optimization of the OCCM architecture for the linear transmission of analogue signals within a bandwidth of about 5 MHz. In addition, we recently started a preliminary study on the behaviour of LEDs and photodiodes at cryogenic temperature. The results were very interesting and showed that AlGaAs LEDs at 77 K behave extremely linear also at very low signal currents, which is the normal operating condition required by the OCCM. Later on we have studied the behaviour of the OCCM with its input stage cooled to 77 K. We verified the increase of the open-loop gain by a factor x 2, and a loop-gain increase by a factor slightly lower than 2 due to a reduction in the photodiode responsivity. The improved performance of the OCCM at cryogenic temperature may open new opportunities for applications with noble liquid calorimeters and other cryogenic detectors.

I. INTRODUCTION

In the frame of ATLAS and CMS various groups have in the past pursued the development of systems for the linear transmission via fibre optics of fast analogue signals [1-3]. Those systems were mostly based on LEDs or VCSEL lasers, or on electro-optic modulators. To preserve linearity, lasers used for that purpose had to be biased with a fairly large DC current, above the threshold. The LEDs had to be pre-biased as well to ensure linearity at low signal levels. The mentioned optical links operated open-loop, i.e. without a feedback mechanism. The performance of those and new optical links have been discussed in this Workshop. Despite the effort put by the various collaborating groups, at least in ATLAS only digital optical links were finally adopted.

The Optically-Coupled Current-Mirror (OCCM) [4-5] is based on a novel optical feedback loop incorporating the advantages of a feedback circuit, while reducing to its minimum expression the complexity of the input stage. In fact, the input stage of the OCCM is fully passive as it consists only on a diode and a LED connected back-to-back. This dipole is the only element, beside the fibres, that is required to be close to the detector cell. All other electronic components can be located outside, even a few meters away. On the other side, limiting the number of components inside a detector, eventually subjected to radiation, reduces the complexity of the circuit and the extent of the radiation damage.

The OCCM architecture has been conceived while looking for a solution to the old problem of recording very slow signals with photomultiplier tubes (PMTs) biased with cathode grounded. So far, the use of positive bias supply was considered to be incompatible with the recording of slow signals, like those left on the PMTs by stars transiting trough the field-of-view (FOV) of the telescopes of the Pierre Auger experiment. A star takes about 10 min to fully transit the FOV of a PMT's photocathode, which has an aperture of 1.5°. A shower signal takes instead 300 ns to 10 μsec depending on the shower geometry. The OCCM made it possible to build a system, integrated into the PMT's base, that returns a voltage referred to ground proportional to the intensity of the light seen while a star is in the FOV of any of the 440 PMTs in each of the first two FD telescopes. High and low magnitude stars were recorded with very high resolution [6].

The purpose of this work is to report on the extension of the OCCM concept to the transmission of fast signals, from different kind of detectors, via fibre optics. We will present the results obtained after the first year of work pointing out the most relevant results obtained.

II. HOW THE OCCM WORKS.

The principle of operation of the OCCM can be understood with the help of the three schemes of Fig. 1. The first scheme indicates the model of a generic ionization detector or a photomultiplier tube. The second scheme shows a dipole, constituted by a back-to-back connection of a LED

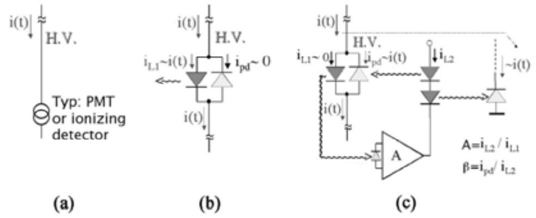

Figure 1: The three steps towards the implementation of the OCCM topology: (a) a conductor where a current signal flows; (b) a LED and a photodiode interposed in the conductor; (c): a feedback loop is closed (see text).

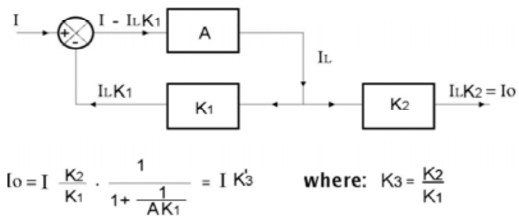

Figure 2: Both the current-amplifier with open-loop gain A, and the feedback loop with a return ratio K_1, include optical links. The ratio K_3 of the coupling constants K_2 and K_1 remains fairly constant when both photodiodes PD_1 and PD_2 are either at the same or at constant temperatures. K'_3 includes K_2, K_1 and the loop-gain.

and a photodiode, interposed in series with the conductor where the detector signal flows. No optical coupling exists between those components. The third scheme represents a feedback circuit that includes optical links both in the feedback and in the forward paths. The following actions take place:

a) A signal current flows through an isolated, or HV biased conductor, corresponding to a detector cell that is modelled as a current source.

b) The detector signal flows trough the dipole and, assuming that no light illuminates the photodiode, the entire signal flows trough the LED that emits light.

c) The dipole's LED is now optically coupled to a standard or an avalanche photodiode (APD) located at the input of a large-gain current-amplifier. The first of the two output LEDs now illuminates the photodiode closing the optical feedback loop. Assuming that the loop-gain is sufficiently large, the signal current now flows almost entirely trough the photodiode. The feedback action has *flipped* the currents in the dipole. As shown in the Fig. 1, the splitting of the currents in the dipole is completely reversed when the optical feedback loop is closed.

d) Finally, a LED of the same type used at the amplifier's output illuminates a photodiode of the same type used at the input stage. This gives origin to an output current ideally identical to the signal current. The signal current has been mirrored from the isolated input stage to the receiving stage that is at ground potential and eventually located far away.

The input stage of the OCCM is completely passive and presents low impedance, both ideal conditions to record current signals flowing trough an isolated or a HV biased conductor.

A block diagram of the optical feedback network is indicated in Fig. 2. The feedback current $I_L.K_1$ is subtracted from the signal current I. The LED of the input stage converts the small error-current into light. An optical fibre conveys the LED light into the forward amplifier of gain A. The gain factor $A=I_L/(I-K_1I_L)$ includes also the intrinsic gain of the APD, which is connected to the amplifier's input, and the attenuation in the LED-Fibre-APD optical coupling. The APD has a typical gain of ~100.

The current I_0 mirrored to ground potential depends on the current I_L stabilized by the feedback loop. The output current $I_0 = K_2 I_L$ is the replica of the input current I multiplied by a factor $K_3= K_2/K_1$ which is close to unity. Taking into account that the loop-gain is finite, the actual K'_3 is $K'_3= K_2/K_1.(1+1/AK_1)^{-1}$. It must be noted that being the OCCM a feedback circuit, possible variations in APD gain do not affect the overall performance, as the loop gain is much higher than unity.

III. Readout of extremely slow signals with PMTs biased with positive supply.

We mentioned in the introduction that the OCCM architecture was conceived while looking for a solution capable to allow recording the very slow signals left by stars that enter into the FOV of an FD telescope equipped with an array of 20 x 22 PMTs in its focal plane. A star takes typically 10 min to fully traverse the photocathode of a single PMT.

An analysis of the balance of the currents in a PMT biased with positive HV shows a feasible solution providing that the current flowing in the upper resistor of the biasing network could be mirrored to ground potential. The only possible solution on that time was using the J.C. Sunderland's scheme [7]. Nevertheless, this well-known scheme requires a low-voltage power supply in each of the 440 PMT's biasing bases. The OCCM, with its passive input stage, demonstrated to be the best solution. No low-voltage power supply is required at the HV potential, Fig 3.

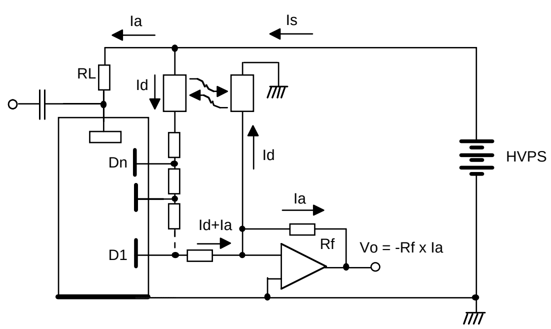

Figure 3: By mirroring to ground potential the upper resistor current Id, and subtracting Id+Ia – Id, a voltage signal proportional to the anode current Ia is developed at the op-amp output.

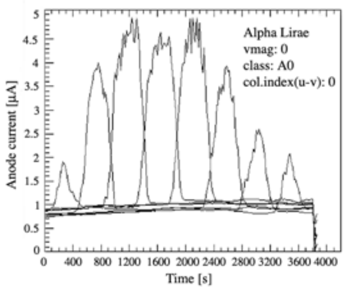

Figure 4: A superposition of signals left in eight PMTs by a low-magnitude star traversing the FOV of one FD telescope of the Pierre Auger experiment.

Recording stars signals with the FD telescopes allows calculating its absolute pointing and long-term stability during the 20 years of estimated life of the experiment. The absolute pointing of the centre of the PMT array and the rotation around it, is determined by fitting several reference star signals with an algorithm developed on purpose. Fig 4 shows, superimposed, the signals left by one of those stars, Alpha Lirae.

We ordered the manufacturing of about 1000 OCCM units integrated in the PMT bases. Their main parameters were evaluated with an automatic system developed on purpose. The performance and uniformity of the lot were satisfactory and within the requirements [8].

The optimization of the OCCM for fast pulses over fibre optics was the next step to follow. This is described in the following section.

IV. SENDING FAST PULSES WITH THE OCCM.

Optimizing the optical feedback loop for the transmission of fast pulses was the next step in the development programme of the OCCM. The scheme adopted is indicated in Fig 5. In that scheme it is shown a fast op-amp plus two LEDs in series: one closing the optical feedback loop, the other mirroring the signal current to ground potential. The optical link at the op-amp input includes an avalanche photodiode (APD) that increases the open-loop gain by a factor x 100. The op-amp is biased with a +12V single supply.

Two resistors and the APD determine the open-loop gain gain $I_{L2}/I_{L1} = \varepsilon_f.M.R_F/R_{AC}$ where M is the APD gain, ε_f the efficiency of the LED-fibre-photodiode coupling and the resistors R_F and R_{AC} are those indicated in Fig 5. To improve still better the open-loop gain we used a multimode fibre of 200/230 μm. The same fibre was used in the feedback loop. The result was that the loop-gain reached 11.5 and the open loop gain exceeds 2000. The signal bandwidth was ~ 5 MHz.

Tests were performed with the input stage at room temperature and at 77 K, immersed in LN_2. The open-loop gain at 77 K was a factor ~ 2 larger compared to that at 300 K.

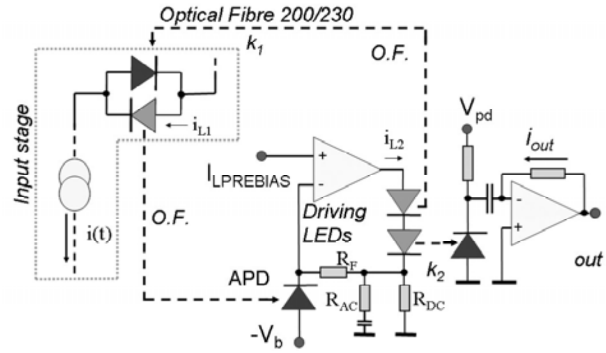

Figure 5: The circuit configuration improved for fast pulses comprises an APD at the input of a high –gain current amplifier. The optical links use 200/300 μm multimode fibres.

We investigated the origin of the large increase of the LED efficiency at 77 K. To do that we plotted the light flux emitted as a function of the current in the AlGaAs LEDs used. The results are shown in Fig. 6. The behaviour at room temperature is completely different compared to the operation at 77 K. At room temperature the first derivative of the light flux curve versus the LED current was 177, quite small for the very little current that pass in the LED under closed-loop conditions. As mentioned in section II, due to the *flipping* of the currents in the input dipole when the feedback loop is closed, the normal operating condition of the input LED is taking a very low current from the signal current. Most of the signal current flows through the input photodiode and a very small current flows in the LED. The plots of Fig. 6 are compatible with a strong suppression of non-radiative recombination processes at 77 K. The characteristic is extremely linear at 77 K and it is a factor 5.6 larger that the linear term obtained at 300 K. The linear term is dominant at the closed-loop operation, i.e. with very low LED current.

We checked several units of the same LEDs and verified a dispersion in their behaviour at 77 K. Nevertheless, in all cases the LED efficiency improves when the LED is cooled down. Regarding the photodiode responsivity, we noticed instead a reduction of about 23 %, when this device is cooled down.

The effects so far verified when the input stage is cooled to 77 K can be summarized as follows:

a) The efficiency of the input LED increases and becomes extremely linear, Fig 6.

b) The closed-loop gain increases from 0.81 to 0.995.

c) There is a ~ 23 % decrease in the photodiode responsivity.

d) Operating with the input stage cooled to 77 K improves the overall performance, in terms of loop-gain and linearity.

The overall input-output characteristics of the OCCM, Fig. 7, has been determined with its input stage operating at

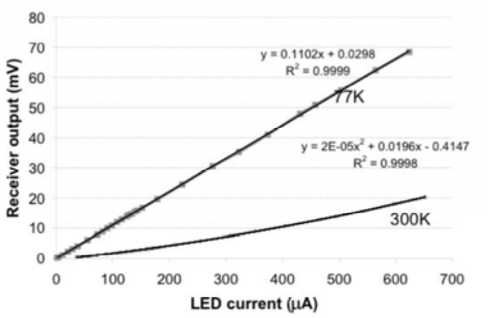

Figure 6: Operating the OCCM with its input stage cooled down to 77 K improves the LED efficiency at very low current by a factor 5.6 The output signal was taken using an Agilent 2406-125 MHz optical analogue receiver.

300 K and 77 K. Once again, the improvement of the performance when the input stage is cooled down to 77 K can be noticed.

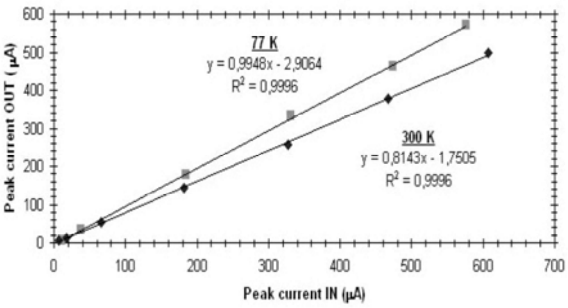

Figure 7: Overall Input-Output characteristics of the OCCM with its input stage at room temperature and immersed in LN_2.

A pulse response taken at 300 K shows an overshoot and a rather long fall time. The input signal was noisy as it was not filtered. The output pulse is cleaner due to the bandwidth at present limited to 5 MHz. The overall gain at room temperature is 0.81 and increases to 0.995 when cooling to 77 K.

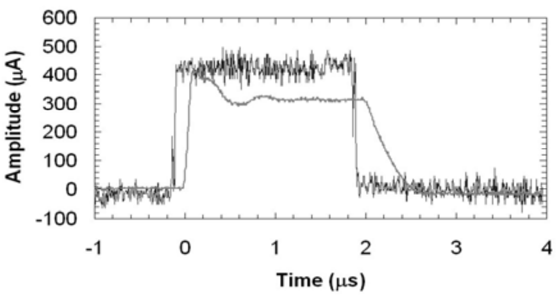

Figure 8: First pulse response taken with the OCCM with its bandwidth extended to 5 MHz. The gain at 300 K is 0.81 and rises to 0.995 at 77 K.

V. SUMMARY AND CONCLUSIONS

The Optically-Coupled Current-Mirror is a novel circuit architecture that allows mirroring to ground potential an analogue signal flowing in an isolated conductor. This concept was conceived while looking for a solution to allow a cathode-grounded PMT to be able to readout extremely slow signals, of the order of 10 min length. Those signals were originated by stars entering the field of view of 880 PMTs of the first two telescopes of the Pierre Auger experiment. The natural extension of the OCCM was to optimize it to send fast analogue pulses via fibre optics.

The OCCM has a passive input stage and therefore it does not require a low-voltage power supply to be brought to the potential of the conductor where the signal flows, as requested in previous schemes. This feature simplifies significantly the problem as only three components are in close contact with a detector cell, eventually exposed to radiation: a LED, a photodiode and an optical fibre.

When the input stage is cooled down to 77 K, the performance of the OCCM improves strongly: the loop-gain increases by a factor two and the signal threshold reduces. This may open new opportunities for the signal readout of cryogenic detectors.

The optimization of the OCCM for fast pulses started one year ago with a signal bandwidth of 1.5 MHz. More recently the bandwidth of the OCCM was extended to 5 MHz and at least a 100:1 dynamic range. We are now in a reasonable starting point with large room for improvement, both in the dynamic range and in signal bandwidth. Although it has still to be proved, the former could be reached by connecting a few input stages in series having different signal gain, while the latter depends mostly on adopting the suitable technology.

VI. REFERENCES

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