First results in the application of silicon photomultiplier matrices to small animal PET

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A B S T R A C T
A very high resolution small animal PET scanner that employs matrices of silicon photomultipliers as photodetectors is under development at the University of Pisa and INFN Pisa. The first SiPM matrices composed of 16 (4 × 4) 1 mm × 1 mm pixel elements on a common substrate have been produced at FBK-irst, and are being evaluated for this application. The MAROC2 ASIC developed at LAL-Orsay has been employed for the readout of the SiPM matrices. The devices have been tested with pixelated and continuous LYSO crystals. The results show the good performance of the matrices and lead to the fabrication of matrices with 64 SiPM elements.

1. Introduction

The second generation of Silicon Photomultipliers (SiPMs) has been produced at FBK-irst with improved characteristics [1]. Among those are a higher fill factor, and thus a higher photon detection efficiency (PDE) up to 20% at 420 nm wavelength, and a reduced noise. In addition, different geometries such as square devices of 1 × 1, 2 × 2, 3 × 3 and 4 × 4 mm², circular devices, and 1D and 2D arrays on a common substrate, have been implemented to fulfill the requirements of several different applications. The SiPM matrices (2D arrays) produced at FBK-irst will be employed as photodetectors in the construction of a small animal PET scanner that is being developed at the University of Pisa. The use of SiPM matrices instead of single elements is necessary to provide position information and minimize the dead area between the pixels, and thus maximize the sensitivity of the photodetector, ensuring a good performance. The PET scanner will consist of four rotating heads, each one composed of three detector layers. Each detector layer will be made of a continuous LYSO scintillator slab coupled to a SiPM matrix structure. Simulations predict a resolution better than 1 mm FWHM with a ^{18}F point source at the center of the field of view employing filtered backprojection for the image reconstruction [2,3].

The first matrices produced consist of 16 (4 × 4) pixel elements (Fig. 1). Each pixel has a size of 1 mm × 1 mm, and 625 microcells of 40 μm × 40 μm. The signals of the pixels are routed to the bonding pads placed on two opposite sides of the matrix, 8 on each side. The breakdown voltage is around 31 V, with a uniformity of σ = 0.31% considering all pixels in the matrix. The gain of the SiPM elements grows linearly with the overvoltage (bias voltage over the breakdown point), and it has a value of 1.5 × 10^6 at 2 V overvoltage.

The tests performed are aimed at verifying the proper operation of the SiPM matrices with both pixelated and continuous crystals. Suitable results obtained with the current prototypes will enable the fabrication of larger SiPM matrices with 64 pixels, that will be employed in the construction of the PET scanner.

2. Experimental setup

2.1. Setup description

Tests have been carried out coupling LYSO scintillator crystals of different geometries to the SiPM matrices, in order to study their response. Both pixelated and continuous crystals have been employed, and ^{22}Na spectra have been acquired in each case. A crystal array that perfectly matches the SiPM matrix has been
used. It consists of a 4 x 4 array of 16 crystals of 0.96 mm x 0.96 mm x 10 mm size, separated by 100 μm of white epoxy resin. The four lateral sides and the back of the array are also covered with white resin. The light produced in each interaction is confined in the crystal in which it takes place, and detected by the corresponding pixel in the SiPM matrix. Therefore the data are acquired independently for each channel and an energy spectrum is acquired per channel. In this case, the interaction position is simply determined by the position of the SiPM that has triggered the event.

Tests have also been performed with a continuous crystal of 4 mm x 4 mm x 5 mm wrapped with white Teflon tape on five faces, coupling the open 4 mm x 4 mm side to the SiPM matrix. The crystal covers the whole matrix, and the light produced in each event is spread in the crystal and it is detected by several pixels. In this case, some data processing with position determination algorithms (center of gravity in the simplest case) is necessary to determine the interaction position of the gamma-ray in the crystal.

In order to study the response of the matrix without the influence of the electronics, the first tests have been performed reading out the signal from one SiPM in the matrix directly with the oscilloscope, without employing an amplifier, and histogramming the signal area.

For the readout of the 16 channels of the SiPM matrix, the MAROC2 ASIC developed at LAL is employed [4]. MAROC2 is a 64-channel ASIC based on AMS Si–Ge 0.35 μm technology. Each channel features a low noise, variable gain preamplifier (6 bits), and two (slow and fast) shapers. The slow shaper has an adjustable shaping time ranging from 50 to 150 ns. The fast (τ = 15 ns) shaper (unipolar and bipolar) is followed by three discriminators. The main application of MAROC2 is the readout of the Hamamatsu H7546 photomultiplier tubes used in the ATLAS luminometer [5], and therefore it is not optimized for SiPM readout. The main limitations for our application have been identified, being principally a too short dynamic range when pixelated crystals are employed at a high overvoltage (above 2 V). A longer shaping time (200–250 ns) would also be desirable, in order to integrate all the charge produced by the scintillation photons generated in the LYSO crystals, that have a decay time of 40 ns. An improved version of this ASIC, MAROC3, better adapted to the requirements of our application will be employed in future tests. In spite of these limitations, the MAROC2 ASIC has allowed us to read out the SiPM matrices, and to perform the first tests very satisfactorily.

A board designed for testing the ASIC is employed for data acquisition. The board hosts an ALTERA FPGA that controls the data acquisition and provides the OR signal of the trigger outputs of all channels in the ASIC. The digitized output signal is provided by a 12-bit ADC located on the board. A sample and hold signal triggered by the OR signal is sent to the ADC, synchronized with the maximum value of the shaped signal. The board also allows us to perform the ASIC calibration. A calibration pulse is sent through a specific input with a variable capacitor to the channel selected by means of a switch, and the ASIC is read out in the same way used for the data acquisition.

![SiPM matrix developed at FBK-irst, consisting of 16 pixel elements of 1 mm x 1 mm size on a common substrate.](image1.png)

**Fig. 1.** SiPM matrix developed at FBK-irst, consisting of 16 pixel elements of 1 mm x 1 mm size on a common substrate.

![Calibration all channels](image2.png)

**Fig. 2.** Response of the 16 ASIC channels used for data acquisition to the calibration input charge.
2.2. ASIC calibration

The ASIC calibration has been performed at the minimum possible gain of the preamplifier. Fig. 2 shows the response of the 16 channels employed for the data acquisition to the charge sent to the ASIC. The ADC value is plotted versus the charge. The ASIC has a linear and uniform response up to 8–10 pC ($\sigma = 0.9\%$ at 7 pC). For higher values of the charge the response is close to linearity, but a change in the slope is observed. For values above 80 pC, the response clearly deviates from linearity ending up in the signal saturation, and the uniformity among channels slightly worsens ($\sigma = 1.5\%$ at 94 pC).

A good understanding of the electronics response is essential for the subsequent tests. Applying a high overvoltage to the matrix results in a higher PDE and therefore in a better energy resolution. However, in the case of the pixelated crystals an overvoltage above 2 V leads to the saturation of the signals in the amplifier, and we are therefore limited in the bias voltage that we can apply to the matrix. With the continuous crystal instead, the light produced in the crystal in each event is shared among all the SiPM pixels in the matrix. Even at 4 V overvoltage, the charge corresponding to the 1275 keV gamma-ray of $^{22}\text{Na}$ in each pixel is below 80 pC.

3. Results

The crystal array described in Section 2 has been coupled to a SiPM matrix. First, data from a single channel have been recorded with the oscilloscope. Fig. 3 shows the resulting $^{22}\text{Na}$ energy spectrum acquired with the crystal array coupled to the SiPM matrix, taking data from one channel directly with the oscilloscope, without employing an amplifier. The 511 keV photopeak can be clearly distinguished, while the 1275 keV photopeak cannot be appreciated. The background is due to the presence of the radioactive isotope $^{176}\text{Lu}$ in the LYSO crystals.

Fig. 4 shows the $^{22}\text{Na}$ energy spectrum acquired with the crystal array coupled to the SiPM matrix, operated in time coincidence with a 1 mm $\times$ 1 mm $\times$ 10 mm crystal coupled to a single SiPM. The background is significantly reduced as compared to Fig. 3.

Fig. 5 shows the $^{22}\text{Na}$ energy spectrum obtained with the crystal array coupled to the SiPM matrix, including data from all channels. The ASIC MAROC2 is employed for data taking.
spectrum obtained histogramming the signal area. The small size of the crystal results in a reduced size of the photopeak with respect to the Compton continuum. The background is due to presence of the radioactive isotope $^{176}\text{Lu}$, with an abundance of 2.6% in natural Lu that causes a typical intrinsic radioactivity of about 500 Bq cm$^{-3}$. The background is significantly reduced when the device is operated in time coincidence with a 1 mm $\times$ 1 mm $\times$ 10 mm crystal coupled to a single SiPM (Fig. 4).

Data from all channels in the matrix have been acquired employing the MAROC2 ASIC and test board. A $^{22}\text{Na}$ energy spectrum is acquired for each channel. The variations in the 511 keV photopeak position among all channels are around $\sigma = 4.5\%$ at 2 V overvoltage. This value includes variations of the gain and PDE of the SiPM pixels in the matrix, electronics response, differences among the crystals in the array and mismatches in the crystal coupling. Taking into account the measured variation in the peak position, it is possible to correct for this differences, and to plot a $^{22}\text{Na}$ energy spectrum that includes the data from all the channels (Fig. 5). The energy resolution cannot be directly calculated from the energy spectrum without correcting the deviation from linearity of both the SiPM and electronics, that are under study. However, the photopeak can be perfectly distinguished from the Compton edge.

Tests have also been performed coupling the 4 mm $\times$ 4 mm $\times$ 5 mm crystal to the matrix. In this case, the signals generated in all the SiPMs in the matrix are corrected for the gain variations and summed to obtain the total energy of the event. The resulting $^{22}\text{Na}$ energy spectrum is shown in Fig. 6. Both the 511 and 1275 keV photopeaks can be perfectly distinguished.

4. Conclusions and future work

Tests with the first SiPM matrices produced by FBK-irst, consisting of 16 SiPM pixel elements on a common substrate, have been performed. Successful results showing the good performance of the matrices have been obtained both with pixelated and continuous crystals.

Tests on position determination and coincidence timing measurements with two detectors are currently in progress. A first prototype of the scanner composed of two rotating heads will be constructed. The rotating gantry will allow the tomographic acquisition of data in time coincidence and thus the image reconstruction of simple sources.

The good performance of these prototype matrices warrants the fabrication of 64-pixel matrices that will be employed in the construction of the PET scanner.

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References