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Development of a Compact Digital Multichannel Analyzer based on FPGA

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Abstract: In this work, we designed and built a digital multichannel analyzer (DMCA) using field-programmable gate array (FPGA), which is used to build a spectroscopic measurement system for a tomography device. DMCA's hardware was built with an ADC with 14-bit resolution and a sampling rate of 105 million samples per second (MSPs) combined with an FPGA board. The models of three functional blocks in DMCA, including pulse shaping filter, peak detection, and spectrum histogram processing, were simulated and optimized in the Matlab environment before they were integrated on the FPGA chip. The performance of DMCA was evaluated based on the high purity germanium (HPGe) detector with standard sources ^{60}Co and ^{137}Cs. The spectrum measured on the DMCA system showed that the drift of the spectral peak over time (100 hours) was of less than 1% and a resolution of 2.6 keV was at 1332 keV ^{60}Co. The DMCA developed in this work demonstrated various advantages: stability, compactness, versatility, and cost effectiveness.

Keywords: *Digital multichannel analyzer, FPGA, digital signal processing, gamma spectroscopy, tomographic gamma scanning.*

I. INTRODUCTION

Magnetic detector pulse processing systems have an important place in radiometric recording systems, which are used in industry, medicine, etc. [1]. Pulse processing is motivated by the goal of increasing resolution and minimizes distortion of the measurement spectrum. These two enable the system to measure and identify radioactive sources based on improved spectral shape.

Various advanced techniques of digital pulse processing have been reported in [2-8] as a promising approach in design of a radiation spectrometry system. Due to the need for superior performance, cost efficiency, and compactness, there has been widespread utilization of FPGA technology, which has recently garnered significant attention.

The FPGA has parallel computing capabilities and ability to be programmed for pulse signal processing [9-11]. Using FPGAs, the system can operate in real time that allows consideration of the generated signal on a pulse-by-pulse basis. The performance of the DMCA based on FPGA was proven reliable and compatible with various detector types [12]. Furthermore, simplification of the hardware design of the MCA and reduction of its cost and power consumption can be achieved [13]. These advantages interest many researchers to use the FPGA to develop DMCA for gamma spectrometry applications.

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In this study, a DMCA was designed and built to improve the resolution of the measurement spectrum of the HPGe detector. Six algorithms, including finite impulse response (FIR), digital trapezoidal filter, peak detection, pile-up rejection, baseline restoration, and specular histogram processing have been integrated in the FPGA of this DMCA.

II. MATERIALS AND METHOD

Fig. 1 presents the block diagram of a gamma spectroscopy that consists of a HPGe detector for gamma-ray detection, combined with a preamplifier and a DMCA unit. The DMCA was formulated by combining two components: an ADC, which serves as a unit for digitizing signals, and an FPGA, which functions as a unit for processing signals in real-time.

The output signal of the preamplifier was converted into digital form by the ADC and thereafter transmitted to the FPGA. The parameters of the ADC (Zmod Scope 1410 of the Digilent) and FPGA board (USB104 A7 Artix-7) are presented in Table 1. A mixer (op-amp AD847) was inserted between the preamplifier and the ADC to synchronize the signal. The clock time between the ADC and the FPGA was synchronized using a clock frequency of 100 MHz.

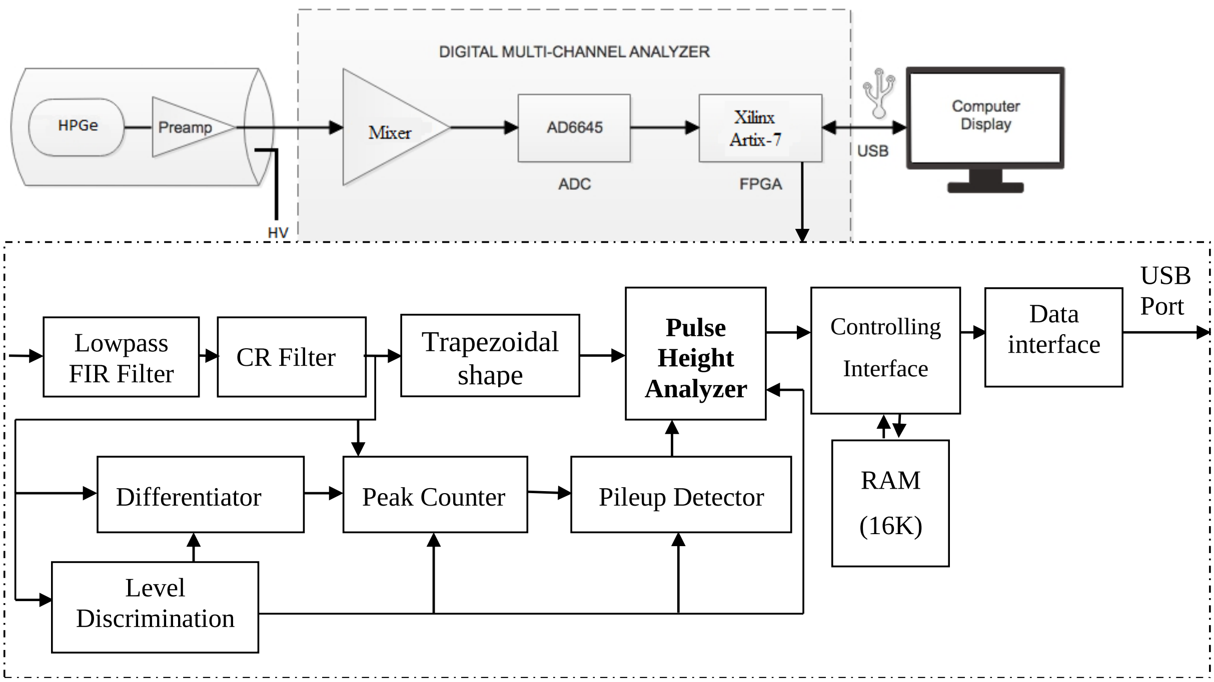

Fig. 1. Schematic block diagram of a gamma spectroscopy with DMCA

Various analysis algorithms were simulated using MATLAB, such as pulse shaping filter, threshold discrimination, pileup treatment, and pulse height analyzer. A FIR low pass filter with a cutoff frequency of 1.5 MHz as Ref. [14, 15] was employed to eliminate high-frequency harmonics of input signal from the ADC. Subsequently, a CR filter was used to enhance the signal-to-noise ratio (SNR), minimize the baseline drifts, and reduce pileup [16]. After pulse filtering, the signal was sent to a level discrimination block to create logic pulse for controlling next function blocks including differentiator, peak counter, pileup detector, and pulse height analyzer.

Table I. Technical parameters of ADC and FPGA board

ADC	FPGA
14-bit resolution	101440 logic cells
Sampling rate of 105 MS/s	240 digital signal processing slices
	4860 kbits memory
	8 GTP 6.6 Gb/s transceivers
	300 I/O pins

A differentiator was used to identify pulse peak and detect pileup. If the signal is larger than a specified threshold, the peak counter treats the signal as a pulse according to the logic of the differentiator. A pileup detector was used to identify and subsequently eliminate pileup pulses, thus compensating for the resolution. The window whose timing is equivalent to the trapezoid shaping time was employed to identify the pileup event, as shown in Fig. 2. The window time is triggered when the trapezoid height exceeds a specified threshold. Fig. 2 (top) shows the preamplifier signal digitized by the ADC, and Fig. 2 (bottom) shows the trapezoid signal which was extracted from the trapezoidal shape block in Fig. 1. The pileup detection algorithm is illustrated in Fig. 2. If the time measured by the pileup detector is longer than the window time, the event is treated as pileup. If the measured time is approximate to the window time, the event is treated as pileup free.

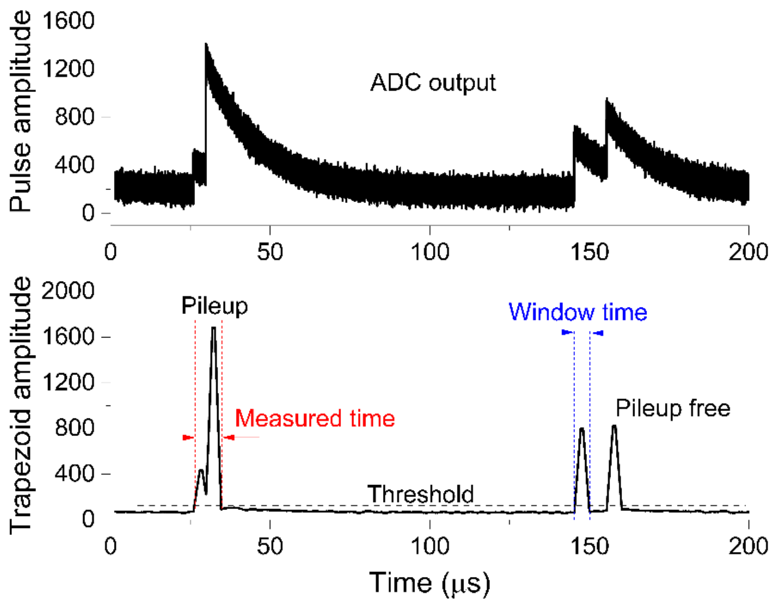

Fig. 2. Timing diagrams of pileup detection algorithm

The real-time baseline value was determined by using a digital variable N-point moving average of the trapezoid baseline near a point where the trapezoid signal exceeds a set threshold. Subsequently, a digital trapezoidal shaping filter was employed to accurately ascertain the pulse height. The peak value of each pulse is added to a 16k spectrum array. At the same time, the DMCA is connected to the computer via the USB port to transmit the measurement spectrum data to the display program.

The device was programmed by using the Xilinx System Generator programming tool. The DMCA design was developed by using the Xilinx Vivado software. The virtual instrument for DMCA was designed with the LabVIEW graphical programming platform [17], which served as an interface for data management, control and visualization.

Several benchmark tests were carried out with a coaxial p-type HPGe detector (Canberra, Model GC2020) that incorporated with a preamplifier (Canberra, Model 2002CSL) to validate the performance of the developed DMCA. Fig. 3 shows the experimental arrangement consisting of an HPGe detector, a ^{60}Co radiation source, and the DMCA with a user interface displayed on PC screen. A high voltage of 2.5 kV was given to the HPGe detector. The output signal from preamplifier was directly connected to the DMCA and the DMCA output was then transmitted to the PC using a USB cable.

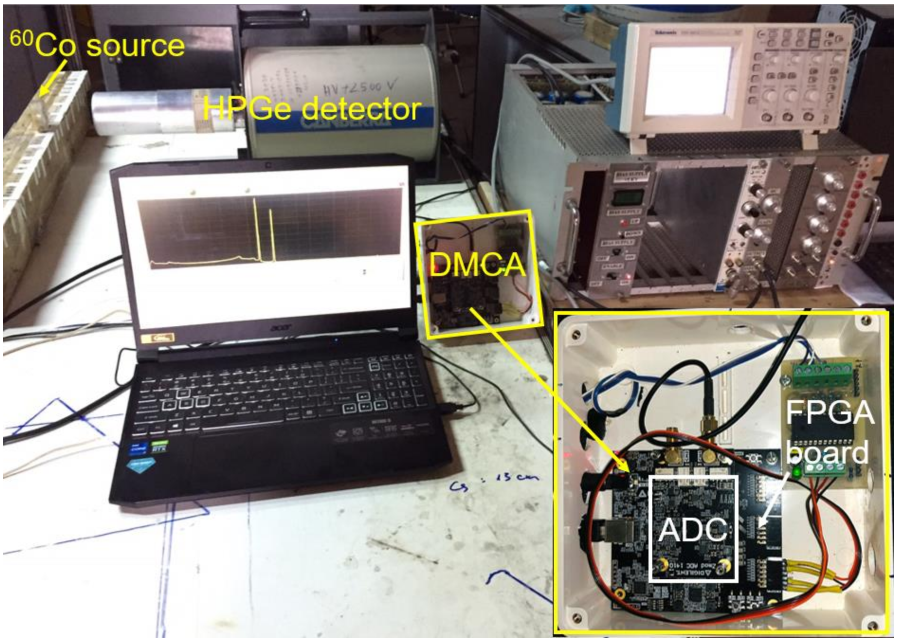

Fig. 3. Experiment arrangement including a HPGe detector, a ^{60}Co radiation source, and the DMCA with a user interface displayed on PC screen

The consistency in pulse height measurement of the DMCA was evaluated. The gamma-ray spectrum of the ^{137}Cs and ^{60}Co sources was continuously measured in several days (100 hours) and the spectrum was recorded regularly. The peak positions, including 1173 keV and 1332 keV of ^{60}Co and 662 keV of ^{137}Cs, were plotted as a function of measurement time, as shown in Fig. 4. The experimental result shows that the pulse height determination was reproducible under a statistical uncertainty below of 1%.

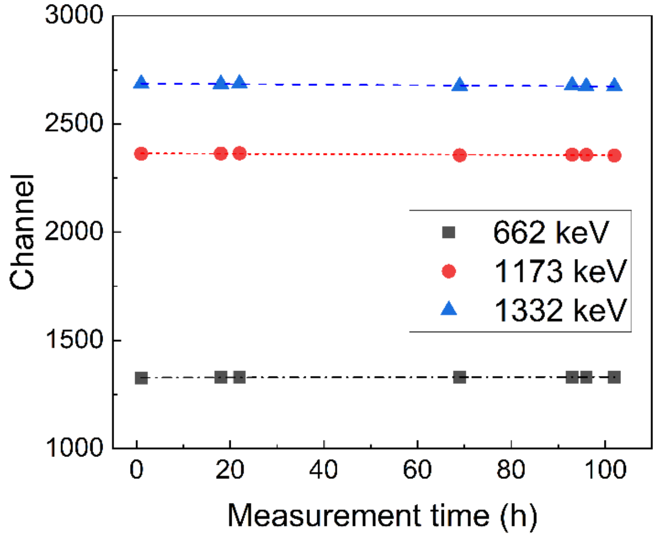

Fig. 4. Pulse height measurement as a function of measurement time

The spectroscopic performance of the developed DMCA was compared with that of the commercial signal processing system of gamma spectroscopy. The signal from the preamplifier was introduced into two signal processing systems individually for comparison: (a) a commercial signal processing system including a spectroscopy amplifier (Canberra, Model 2022) and a multiport 16k channel analyzer (Canberra, Model MP2-6U); and (b) the developed DMCA, respectively. Fig. 5 displays the spectrum of the ^{137}Cs and ^{60}Co sources with a total input rate of 850 counts per second, obtained with the Canberra system and the DMCA, respectively. The gain settings on the spectroscopy amplifier were adjusted to bring the energy spectrum in alignment with that of the DMCA.

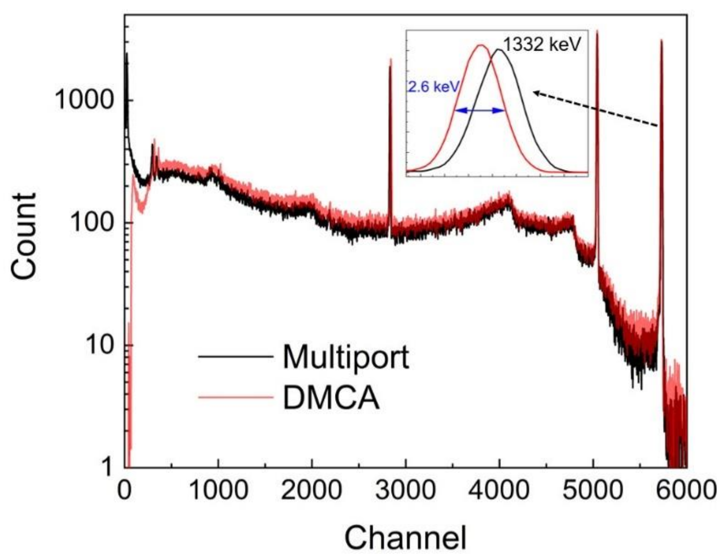

Fig. 5. Comparison in pulse height spectrum of ^{137}Cs and ^{60}Co sources (at input rate of 850 counts per second) obtained with the developed DMCA and the commercial signal processing system (Canberra)

In order to examine the system's throughput performance, two radioactive sources, ^{60}Co and ^{137}Cs, were utilized for the experiment. The setup is based on monitoring the count rate from the ^{137}Cs source independently and in the presence of the ^{60}Co source. The ^{137}Cs source was stationary while the position of the ^{60}Co source was varied to obtain different count rates. The intensity of the ^{60}Co was gradually increased to observe the deterioration of the ^{137}Cs peak area.

The obtained gamma-ray spectrum using the DMCA with various intensity of the ^{60}Co source is shown in Fig. 6. The actual input rate to the system was estimated by using numerical simulation [18]. The absolute detection efficiency was calculated based on the detector properties and the details of the measuring geometry. As it can be seen in Fig. 6, there was a decrease in the peak area of ^{137}Cs as the strength of the ^{60}Co peak intensity increased.

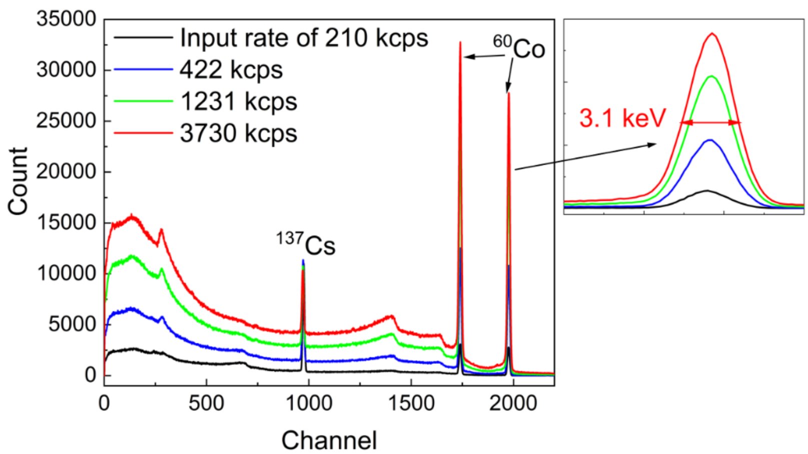

Fig. 6. Obtained gamma-ray spectrum as a function of input rate of ^{60}Co source

III. RESULTS AND DISCUSSION

The linearity in pulse height measurement of the DMCA was examined by using some standard radiation sources, i.e., ^{60}Co, ^{137}Cs, ^{133}Ba. The channel number was plotted as a function of the gamma energy, as shown in Fig. 7. A linear correlation (R^2 = 0.99) between the measured pulse height and the gamma energy was observed.

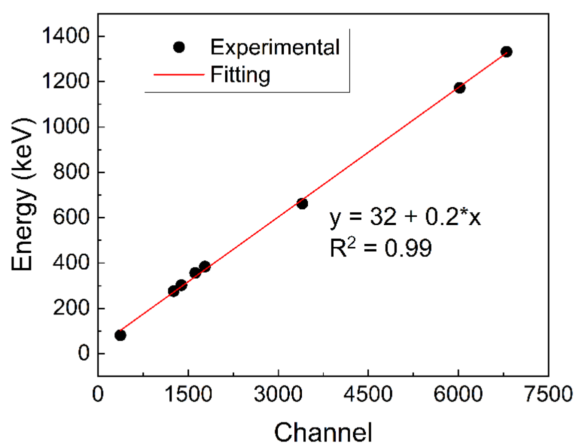

Fig. 7. Correlation between gamma energy and measured pulse height

Linearity and consistency in pulse height measurement are important factors of a gamma spectroscopy. Commonly, using the commercial MCA, a disproportionality in the energy - channel (pulse height) relationship may occur when the measuring time is sufficiently long. The results in Fig. 4 and Fig. 7 indicate that the digital signal processing system is eligibility for the long-time measurement.

In Fig. 5, both spectra obtained with the DMCA and the commercial signal processing system show the same features as the 662 keV, 1173 keV, 1332 keV photopeaks and the Compton edges. The performance of the DMCA is comparable to that of the commercial system in the throughput and the energy resolution. The energy resolution of 2.6 keV at 1332 keV ^{60}Co was achieved by using the DMCA.

In gamma spectrometry system, the degradation in throughput performance is dependent on the input rate. As shown in Fig. 6, the observed rate of the ^{137}Cs peak area is dependent on the intensity of the ^{60}Co source. Firstly, the ratio of the ^{137}Cs peak area to the Compton continuum below the peak decreased as the input ratio of ^{60}Co pulses increased. This effect is not avoidable and it decides the SNR. Secondly, the ^{137}Cs peak area is decreased due to pileup that increased as a function of the input rate. The ^{137}Cs photopeak signal and the Compton signal at that energy produce the pileup that causes count loss of the ^{137}Cs peak area. By employing the digital signal processing technique, it is possible to improve the throughput of the spectroscopy by reducing the pileup. This study involved a comparison of the throughput performance of spectroscopy using a newly created DMCA and a commercially available signal processing system from Canberra.

Fig. 8 illustrates the throughput curves under different spectroscopic measurement configurations, with the same counting geometry. The real-time mode curve (green curve) of the commercial system (Canberra) shows the lowest ^{137}Cs peak area. It can be seen that the throughput curve is improved by using the live-time mode (blue curve). The result measured with the DMCA (red curve) is superior to the live-time mode curve of the commercial system.

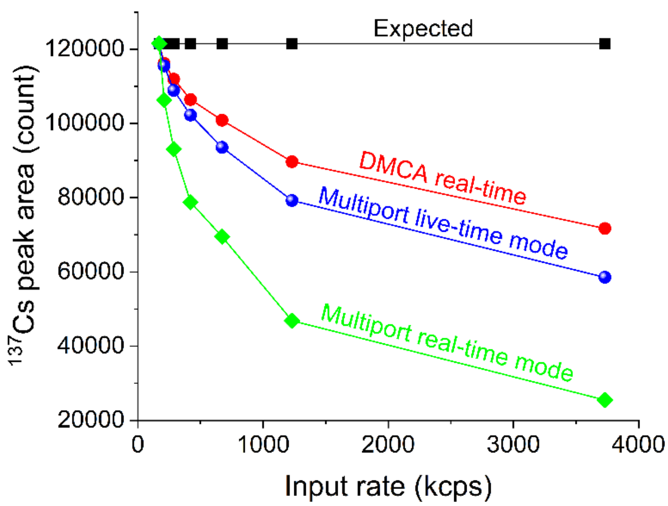

Fig. 8. Comparison in throughput between various spectroscopic measurement configurations: DMCA, real-time mode of Multiport, and live-time mode of Multiport. (All configurations measured with similar shaping time)

In the red curve of the commercial system in real-time mode (Fig. 8), the count loss is observed as a result of both the pileup issue and the deadtime. Enhancing the throughput can be achieved by utilizing the live-time mode, which offsets the period of deadtime. However, the number of pileup event is not considered in this mode.

In addition, it is noted that the duration of the measurement time in the live-time mode varies depending on the duration of deadtime, which is determined by the input rate. This could cause discomfort in certain applications, such as tomographic gamma scanning of radioactive waste drums. In order to simplify the scanning procedure, the measuring duration for each cell must be constant.

In the digital signal processing approach, the deadtime in the signal processing unit may not exist because all functions are processed with hardware in real time on a pulse-by-pulse basis. All pileup free events are recorded, while the pileup events that lead to resolution degradation are rejected. Overall, the developed DMCA in this work is adapted in gamma spectroscopy for tomographic gamma scanning; where the consistency in the pulse height measurement and the scanning time for each cell, and the high performance in throughput, are required.

IV. CONCLUSION

The research has successfully built a DMCA based on a real-time FPGA digital pulse processing system. The DMCA has comparable spectroscopic performance to that of a commercial MCA. Gamma-ray spectrum obtained with the DMCA has the same features as that measured with a commercial MCA. A high energy resolution (2.6 keV at 1332 keV ^{60}Co) was achievable. In addition, the pulse height measurement is linear and consistent over a long-time operation basis (several days). A superior throughput performance of the DMCA as compared to the traditional analog system was observed experimentally. The digital pulse processing technique provides the stability, compactness, versatility, and cost effectiveness. The techniques and the DMCA as developed in this work can be applicable to current radiation detection systems.

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