Hand-Held Gamma-Ray Spectrometer Based on High-Efficiency Frisch-Ring CdZnTe Detectors

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***Abstract*—Frisch-ring CdZnTe detectors have demonstrated both good energy resolution, $< 1\%$ FWHM at 662 keV, and good efficiency in detecting gamma rays, highlighting the strong potential of CdZnTe materials for such applications. We are designing a hand-held gamma-ray spectrometer based on Frisch-ring detectors at Brookhaven National Laboratory. It employs an 8×8 CdZnTe detector array to achieve a high volume of 19.2 cm^3, so greatly improving detection efficiency. By using the front-end application-specific integrated circuits (ASICs) developed at BNL, this spectrometer has a small profile and high energy-resolution. It includes a signal processing circuit, digitization and storage circuits, a high-voltage module, and a universal serial bus (USB) interface. In this paper, we detail the system's structure and report the results of our tests with it.**

***Index Terms*—CdZnTe, CZT detector array, Frisch-ring detector, gamma-ray spectrometer.**

I. Introduction

CADMIUM Zinc Telluride (CdZnTe or CZT) is a very attractive material for using as room-temperature semiconductor detectors because it has a wide bandgap and a high atomic number [1]. However, because of the material's poor hole mobility, several special techniques were developed to ensure its suitability for radiation detection. Among them, the Frisch-ring CZT detector is an attractive option, having a simple configuration, yet delivering an outstanding spectral performance [2]–[4]. The goal of our group in Brookhaven National Laboratory (BNL) is to improve the performance of Frisch-ring CZT detectors; most recently, we focused on the non-contacting Frisch-ring detector [5]–[7] that allowed us to build an inexpensive large-volume detector array with high energy-resolution and a large effective area.

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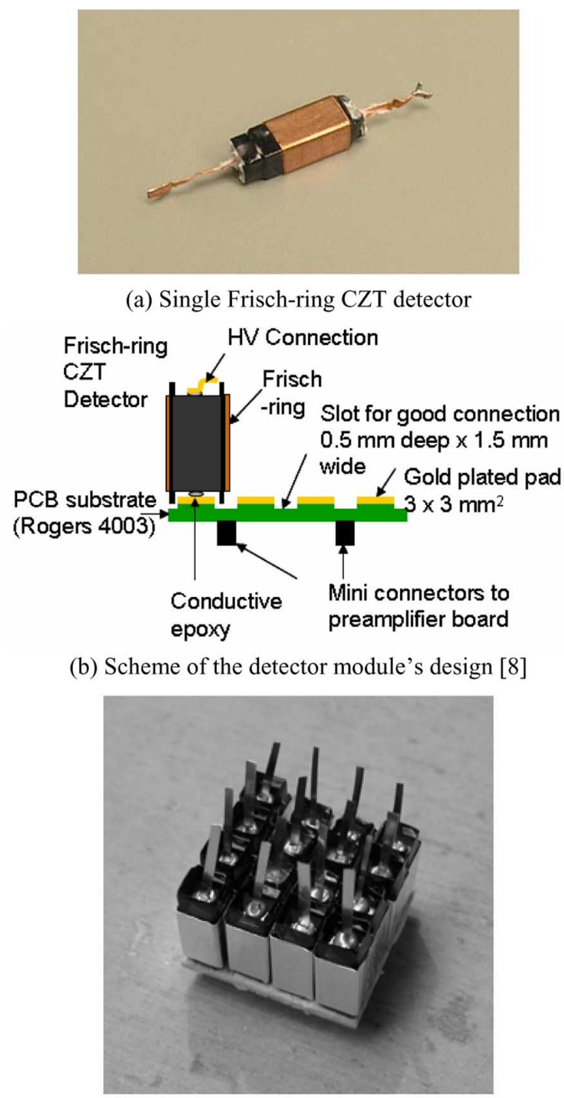


(a) Single Frisch-ring CZT detector

(b) Scheme of the detector module's design [8]

(c) Detector module

Fig. 1. Assembly of the detector module.

Highly efficient, compact radiation spectrometers are highly demanded in nonproliferation applications, non-destructive detection, radiation imaging, and homeland security (for example, monitoring vehicles and containers, custom inspections, and radiation-field surveys). Most of these applications require an inexpensive, compact instrument incorporating room-temperature operation, high gamma-ray energy resolution, and absorption efficiency. Gamma-ray spectrometers based on CZT detectors

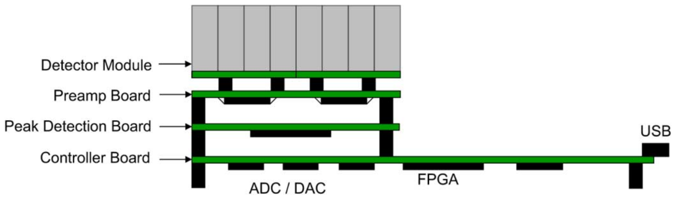
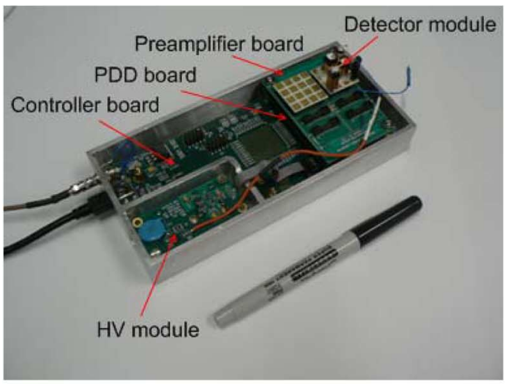


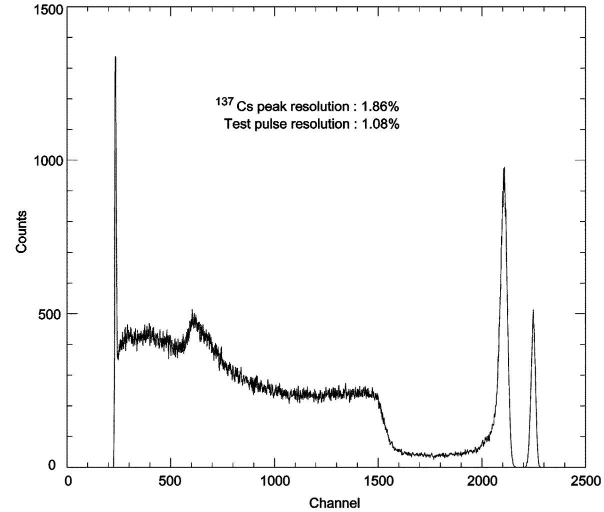
Fig. 2. The system structure of the hand-held spectrometer.



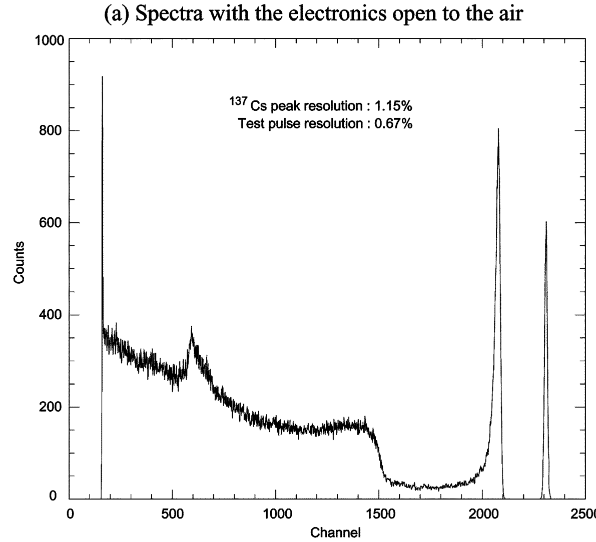
(a) Partially assembled hand-held device

(b) Completed hand-held device

Fig. 3. The DAQ system for the CZT detector array.



(a) Spectra with the electronics open to the air



(b) Spectra with the system enclosed in the box and cooled down to 26°C

Fig. 4. Spectra of the $^{137}\mathrm{Cs}$ and the test pulse.

were developed previously, but they either are very expensive or their absorption-efficiency is low. Our improvements in the Frisch-ring technique allowed us to assemble a detector array meeting the above requirements.

To facilitate the applications of CZT detectors, we developed several application-specific-integrated-circuits (ASICs) at BNL to readout signals from these detectors [9]–[12]. With these ASICs, we integrated a data-acquisition system to test Frisch-ring CZT detector arrays in the laboratory. The noise and spectral performance of this system were reported earlier [8]. However, this system was bulky and populated two $28 \times 20 \times 10\ \mathrm{cm}^3$ metal boxes.

To demonstrate the feasibility of employing Frisch-ring CZT detectors in portable applications, we are devising a hand-held gamma-ray spectrometer based on them. The system's structure resembles that of our previous one, but it is much smaller. It can read out an 8×8 array of Frisch-ring CZT detectors, each of $5 \times 5 \times 12\ \mathrm{mm}^3$. The whole system achieves an effective detection volume of 19.2 cm^3, i.e., ten times larger than commercial co-planar grid (CPG) CZT detectors. Therefore, the detection efficiency is improved significantly. Compared with pixilated CZT detectors, our system uses 75% fewer readout channels.

In this paper, we describe the fabrication of the Frisch-ring CZT detector and the structure of our first prototype system, and discuss test results with it.

II. Detector Design and Detector Module Assembly

To make the single detectors [Fig. 1(a)] we wrapped the CZT crystals with copper tape, forming the Frisch-ring shielding. This shielding is isolated from both the detector's anode and cathode by a shrinking tube. Using this configuration, we can apply ground potential to the Frisch-ring shielding, so that it can cover the crystal's entire side surface. Completely shielding on the side surfaces ensures better charge collection, and hence, better energy resolution.

To integrate the detector module, we used the same substrate as the one in our previous system [8]. The scheme in Fig. 1(b) shows the side view of this module. Due to the limited availability of CdZnTe crystals, only two full-size detector modules were fabricated. One of them is shown in Fig. 1(c).

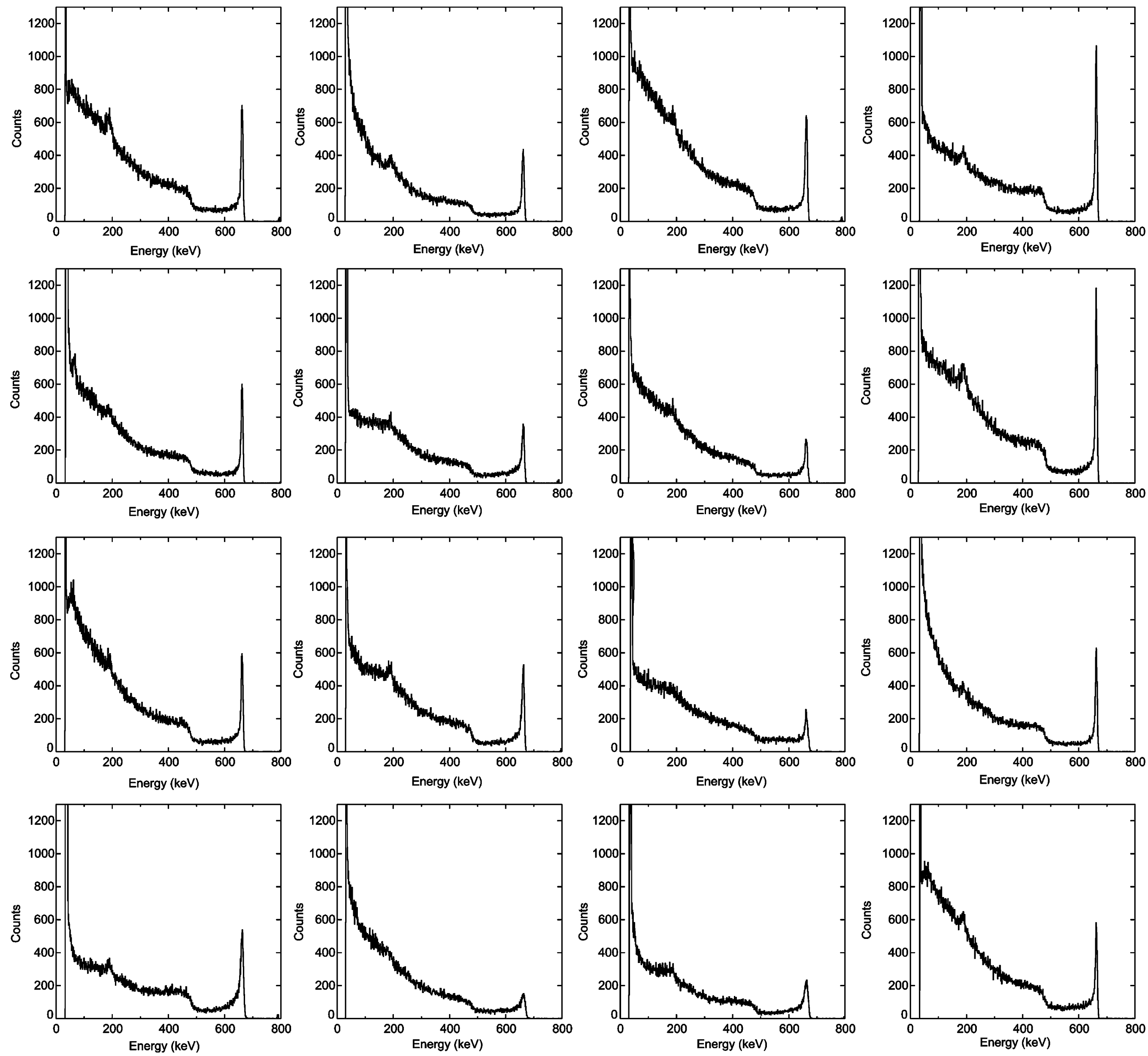


Fig. 5. Spectra of the $^{137}\mathrm{Cs}$ from one 4×4 CZT detector array.

III. Electronics Design

The circuit of our hand-held spectrometer is similar to that of our previous test system [8]. However, we took several approaches to minimize the size of this hand-held device while maintaining the system's same performance.

First, we partitioned the system into three PCB boards and integrated them into a stacked structure (Fig. 2). The top one, the preamplifier board, has four charge-sensitive-amplifier (CSA) ASICs to readout signals from 64 CZT detectors. The middle one, the peak detection board, has two peak detection/derandomization (PDD) ASICs that sense the input signals and save the information (amplitude and time of occurrence) into an on-chip analog FIFO. The PDD ASIC also is a 32:1 multiplexer, thereby significantly reducing the number of ADC needed for digitization. These two PCB boards are $6.6 \times 5\ \mathrm{cm}^2$. By separating the front-end circuits into these two boards, we were able to put them directly underneath the detector modules. The bottom board is the control board with ADCs to digitize the analog signals, an FPGA to control the readout logic, and a cypress USB interface to communicate with the computer. This stacked structure also helped us to avoid interference to the analog front-end circuit by the digital circuits.

Second, by using the PDD ASIC and the FPGA, we were able to simplify the circuit and reduce the size of the PCB board. Using the PDD ASICs helped us lower the number of ADCs from 64 down to 4 (2 for amplitude signals and 2 for timing signals). All the digital logic and memory were put into a low-power FPGA, thereby saving more space on the PCB board.

In addition, we selected low-profile packages for all the components on the board, from the ADCs to the USB interface and the high-voltage module.

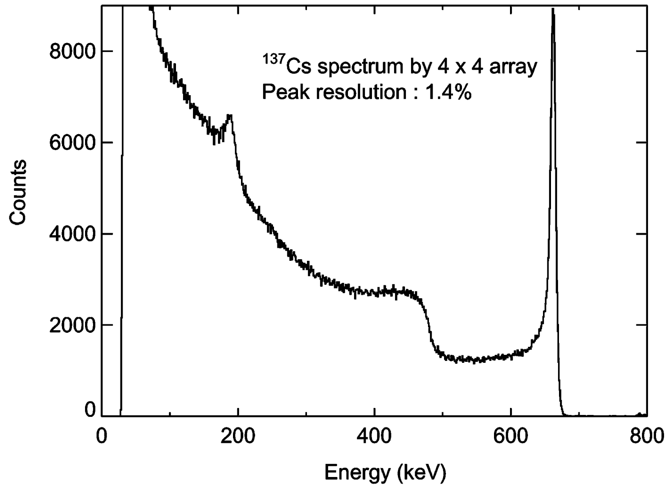


Fig. 6. Overall spectral response of one full-size detector module to the ^{137}Cs source.

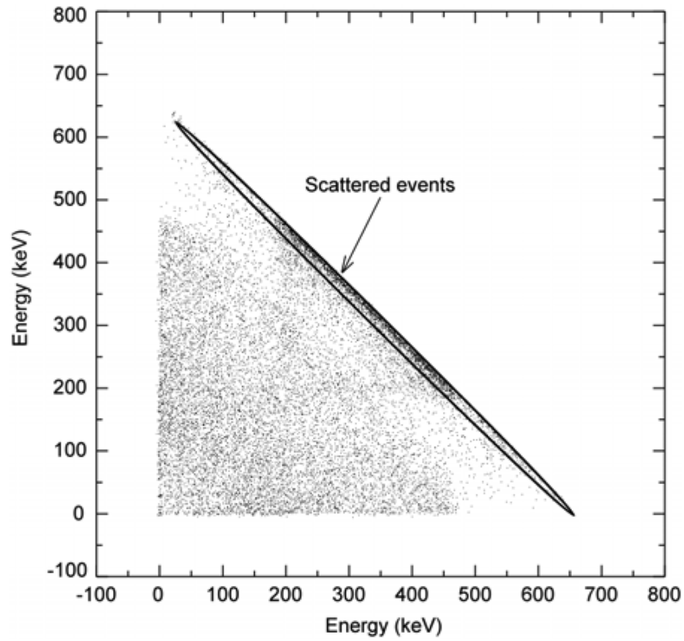


Fig. 7. Correlation of scattered events between two adjacent detectors.

Fig. 3(a) is a tear-down view of this hand-held device. Fig. 3(b) compares its size with that of a marker pen.

IV. Test Results

We tested the system in the laboratory using both a pulse generator and a ^{137}Cs gamma ray source. For the tests, the detector arrays were biased at -1800 V. The peaking time of charge preamplifiers was set at 2.4 μs, following our previous finding in [8]. Here, we discuss some results with the detector module in Fig. 1(c).

A. Spectral Response of Individual CZT Detectors

Fig. 4(a) shows the spectra for $^{137}\mathrm{Cs}$ and the test pulse, obtained over two hours with the electronics open to the air. Because the front-end ASIC was designed six years ago using an old process, it consumed much power. Hence, during the test, the ASICs and the detectors heated up, and the temperature around them rose to 50°C. This rise, in turn, increased the leakage current and the thermal noise of the front-end transistors, thus generating a higher noise level overall. Even under those poor conditions, we recorded 1.86% energy resolution $(\mathrm{FWHM} = 12.3\ \mathrm{keV})$ at the ^{137}Cs 662-keV peak. The pulse test showed an electronics noise of 3 keV (RMS).

To eliminate the ASIC's heating effect, we installed a thermal sink on top of the ASICs, enclosed the device in an aluminum box, cooled the box down, and held it around $26\pm0.5°\mathrm{C}$. Thereafter, the energy resolution improved to 1.15% $(\mathrm{FWHM} = 7.6\ \mathrm{keV})$ at the ^{137}Cs 662-keV peak [Fig. 4(b)]. The electronic noise in the pulse test also declined to 1.88 keV (RMS) (shown in the same figure), reflecting the fall in temperature.

B. Spectral Response of CZT Detector Modules

We tested the spectral response of two detector modules; Fig. 5 shows the spectra from all the 16 detectors on one of them. These 16 crystals were purchased from two different vendors, and thus were grown under different conditions. Most of the detectors had good spectral response—high energy-resolution and high photon-peak efficiency, but some exhibited low peak efficiency due to the crystal's poor quality.

By simply combining all these 16 spectra, we obtained the spectral response of the entire detector module with a detection volume of 4.8 $(2\times2\times1.2)\ \mathrm{cm}^3$. As depicted in Fig. 6, before recovering the scattered events, we achieved an overall energy resolution of 1.4% $(\mathrm{FWHM} = 9.27\ \mathrm{keV})$ at 662 keV without correcting for variations in gain between detectors or for electron trapping in the bulk.

Fig. 6 also reveals that the spectrum has a high Compton contribution. However, with the high-energy resolution of CZT detectors, and capability of the PDD ASIC to detect the time of occurrence of events, we can recover the scattered events between detectors. Considering the drift time of charge carriers in CZT detectors, we selected all the event pairs from two adjacent detectors that have a short time difference $(< 400\ \mathrm{ns})$, and plotted their distribution in Fig. 7. All the events are distributed within a triangular area. Especially, the events distributed along the diagonal side of this triangle are scattered ones. By summing the energies of these events, we can recover scattered events back to photon-peak events. After such recovery, we can increase the photon peak-detection efficiency of CZT detector arrays. We are developing the algorithm for the on-line recovery of scattered events, and will implement it in the FPGA to achieve better spectra in real-time. The results will be reported later.

V. Conclusions

We completed fabricating a prototype system for a hand-held gamma-ray spectrometer using Frisch-grid CZT detector arrays. This device demonstrated the advantages of our improvements on the virtual Frisch-grid CZT detector design: easy fabrication, easy integration with simple electronics, low cost, and good energy resolution.

Compared with pixilated CZT detectors, Frisch-ring CZT detectors need far fewer readout electronics channels. For a $20 \times 20 \times 15\ \mathrm{mm}^3$ detector module, we needed 16 readout channels (4×4 Frisch-grid detector array). For a pixilated detector, 122 channels are required [14]. Therefore, integrating radiation-detection systems based on Frisch-grid CZT detectors can be much easier. In addition, fewer readout channels also mean less power consumption and less heat generated during operation. As we discussed, overheating can significantly downgrade the detector's performance; thus, less heat will guarantee a better performance.

The overheating problem encountered in our device is not due to the number of readout channels, but to the obsolete ASIC used. With new technologies, we plan to develop a new ASIC bringing down the power consumption from 25 mW/ch to 2–5 mW/ch, comparable to the ASICs developed in [15], [16]. Thereafter, overheating will not be a big issue.

The energy resolution of CZT Frisch-ring detectors can be further improved by reading out signals from both the anode and the cathode, and measuring the depth of the interaction. This approach also will be implemented in the new design, and the results reported later.

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