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Cryogenic readout for multiple VUV4 Multi-Pixel Photon Counters in liquid xenon

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ABSTRACT

We present the performances and characterization of an array made of S13370-3050CN (VUV4 generation) Multi-Pixel Photon Counters manufactured by Hamamatsu and equipped with a low power consumption preamplifier operating at liquid xenon temperature ($\sim$ 175 K). The electronics is designed for the readout of a matrix of maximum dimension of 8×8 individual photosensors and it is based on a single operational amplifier. The detector prototype presented in this paper utilizes the Analog Devices AD8011 current feedback operational amplifier, but other models can be used depending on the application. A biasing correction circuit has been implemented for the gain equalization of photosensors operating at different voltages. The results show single photon detection capability making this device a promising choice for future generation of large scale dark matter detectors based on liquid xenon, such as DARWIN.

1. Introduction

Liquefied noble gas targets are at the forefront of the search for dark matter [1–3]. In the upcoming generation of large scale detectors, a great emphasis will be given to compact photosensors suitable for cryogenic environment, with single photodetection response and allowing for large area coverage [4]. A reduced radioactivity contribution to the total budget in order to minimize the experimental background is also crucial. Direct detection of vacuum ultraviolet (VUV) light is required by liquid xenon (LXe) based experiments ($\lambda_{\text{scintillation}} \approx 178$ nm) [5], while in liquid argon (LAr, $\lambda_{\text{scintillation}} \approx 125$ nm) a wavelength shifter is usually needed [6]. A wavelength shifter is commonly used to shift the 125 nm scintillation light towards longer wavelengths [6]. According to the most common WIMP models, the energy released in the interaction between dark and baryonic matter is supposed to be of the order of few tens of keV [7,8].

To date, photomultiplier tubes (PMTs) are still the most widely used devices for scintillation light collection. In order to reach a more efficient coverage and to reduce the contribution of the photosensors to the total radioactivity budget of the detector, smaller devices are being investigated. With light yields in the liquid phase of the order of a few tens photons/keV, to be able to achieve enough sensitivity, the 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). A promising candidate is the Silicon Photomultiplier (SiPM) or Multi-pixel Photon Counter (MPPC) [9].

The detector presented in this work is based on the use of the fourth generation of vacuum ultraviolet (VUV) multi-pixel photon counters (VUV4-MPPC) manufactured by Hamamatsu: the 3×3 mm^2 S13370-3050CN, shown in Fig. 1.

The most interesting features of a VUV4 MPPC are listed below:

1. meant to be used in cryogenic environment,
2. single photon counting capability,
3. PDE close to 25% at 178 nm,
4. can be operated at gains larger than 2×10^6.

To offer the equivalent area of a standard photomultiplier tube while keeping the same number of electronic channels, the grouping of several tens of MPPCs is needed. This requirement poses a challenge in the design of the readout. A few typical readout examples are described in [10]. More specifically, for a detector based on the use of a number N of MPPCs, there are three configurations:

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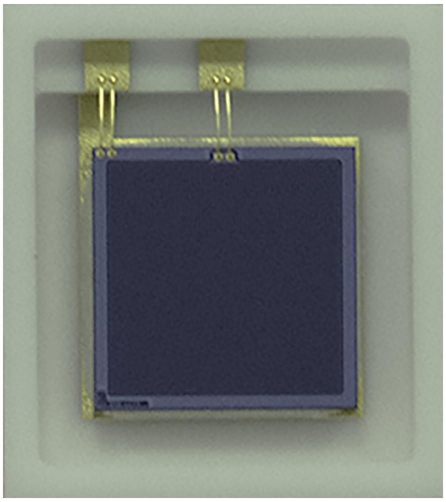

Fig. 1. One of the 3×3 mm^2 S13370-3050CN MPPCs used in the experiment.

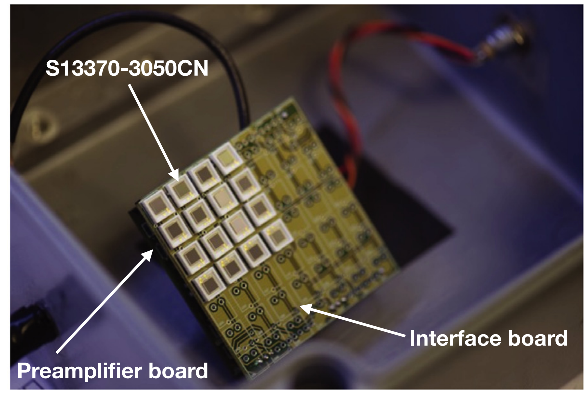

Fig. 2. The detector with the 16 individual MPPCs used in the experiment. Due to the ceramic package, the maximum number of S13370-3050CN that can fit on the interface board is in fact 49.

- parallel of N MPPCs,
- series of N MPPCs,
- hybrid: parallels of two (or more) MPPCs connected in series.

The main characteristics of the possible configurations listed above are reported in Table 1.

The noise contribution of each MPPC is due to its parasitic capacitance C_s and to the resistance R_s used for the connection to the operational amplifier inverting input.

In the ideal case, for which the parasitic capacitance is extremely low ($C_s \simeq 0$), the contribution to the overall noise is given by the input voltage noise of the operational amplifier. In the real case, the contribution to the overall noise is given by the number of connected MPPCs, weighed by the ratio between the feedback resistance R_f and R_s. The R_f value is constrained by the characteristics of the operational amplifier in use, while the R_s value has to be optimized.

The challenge is to provide a cryogenic readout that can deal with the capacitance of individual MPPCs, limiting the associated noise and providing a signal to noise ratio larger than one. Section 2 describes the detector used in this experiment. The experimental setup and its readout are discussed in Sections 3 and 4. The results are presented in Section 5.

2. The detector

In Fig. 2, the prototype of the VUV detector subject of this paper is shown. It consists of an array of 16 MPPCs soldered to an interface board that is in turn connected to the preamplifier board.

The decision to split the readout into interface and preamplifier boards has been taken to have the flexibility of testing different types of MPPCs (individually or grouped in tiles). The electronics is designed to readout up to 64 individual channels; however, due to the ceramic frame of the devices under test, the maximum number of S13370-3050CN that can fit on the interface board is in fact 49.

It is worth mentioning that the AD8011 operational amplifier had been already used by our group, in a preamplifier circuit for the Hamamatsu PMT R11410. The preamplifier was successfully tested at LXe conditions [11].

3. Experimental setup

The characterization of the detector has been performed at cryogenic conditions and more specifically at LXe temperature (175 K) by using a cold finger partially immersed in liquid nitrogen and in direct contact with the setup. Varying the liquid level allows for the control of the temperature. The MPPC array and its electronics have been placed in an aluminum box (see Fig. 3) equipped with connectors for signal readout, for detector and preamplifier biasing, and with an optical diffuser to isotropically deliver light from a pulsed LED towards the sensitive detector surface. To constantly monitor the temperature and to correct the biasing voltage accordingly, a PT100 has been used. Gas nitrogen has been flushed through the box, to avoid discharges arising from water condensation.

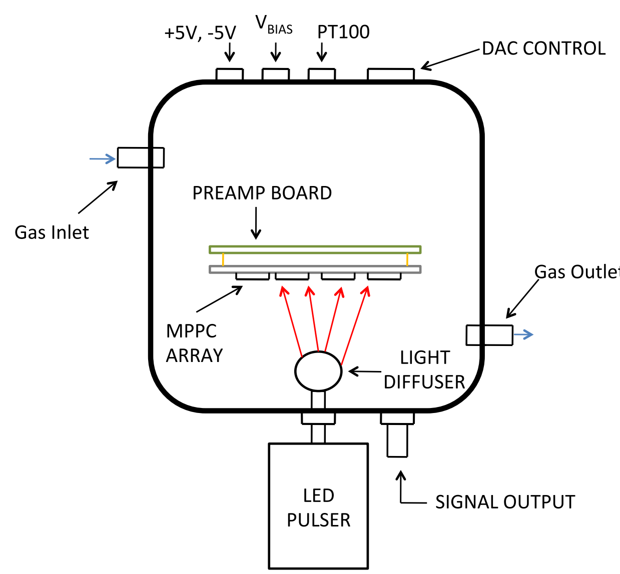

Fig. 3. A sketch of the test unit used in the experiment.

To compensate the effect of different breakdown voltages of the 16 MPPCs, (in the range 55.56 V ÷ 55.78 V) the biasing section has been equipped with a Digital to Analog Converter (DAC) to equalize the over-voltages.[1] All the 16 MPPCs have been biased by an Agilent E3645A, while a linear DC Elind 32DP8 power supply has been used to operate the preamplifier. The readout of the temperature through the PT100 has been performed by a Keithley 2100 digital multimeter. A LeCroy HDO6104 high definition oscilloscope has been used for signal readout and data acquisition.

Each waveform has been collected in 1 μs time window and sampled with 2500 points (2.5 samples per ns) at 12 bits at full bandwidth (1 GHz). All the results shown in this paper are presented without using

[1] The over-voltage (V_{OV}) is the voltage above the breakdown.