A Multi-Pixel Photon Counter detector prototype for direct detection of scintillation light in liquid xenon.

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Abstract.
This work concerns the preliminary tests and characterization of a cryogenic preamplifier board for an array made of 16 S13370-3050CN (VUV4 family) Multi-Pixel Photon Counters manufactured by Hamamatsu and operated at liquid xenon temperature. The electronics for the proposed prototype is based on the use of the Analog Devices AD8011 current feedback operational amplifier, but other models can be also considered. The detector allows for single photon detection, making this device a promising choice for future generation of neutrino and dark matter detectors based on liquid xenon targets.

1. Introduction

Technology advancements in material science, electronics and devices gave a tremendous contribution not only to the industry, but also to the fundamental physics opening for the last generation astroparticle experiments.

Liquefied noble gases based detectors are at the forefront of Dark Matter search [1, 2, 3, 4]. In this scenario, the intrinsic detector background and the few photons expected in a WIMP (Weakly Interacting Massive Particle) - Nucleus interaction are carefully taken into account.

The screening of materials is a common approach to select the cleanest components (in terms of radiopurity) for the actual realisation of the cryostat containing the high purity liquefied noble gas. On the other hand, the selection of the photosensor needs to take into account many parameters (quantum efficiency in the region of interest, reliability, geometrical coverage, bulkiness, costs, etc.)

Photomultiplier tubes (PMTs) are still the most common option, however, in order to achieve optimal geometrical coverage and to scale down the total radioactivity budget of the detector, more compact cryogenic photosensors with single photon detection capability are being considered for the instrumentation of large volumes.

The requirements for a photosensor to be a good candidate are mainly driven by the limited light yields in the liquid phase (order of a few tens photons/keV): to improve the sensitivity, the ideal dark matter detector must have a high geometrical coverage, single photon counting capability, adequate photon detection efficiency (PDE, larger than 20% at the scintillation emission peak) and large gain (in the order of $10^6$).

Photosensors used in liquid xenon based experiments are usually required to be sensitive in the wavelength region of vacuum ultraviolet (VUV) where the scintillation happens ($\lambda_{\text{scintillation}} \approx 178$ nm).
Silicon Photomultiplier (SiPM) or Multi-pixel Photon Counter (MPPC) are the most promising candidate to replace PMTs in the next generation of large scale dark matter detectors [5].

The prototype presented in this work consists of 16 \(3 \times 3\) mm\(^2\) S13370-3050CN, the fourth generation of vacuum ultraviolet (VUV) sensitive multi-pixel photon counters (VUV4-MPPC) manufactured by Hamamatsu. The VUV4-MPPC family:

(i) can be operated at low voltage (< 60 V) in LXe,
(ii) shows single photon counting capability,
(iii) has PDE close to 25% at 178 nm,
(iv) can be operated at gains larger than \(2 \times 10^6\).

To get the equivalent coverage of a PMT, by keeping the same number of readout channels, several tens of MPPC needs to be readout as they were a single channel (in form of arrays or matrices of sensors with one single channel of biasing and signal output). The readout of many devices as a single channel is still challenging. A few typical readout examples are described in [6].

The aim of this work is therefore to provide a single output cryogenic amplifier readout for 16 MPPCs for liquid xenon based experiments.

2. The detector and the experimental setup

The detector shown in figure 1 is an array of 16 MPPCs soldered to an interface board that is in turn connected to the preamplifier board.

![Figure 1. The 16 MPPCs array used in the experiment.](image)

The preamplifier circuit is based on the use of the Analog Devices AD8011 operational amplifier. This latter had been already successfully test in a preamplifier circuit for the Hamamatsu PMT R11410 [7].

The array has been characterized at LXe temperature (175 K), the setup has been cooled down by using a cold finger immersed in a liquid nitrogen reservoir. A change in the liquid height reflects a variation in the operational temperature. The MPPC array and its electronics have been mounted in a light tight metal enclosure (see figure 2) instrumented with all the required IN/OUTPUT connectors along with an optical diffuser to isotropically shine light from a pulsed UV LED. A PT100 has been used for temperature measurement and consequently to compensate the biasing of the MPPCs in the array. Gas Nitrogen has been constantly flushed through the box in order to prevent water vapor condensation.
Figure 2. A sketch of the test unit used in the experiment.

A Digital to Analog Converter (DAC) has been implemented in the biasing circuit to equalize the gain of the 16 MPPCs due to their different breakdown voltages (in the range 55.56 V \(\pm\) 55.78 V) by fine tuning the over-voltages\(^1\).

An Agilent E3645A has been used for the biasing of the MPPCs, while for the amplifier unit a linear DC Elind 32DP8 power supply has been used. The temperature measurements has been acquired through a Keithley 2100 digital multimeter. A LeCroy HDO6104 oscilloscope has been used to collect waveforms in 1 µs time window and sampled with 2500 points at 12 bits at full bandwidth.

Typical waveforms corresponding to single and double photon event families are shown in figure 3.

3. The Electronics

An MPPC can be represented by a matrix of independent channels connected in parallel [8], each one consisting of a series of one avalanche photodiode (APD) and a quenching resistor. The equivalent circuit of a MPPC is reported in figure 4.

An avalanche photodiode can be modeled through a junction capacitance \(C_j\), a voltage source (breakdown voltage \(V_{bd}\)), a junction resistance \(R_j\) and a switch \(S\) that closes when a photon hits the sensor. The resistor \(R_q\) quenches the signal and restore \(S\) to the open position. Current limiting resistors \((R_a)\), bypass capacitances \((C_b)\) and the decoupling resistors \((R_S)\) are all wired outside the MPPC.

The resistor \(R_S\) is used to decouple the MPPC equivalent parasitic capacitance \(C_S\) of any non-fired photosensor from the operational amplifier.

figure 5 is an effective approximation of the array being exposed to a single photon.

The signal is represented by the current generator \(I_S\) connected in parallel with \(C_S\) towards ground. Since all the quenching resistors are connected in parallel, the equivalent resistance is negligible with respect to \(R_S\).

\(^1\) The over-voltage \((V_{OV})\) is the voltage above the breakdown
Figure 3. Example of typical waveforms corresponding to a single photon and to 2 photons event taken at 175 K, $V_{OV}=2$ V (50 Ω termination).

Figure 4. Equivalent circuit of a MPPC.

Figure 5. Scheme of the equivalent circuit of a single fired MPPC.

The operational amplifier output voltage is the product between the value of the feedback resistance ($R_f=1$ kΩ) and the current $I_S$ (the effect of $C_S$ and $R_S$ is negligible).

From the measurements, the average amplitude of a typical single photon signal (see figure 3) is $\sim 2.5$ mV corresponding to $I_S=5$ µA ($R_f=1$ kΩ and $R_0=50$ Ω).
4. Results

Single photon detection capability has been assessed by exposing the array at pulsed UV light and operated at \( T = 175 \) K, \( V_{OV} = 3 \) V.

The measurements have been performed at lowest achievable intensity to maximize the probability of having only one photon per event (see figure 6).

![Waveforms taken in persistence mode at 175 K, \( V_{OV} = 3 \) V, by illuminating the detector with a LED pulser (used as trigger too). The spacing between signal families is the consequence of the preserved single photon counting capability after summing up the 16 individual MPPCs.](image)

The separation among signals corresponding to different number of photons detected in a single event is visible in figure 6. The first family, below the baseline band, corresponds to single photon events (1 p.e.), the second family to a double photons events (2 p.e.), etc.

The typical photoelectron charge spectrum, obtained by integrating the acquired waveforms, has been fitted with a set of multiple gaussians (see figure 7): the measured pedestal (0 p.e.) charge is \((1.47 \pm 0.16)\) pC, while for the 1 p.e. is \((3.21 \pm 0.26)\) pC, corresponding to an overall gain of \(\sim 2.0 \times 10^7\) (175 K, \( V_{OV} = 3 \) V).

![Photoelectron charge distribution with the array operated at 175 K, \( V_{OV} = 3 \) V. The data have been fitted by using a set of multiple gaussians. The measured charge of the 0 p.e. peak (baseline) is of the order of 1.5 pC, while the measured charge of the single photoelectron peak is about 3.2 pC.](image)
main contributions to the sigma of each photoelectron peak are in fact due to noise ($\sigma_{ELE}$), dark counts ($\sigma_{DC}$), afterpulses ($\sigma_{AP}$), crosstalk ($\sigma_{CT}$) and gain fluctuation ($\sigma_{GF}$). The equation:

$$\sigma_{p.e.}^2 = \sigma_{ELE}^2 + \sigma_{DC}^2 + \sigma_{AP}^2 + \sigma_{CT}^2 + \sigma_{GF}^2 \tag{1}$$

Since $\sigma_{p.e.}$ of the first photoelectron peak is 0.26 pC and $\sigma_{ELE}$ is 0.16 pC, the contributions due to the detector (AP+DC+CT+GF) is dominant (0.20 pC).

5. Conclusions
This work concerns the design and tests of a photo detector prototype based on the use of 16 S13370-3050CN (VUV4 family) Multi-Pixel Photon Counters manufactured by Hamamatsu sensitive to VUV light.

The array is readout as a single detector through an electronics based on the use of an operational amplifier suitable for cryogenic environments (AD8011).

The measurements show an excellent photo detection capability, that is one of the most stringent requirements for the new generation of dark matter experiments. Overall, the performance of this device encourages for further studies for its use in liquid xenon based detectors.

References
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