Design and Initial Performance Evaluation of a Novel PET Detector Module Based on Compact SiPM Arrays

Tianpeng Xu, Peng Fan, Tianyu Ma, Shi Wang*，Zhi Deng, Lingjun Lu, Yaqiang Liu

***Abstract*–Silicon Photomultiplier (SiPM) has been demonstrated to be a high performance PET sensor as alternative to conventional photomutiplier tubes. The aim of this work is to develop a PET detector module with compact SiPM device which consists of 3x3 SiPM arrays (4x4 pixels each array,3.17x3.17 mm^2 each pixel). A compact design of readout electronics is proposed based on discretized position-sensitive readout circuits (DPC) and time based readout ASIC. The function of the ASIC is to convert all signals' energy and timing information into digital timing pulses which can be processed by back-end simple Time-Digital-Convertor (TDC). So we get highly integrated electronics because the traditional Analog-Digital-Convertor (ADC) and Constant-Fraction-Discriminator (CFD) are replaced. A temperature-dependent gain control module including a microcontroller, a DAC and a DC-DC converter is designed to stabilize the gain of SiPM arrays against the variance of ambient temperature, which is based on the temperature sensor and serial identification chip intergrated in the SiPM array package. An preliminary experimental study was conducted, in which one SiPM array was coupled to a 6x6 LYSO crystal block. With a resistor charge-division chain readout circuit, a flood histogram map was acquired in which the crystals were clearly identifiable. With the correction of the gain control module,the maximum gain drift of SiPM decreases from 79.67% to 11.03% as the temperature varies from 27℃ to 50℃. The result indicates that the developed gain control module can contribute to improving the stability of SiPM based PET detector.Through some basic tests, the ASIC has demonstrated good performances of linearity and uniformity.We conclude that the proposed design is feasible for developing a compact SiPM PET detector module.**

I. INTRODUCTION

Silicon Photomutiplier (SiPM) has drawn dramatically increasing interests as a novel photo-electric sensor for Positron Emission Tomography (PET) thanks to its many advantages: high gain, high photon detection efficiency, low noise level , low bias voltage, insensitivity to magnetic field, compact size and potential low cost.

Recently we are developing a modular acquisition system for PET block detector with a new type of compact SiPM array. In this system, a resistive charge-division network is used to read out event signals to reduce the number of readout and processing electronics channels. New 8-channel ASIC chips will play the role in measuring the energy and timing information from the detector instead of using Analog-Digital-Convertor (ADC) and Constant-Fraction-Discriminator (CFD). The SiPM array contains a temperature monitor, so a temperature-dependent gain control system is also developed to compensate for the change in SiPM gain.

II. IMPLEMENTATION

Fig. 1 shows a block diagram of the detector and data readout system architecture. The output signals of SiPM array are initially processed by a resistor network and then digitized by a mixed signal ASIC. Time-to-Digital Converter (TDC) programmed inside FPGA will process the digital timing pulses from the ASIC chip. And data are transferred to the PC via USB 2.0 protocol. A temperature-dependent gain control system is proposed to improve the stability of this system.

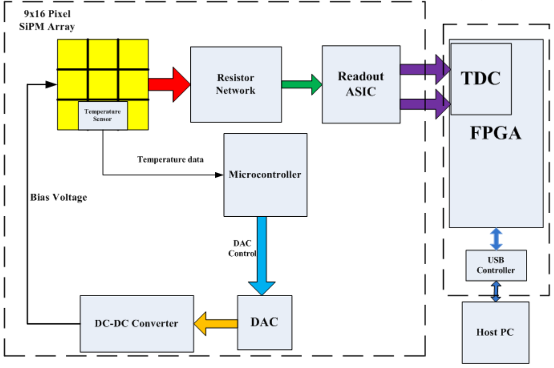

Fig.1.Block diagram of the detector system

A. *SiPM Array*

A novel compact SiPM array,Array4p9 (SensL,Ireland) is used in this study. It has 3x3 blocks which consists of 4x4 pixels, producing a 12 by 12 array of SiPM pixels. The size of each SiPM is 3.17x3.17 mm^2.The gap between adjacent pixels is around 0.2 mm, and the block-to-block gap is around 2.72mm. The recommended operating voltage is +29.7V.As shown in Fig.2.(b), in this SiPM array, a temperature sensor

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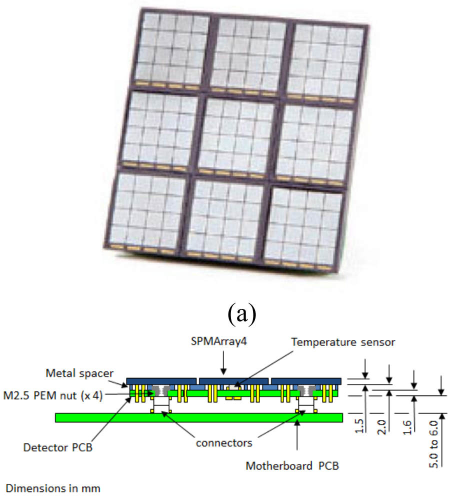
and serial identification chip is placed in the center of the package, allowing the temperature to be continuously monitored. Furthermore, the array package has minimal dead space over its sides which allows coupling to a very large area detectors by tiling multiple array packages.


(a)

(b)

Fig.2. (a) top-view of the Array4p9 and (b) Cross sectional side view of the Array4p9

B. *Read-out Circuits*

In order to reduce the number of signals ,we used discretized position-sensitive readout circuits (DPC). The DPC circuit is based on the orthogonal positioning algorithm used in single-wire position-sensitive proportional counters[1]. Fig.3 shows the DPC circuit diagram. For each block of SiPM, 16 channels are processed to 4.

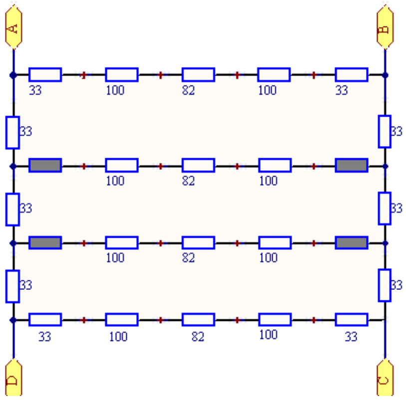


Fig.3. DPC resistor chain charge division circuit. All resistor values in ohms. The gray filled resistors are 0 Ω.

Based on 2D Anger logic, the positioning is determined by following equations:

$$X = \frac{B+C}{A+B+C+D}$$

$$Y = \frac{A+B}{A+B+C+D}$$

In the proposed design, the output signal A, B, C and D are connected to a mixed signal ASIC. The 8-channel ASIC chip of time-based readout (TBR) electronics has been developed and evaluated [2] .The main function of the ASIC is to convert a current signal from SiPM into two digital timing pulses which stand for energy and timing information separately. The ASIC simplifies circuit design because ADC and CFD are replaced[3]. So one ASIC chip can process all signals from two blocks of SiPM.

Digital timings signals from ASIC are processed by TDC programmed inside an FPGA (Cyclone II from Altera) .With the PLL of the FPGA we get a clock of 720M Hz, so the resolution of the TDC can achieve 1.4 ns. Finally data are transferred to the PC through an USB cable. The test setup is shown in Fig.4.

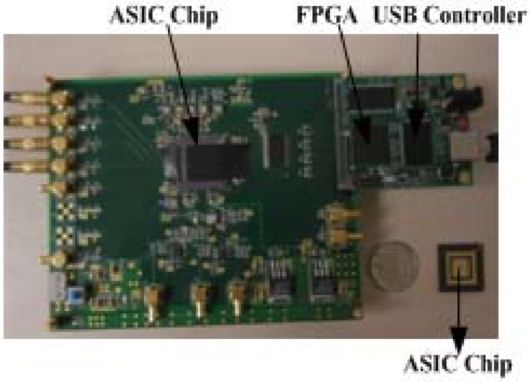


Fig.4. ASIC test circuit board

C. *Temperature-dependent gain control module*

One drawback of SiPM is that its gain is sensitive to ambient temperature which affects the stability of the detection system. A solution for solving this problem is to adjust the bias voltage of SiPM according to the temperature. A gain-correction system is developed as shown in Fig.6. The system consists of a microcontroller, a temperature sensor (DS1822, in SiPM array4p9 board), a DAC, a DC-DC converter. The temperature sensor measures the temperature of SiPM and transfers the data to the microcontroller. The microcontroller gets the data and control the output of the DAC,then we can control the output of the DC-DC converter. For an output voltage with 5 volts range, the voltage control precision can achieve about 5mV in the abstract as the DAC is a 10-bit one. With this method we can adjust the bias voltage of SiPM according to the current temperature and minimize the gain drift caused by the change of temperature.

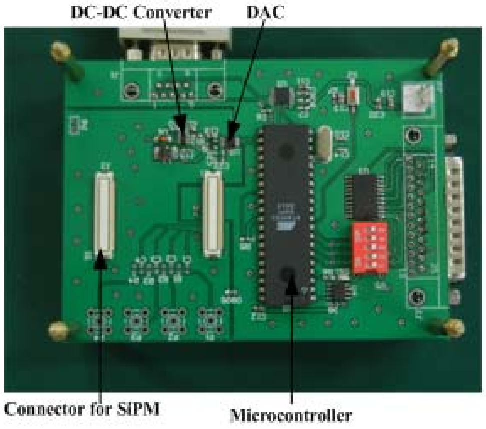


Fig.6. Evaluation board of temperature-dependent gain control module

III. RESULTS

A. Prelimary testing study of SiPM Array

A LYSO scintillation crystal array were optically coupled to a central block of the SiPM array. The LYSO array had 6x6 crystal pixels. The size of each crystal was 2.1x2.1x12mm^3. Every crystal was glued mirror reflector film (3M) on the side surfaces.

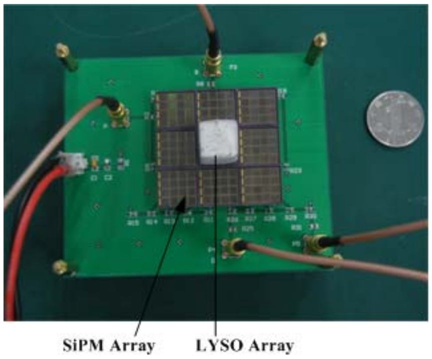


Fig.7. Experiment setup for SiPM array performance evaluation

The experiment setup is shown in Fig.7. The ^{176}Lu background radiation of LYSO crystal was utilized to collect scintillation events. Data acquisition was processed by a digital oscilloscope (LeCroy WaveRunner 104MXi-A).

Fig.8 shows a flood map after collection 100,000 events of ^{176}Lu background radiation. All 6x6 crystals are well separated and identified. The peak-value ratio is around 4:1.

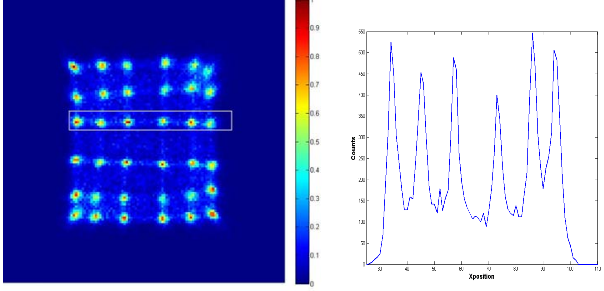


Fig.8.Crystal map measured from background radiation of LYSO (left) and profile plotted from the third column of crystals with peak-valley ratio around 4:1(right)

B. Performance of the gain control module

The temperature characteristics of the SiPM array were tested with a 2.1mm×2.1mm×12mm LYSO crystal coupled to the first pixel and by measuring the SiPM gain (relative value) with the ambient temperature varing from 25℃ to 50℃ in a constant bias voltage (33V). The results are shown in Fig.9, which indicates that the SiPM gain change linearly with the ambient temperature.Without the gain control module, the temperature-dependent gain shifts of the SiPM were 79.67%.

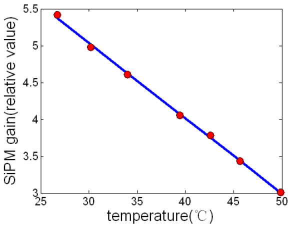


Fig.9. Temperature-dependent gain variation of the SiPM array without correction

With using our temperature-dependent gain control module, We measured the SiPM gain with changing the ambient temperature from 25℃ to 50℃ just in the same way as measuring the temperature characteristics of the SiPM array. As a result, we obtained the gain fluctuation of 11.03%, as shown in Fig.10.

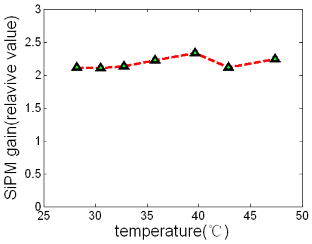


Fig.10. Temperature-dependent gain variation of the SiPM array after correction

C. ASIC Performance test

Currently some tests of the ASIC have been carried out in order to prove the excellent performances of our signal processing system in terms of linearity and uniformity. Measurements were performed with arbitrary-function generator (Tektronix AFG3252).

Linearity of ASIC (see Fig.11) has been demonstrated to be good besides at the low level of input signals which is out of the region of typical signal in PET application.

8 channels of the ASIC have been tested in the same situation in order to prove the high uniformity. As shown in Fig.12, red lines and blue lines are separately plotted from the digital timing pulses of energy information and timing information. The 8 channels of the ASIC has demonstrated very good uniformity.

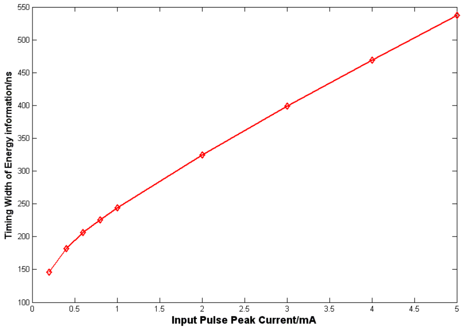


Fig.11. Linearity measured from a typical channel of ASIC

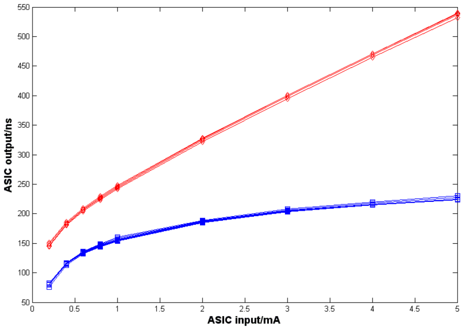


Fig.12. Uniformity test for 8 channels of ASIC. Red lines are for the width of digital pulses for energy information and blue lines are for the width of digital pulses for timing information.

IV. SUMMARY

The purpose of this work is to develop a detector module for PET application based on compact SiPM arrays. A new type of scalable detector is used building on SensL SPM technology. In order to highly integrate the full acquisition chain of events, resisitor charge-division network and time based readout ASIC chips are used to replace the conventional ADC and CFD based electronics. Though our tests, the ASIC has demonstrated good performances of linearity and uniformity. Moreover, a temperature-dependent gain control system is proposed to increase the stability of this detection system. We conclude that the proposed design is feasible for developing a compact SiPM PET detector module.

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