Compact Readout Electronics Based on a Resistor Network for SiPM-Coupled Scintillator Arrays in MeV Gamma-Ray Detection

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Abstract

SiPM-coupled scintillator arrays offer high detection efficiency and low cost, making them promising candidates for space-based MeV gamma-ray observations. However, the large number of readout channels poses substantial challenges for electronics design. Resistor network readout, which encodes position information through voltage division, provides an effective approach to reducing the number of channels.

In this study, we systematically evaluate two widely used resistor network schemes, Symmetric Charge Division (SCD) and Discretized Positioning Circuit (DPC), for MeV gamma-ray detection across different scintillator array sizes. Experimental results show that SCD exhibits superior uniformity and crystal discriminability for all array configurations, with significantly higher average peak-to-valley ratios of 35.36, 17.64, and 14.56 for the three arrays, compared with 11.84, 2.52, and 2.75, respectively, for DPC. Based on these findings, we implemented single-crystal energy spectrum readout for an 8$×$8 scintillator array using the SCD method, achieving an energy resolution of 7.82% at 511 keV.

Full Text

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SiPM-coupled scintillator arrays offer high detection efficiency and low cost, making them promising candidates for space-based MeV gamma-ray observation. However, the large number of readout channels poses significant challenges for electronics design. Resistor network readout, which encodes position information through voltage division, provides an effective approach to reduce the number of channels. This study systematically evaluates two widely used resistor network schemes—Symmetric Charge Division (SCD) and Discretized Positioning Circuit (DPC)—across different array sizes for MeV gamma-ray detection applications. Experimental results demonstrate that SCD exhibits superior uniformity and crystal distinguishability across all array sizes, with significantly higher average peak-to-valley ratios of 35.36, 17.64, and 14.56 for the three array configurations, compared to 11.84, 2.52, and 2.75 for DPC. Based on these findings, we implemented single-crystal energy spectrum readout for an 8$×$8 scintillator array using the SCD method, achieving an energy resolution of 7.82% at 511 keV.

Keywords: SiPM; MeV; Compton telescope; Resistive network

Introduction

MeV gamma-ray astronomy holds significant scientific importance in high-energy astrophysics and cosmology. Gamma rays in this energy range can propagate over long distances in space with minimal absorption and attenuation, serving as crucial information carriers for studying extreme astronomical phenomena [?]. However, in the energy range from approximately 0.2 MeV to 100 MeV, the sensitivity of existing space-based gamma-ray detectors decreases significantly compared to other energy bands, creating a notable sensitivity gap that limits current observational capabilities [?].

In the MeV regime, gamma-ray interactions with matter are dominated by Compton scattering, which has a relatively low cross section. Effective reconstruction of Compton scattering events requires precise measurements of the interaction positions and deposited energies of both recoil electrons and scattered photons, thereby imposing stringent requirements on detector design and readout electronics [?].

Current Compton telescope technologies include semiconductor detectors and time projection chamber approaches, such as COSI (the Compton Spectrometer and Imager) and LXeGRIT (the Liquid Xenon Gamma-Ray Imaging Telescope). However, semiconductor detectors typically suffer from high cost and limited detection efficiency, while liquid xenon systems face challenges in energy resolution and system complexity [?, ?]. In contrast, scintillator materials offer high detection efficiency and relatively low cost, with position resolution improvable through smaller crystal dimensions. Limited by the size and integration level of early photodetectors, scintillator-based Compton telescopes faced constraints in position resolution capability (e.g., COMPTEL) [?]. Recent advances in Silicon Photomultiplier (SiPM) technology have enabled readout of highly integrated scintillator crystal arrays. However, this introduces a significant increase in readout channel count, challenging the complexity and scalability of front-end electronics systems.

Resistor networks are widely employed in Positron Emission Tomography (PET) to substantially reduce readout channels [?]. Different resistor network schemes and array sizes significantly affect detector performance [?]. Moreover, while PET emphasizes timing and position resolution, Compton telescopes prioritize energy and position resolution. These differing requirements necessitate re-evaluation and optimization of resistor networks for Compton telescope applications.

This study optimizes and evaluates the two most widely used resistor network schemes, SCD (Symmetric Charge Division) and DPC (Discretized Positioning Circuit), for Compton telescope applications [?]. Using a ^{22}Na radioactive source, we compare the flood maps, horizontal profiles, and pulse widths of both methods across 4\$$\times 4, 6\times 6, and 8\times$\$8 array configurations, and measure the energy spectrum of individual crystals. The entire readout electronics architecture requires only four readout channels, significantly reducing design complexity. Test results demonstrate excellent system performance, providing a foundation for future development of large-area scintillator array Compton telescopes.

Materials and Methods

A. Detector

PET detectors typically employ crystal sizes smaller than the SiPM dimensions for light sharing (many-to-one) coupling [?]. This approach improves position resolution beyond the limits of minimum SiPM size but significantly compromises energy resolution [?]. Therefore, we adopted one-to-one coupling between crystals and SiPMs.

The detector consists of 64 detection units arranged in an 8\$$\times 8 array.EachunitcomprisesaSiPMcoupledtoaCs$
array.

Based on simulation results, crystals with dimensions of 2 mm × 2 mm × 1 mm, 3 mm × 3 mm × 1.5 mm, and 4 mm × 4 mm × 2 mm introduce angular uncertainties $\Delta\theta$ with FWHM values of 0.15°, 0.18°, and 0.22°, respectively. Smaller crystal dimensions provide marginal improvement in angular resolution while increasing cost and degrading energy resolution. Considering available SiPM options, we selected 3 mm crystals with Onsemi J-30035 SiPMs [?].

B. Detection Principle

Figure 1 [FIGURE:1] shows the SiPM and CsI(Tl) array (left) and the detector structure schematic with dimensions (right). When a gamma ray interacts with

Figure 3

Figure 1: Figure 3

a scintillator crystal, scintillation photons are produced in proportion to the deposited energy. These photons are absorbed by the SiPM, which outputs a current signal proportional to the number of scintillation photons. Measuring this current signal provides the deposited gamma-ray energy. SiPM signals are routed through a backplane connector. Since crystals and SiPMs have one-to-one correspondence, the position of the triggered SiPM directly indicates which crystal was hit.

C. Resistor Networks

Both DPC and SCD are based on resistive voltage division, where SiPM signals from different positions produce different voltage division ratios across four output ports. The signal position can be determined by measuring these ratios. The resistor R_g improves circuit bandwidth and reduces crosstalk [**?**]. SiPM output signals are connected in series by row and column, then distributed through R_{nA} and R_{nB} resistors. The resistor values are calculated using Eq. (3) [**?**].

Resistor networks used in PET typically require coupling capacitors for optimal timing resolution [**?**]. However, for Compton telescopes where energy resolution is paramount, larger resistor values are employed to improve energy resolution [**?**]. This study designed resistor networks for both methods across 4\$$\times 4, 6\times 6, and 8\times$\$8 array sizes. The circuit designs and position calculation methods for both approaches are described below.

1. DPC The DPC circuit is based on the orthogonal positioning algorithm used in single-wire position-sensitive proportional counters [**?**, **?**]. Figure 2 [FIGURE:2] shows the circuit schematic for the 8\$$\times$\$8 configuration. Signal position is calculated using Eq. (1).

2. SCD The SCD circuit schematic is shown in Fig. 3

. For clarity, a 4\$$\times$\$4 configuration is illustrated. Signal position is calculated using Eq. (2).

The resistor values are determined by:

$$R_{nA} = (n-1) \cdot G^{-1} N^{-1} + 1, \quad R_{nB} = (N-n) \cdot G^{-1} N^{-1} + 1$$

Here, R is the maximum resistor value in the network, G is the maximum conversion gain from input to output, N is the number of readout channels, and n is the channel index. When R is set as the amplifier feedback resistor, the gain from node (R_{1A}, R_{1B}) to node (R_{NA}, R_{NB}) varies linearly from 1 to G according to channel index.

Figure 4

Figure 2: Figure 4

We used $G = 2$, $R = 470\,\Omega$, with N varying among 4, 6, and 8 configurations, and 1% precision resistors. Table 1 lists the calculated and actual resistor values for R_{nA}. The calculation for R_{nB} is analogous and not shown.

Readout Electronics System Design and Implementation

The readout electronics system block diagram is shown in Fig. 4

. Signals from the SiPM array are encoded into four channels through the resistor network. The encoded signals are processed by a two-stage amplifier circuit: the first stage performs signal amplification, and the second stage converts single-ended signals to differential signals for ADC sampling.

The amplifiers selected are OPA656 and AD8138, with bandwidths of 550 MHz and 320 MHz, respectively. The amplified signals are digitized by an ADC14155QML with 14-bit precision and maximum sampling rate of 155 MSPS. The FPGA controls the ADC and handles scientific data transmission.

The system employs a modular design comprising four PCB boards (resistor network board, amplifier board, ADC board, and DAQ board) and host control software. The DAQ board design is described in Ref. [**?**]. The host software, developed in LabWindows/CVI, enables parameter adjustment and real-time display of energy spectra for each channel. Figure 5 [FIGURE:5] shows the assembled readout electronics system.

The system uses digital triggering to select valid events. ADC input signals are delayed by 1 µs through cascaded shift registers. When the ADC value of the original signal exceeds a preset threshold, the delayed signal is sampled for 15 µs, preventing loss of leading-edge information. The FPGA identifies the signal peak value and the accumulated value within the sampling window (i.e., signal waveform area). Peak values are used for position calculation, while accumulated values are used for energy spectrum accumulation. The trigger logic is illustrated in Fig. 6 [FIGURE:6].

Experimental Results

A. Experimental Setup

We tested the detector and readout electronics performance using a ^{22}Na radioactive source placed 10 cm from the detector. A CAEN DT5485P high-voltage module provided the bias voltage of +29 V. Figure 7 [FIGURE:7] shows the experimental setup. The silver container houses the ^{22}Na source. The small black package is the encapsulated SiPM array, connected to the resistor network board via an FPC connector.

B. Performance Comparison of DPC and SCD

We measured the flood maps, horizontal profiles, and pulse widths for both DPC and SCD methods across 4$×4, 6×6, *and*8×$8 array sizes. The results are shown in Fig. 8 [FIGURE:8]. Both methods can clearly distinguish individual crystals. The DPC method maintains good uniformity at smaller scales but produces significant distortion as array size increases. The SCD method maintains good consistency across all array sizes. The horizontal profiles show that DPC distortion can generate spurious peaks. We calculated the peak-to-valley ratio (ratio of signal peak to valley) from the horizontal profiles. The average peak-to-valley ratios for DPC are 11.84, 2.52, and 2.75 for the three array sizes, while SCD achieves 35.36, 17.64, and 14.56, respectively.

Regardless of array size, SCD consistently achieves significantly higher peak-to-valley ratios than DPC. The average peak-to-valley ratio decreases with increasing array size. Additionally, the DPC pulse width is approximately 15 µs, compared to approximately 5 µs for SCD. Larger pulse widths increase the likelihood of signal pile-up and result in longer dead times.

Given the clear advantages of SCD for larger arrays, we used the SCD method for single-crystal energy spectrum readout of the 8$×$8 array to evaluate SCD and detector performance.

C. Energy Spectrum Measurement Results

Figure 9 [FIGURE:9] shows the energy resolution distribution of each detection unit at 511 keV. The energy resolution distribution shows a clear pattern between edge and central regions. The average energy resolution is 8.27% for edge crystals and 7.82% for central crystals.

Figure 10 [FIGURE:10] presents the statistical distribution of energy resolution values, with an average of 8.02%, RMS of 0.31%, best resolution of 7.67%, and worst resolution of 9.66%. Figure 11 [FIGURE:11] shows the energy spectrum of the detection unit with the best energy resolution.

Conclusion and Discussion

Scintillator arrays coupled with SiPM readout represent a viable approach for MeV gamma-ray detector design, though the large number of readout channels must be addressed. This study successfully reduced the readout channels to four by implementing resistor networks widely used in PET systems, and systematically evaluated the performance of DPC and SCD schemes for Compton telescope applications.

Results show that DPC produces significant distortion in large-scale arrays and considerably degrades signal timing response. In contrast, SCD maintains good uniformity in larger arrays with higher overall peak-to-valley ratios and minimal impact on timing response.

The inferior DPC performance is attributed to excessive resistors and directly series-connected SiPM capacitances, which cause substantial RC delay and increase signal rise time and pulse width. As array size increases, peak-to-valley ratios decline because larger arrays accumulate more SiPM noise in series, and the reduced voltage division differences between channels become more susceptible to noise interference.

We subsequently used SCD for single-crystal energy spectrum readout of the 8$×$8 array. As shown in Fig. 9, edge and corner regions exhibit notably degraded energy resolution. While thicker light guides improve crystal distinguishability in light sharing coupling scenarios [?], in one-to-one coupling, thicker light guides reduce light collection efficiency for edge crystals, thereby degrading energy resolution. The worst energy resolution of 9.7% may result from the combined effects of intrinsic performance variations in the SiPM and the scintillation crystal, together with the edge position.

Overall, the detector performance meets expectations, demonstrating the feasibility of resistor network readout for scintillator arrays. Future work will employ thinner light guides to improve edge crystal performance, extend resistor network readout to larger arrays, and develop multi-layer detector configurations to validate Compton imaging capabilities.

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