Journal of Magnetics 25(4), 626-631 (2020)

ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
https://doi.org/10.4283/JMAG.2020.25.4.626

Hybrid RCD-WTA Multiplexer for MR-compatible PET Detector

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(Received 27 October 2020, Received in final form 8 December 2020, Accepted 9 December 2020)

A hybrid multiplexer readout circuit one dimensional resistive charge division (1D-RCD) chain and winner takes all (WTA) circuit was proposed for MR-compatible PET detector modules. To prove the effectiveness of the circuit, three different readout circuits including WTA, 2D-RCD and proposed hybrid RCD-WTA multiplexer were evaluated for 4 × 4 LYSO-GAPD PET detector. Various parameters were precisely measured and quantitatively characterized. While there were considerable differences observed in rise time, fall time, pulse width and amplitude of analog output waveforms for each circuit, the detector performance was quite similar in crystal identification and energy resolution. However, pincushion distortion was observed in the flood histogram of 2D-RCD, and spatial linearity was relatively degraded. The coincidence time resolutions were 487 ps, 955 ps, and 676 ps for WTA, 2D-RCD, and hybrid RCD-WTA multiplexer, respectively. These results demonstrated that proposed hybrid multiplexer could effectively reduce the number of analog electronic channels from N^2 to only 2 for an N × N photosensor array, while maintaining intrinsic performance of multichannel PET detector requiring energy, position and time information for incidence photons.

Keywords : hybrid multiplexer, resistive charge division (RCD), winner takes all (WTA), non-magnetic LYSO-GAPD PET detector, mutual interface

1. Introduction

There are significant needs and efforts to develop simple and cost effective readout electronics providing energy, position and time information for each annihilation event for positron emission tomography (PET) detector. Significant milestones have been achieved in efforts to develop more efficient readout PET detectors that will overcome the current challenges including, system complexity and manufacturing cost, while maintaining intrinsic signal characteristics and PET detector performances. Also, most technical challenging issues associated with the mutual interference between PET and MRI should be mitigated by locating PET digital-electronics outside MR bore for the development of MR-compatible PET system. So far several multiplexing schemes that effectively reduce the number of signal channels have been proposed and utilized [1-11].

A resistive charge division (RCD) has been widely utilized in nuclear medicine field, owing to its simplicity, cost effectiveness, good MR-compatibility and easy application in multiplexing the numerous readout channels to four analog signals [1-4]. However, it has several disadvantages, including increased noise due to additional input channels connected to the resistive charge divider, and decreased positioning linearity due to inadequate light spread at the corners of the detector [5, 6]. Moreover, the total resistance and capacitance increase with increase in the number of resistors leading to a degradation in the timing performance of the detector, due to a slow rise time and a wide pulse width [7, 8].

A winner takes all (WTA) circuit has also been used to multiplex detector signals to one analog energy signal and a few digital address signals. It is designed with one-to-one coupling between the individual scintillation crystal and the separate photosensor channel in PET detector [9-11]. However, the WTA circuit only allows one-to-one crystal sensor coupling, which limits the spatial resolution to less than the photosensor channel size [7]. In addition, each photosensor pixels requires its own dedicated preamplifier and a comparator circuit; the complexity, power consumption and manufacturing cost of the system's back-end architecture and data acquisition could increase in scalable detector readout scheme with a few thousands

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of scintillator pixels. Moreover, it is difficult to locate these bulky electronics inside MR-bore without major modifications of the magnet design and to minimize mutual interference between PET and MRI without introduction of electromagnetic PET components shielding methods.

The goal of this study was to develop and characterize a hybrid multiplexer readout circuit combining 1D-RCD and WTA circuit which effectively reduce the number of analog electronic channels from N^2 to only 2 for an N by N PET detector array. We designed and built three representative readout circuits: WTA, 2D-RCD and the proposed hybrid multiplexer, and evaluated their performance. The following parameters were measured and characterized: effect of the readout circuits on analog output waveforms (rise time, fall time, pulse width, amplitude, and area under curve), crystal identification accuracy (peak-to-valley ratio, distance-to-width ratio, and spatial linearity), individual energy spectra for each crystal position from the generated flood histograms, and coincidence timing resolution.

2. Materials and Methods

2.1. PET Detector Configuration

The PET detector consisted of lutetium yttrium oxyorthosilicate (LYSO) and Geiger-mode avalanche photodiode (GAPD) arrays of 4 × 4 individual pixels arranged with a pitch of 3.36 mm. The LYSO array (Epic crystal, China) had an individual size of 3.28 × 3.28 × 20 mm^3. All crystals were polished and separated by 0.08 mm thick reflector film (ESR; 3M, USA). An individual LYSO crystal was coupled one-to-one to a separate pixel of the GAPD array with a pixel size of 3.16 mm × 3.16 mm (ARRAYJ-30035-16P-PCB; On Semiconductor, Phoenix, Arizona, USA).

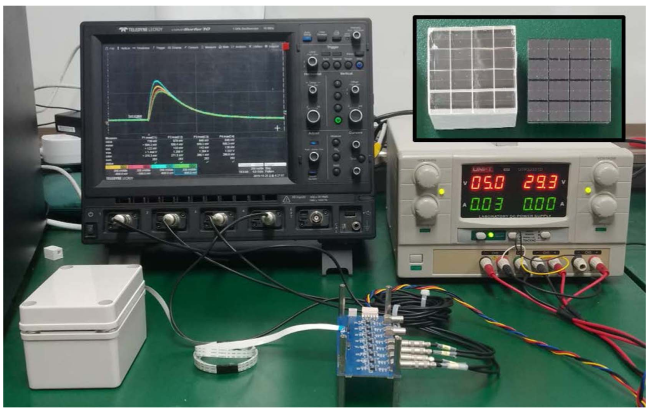

Fig. 1. (Color online) The experimental setup including MR-compatible LYSO-GAPD PET detector, custom-made electronics, DC power supply, and oscilloscope for the performance evaluation of WTA, 2D-RCD and proposed hybrid RCD-WTA multiplexer.

2.2. Hybrid RCD-WTA Multiplexer with Two Analog Output Channels

The proposed multiplexed readout circuit was designed by combining RCD and WTA circuit to reduce the number of analog output channels from 16 to only 2. The hybrid circuit uses one dimensional resistive chain in only X-direction in RCD circuit, and the current-ratio positioning ranges from 1/5 to 4/5, in 1/5 steps, for resistor value of 50 ohm. Analog outputs of both ends were fed into current sensitive preamplifiers and the amplified signals were then split into two signal groups (Fig. 2).

One signal group (A#N and B#N) was fed into the second preamplifiers and was connected to 2-channel analog-to-digital converter (ADC) through analog switch for identification of energy and fine position information. The other signal group was fed into the 2-channel summing amplifier and then to the comparator. Trigger signals from each comparator were connected to the WTA circuit based on field programmable gate array (FPGA) which monitored and identified winner group with the fastest signal. Threshold voltage level of each comparator was

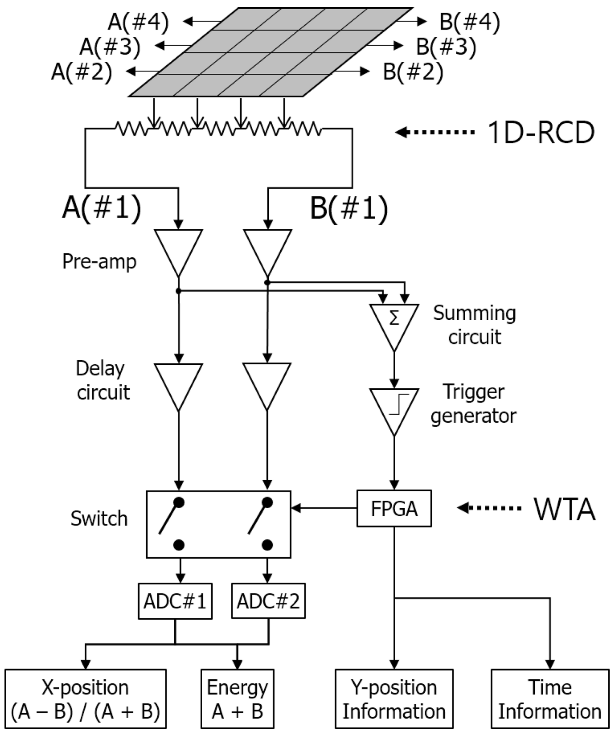

Fig. 2. Block diagram of the hybrid RCD-WTA multiplexer combining 1D-RCD and WTA circuit to reduce the number of analog output channels from 16 to only 2 for an N by N PET detector array.

adjusted using an external controller based on digital-to-analog converter (DAC).

When the output voltage of summing amplifier was above the low level discriminator threshold, a trigger signal was generated in the comparator and winner group with the fastest signal was identified in the FPGA. Then, digital address corresponding to Y-axis position information and time mark determining for coincidence event were fed into the data acquisition system (DAQ) module. Simultaneously, FPGA generated enabling signal to turn on the analog switch of the winner group and ADC digitized amplitude of the selected analog pulses. The two digitized outputs were post-processed by oscilloscope and custom-made DAQ system.

2.3. Performance evaluation of the multiplexed readout circuit

Three readout circuits including WTA, 2D-RCD and proposed hybrid RCD-WTA multiplexer were evaluated using the same experiment setup [3, 4, 9, 11]. The circuits were compared with regards to analog signal waveforms and PET detector performances. The following four parameters were measured using oscilloscope (Wavesurfer10; Teledyne Lecroy, Chestnut Ridge, NY, U.S.A.) with a bandwidth of 1 GHz, sampling rate of 10 GSPS, and channel memory of 10 Mpts: Amplitude, rise time, fall time, and pulse width of output signal for each readout circuit. The pulse data were acquired over 10k counts to reduce the statistical uncertainty (< 1 %). These measurements were taken three times at room temperature to examine the reproducibility of the results, which could be caused by imprecise measurements caused by random error, gain variations and electronic noise.

In addition, the following three investigation studies were performed using a custom-made DAQ system with 100 MHz sampling rate and 12 bit vertical depth: Flood histogram, energy spectra and time spectra. Flood histograms were obtained by irradiating the crystal array with a Na-22 point source from the top of the PET detector. The peak-to-valley ratio (PVR), distance-to-width ratio (DWR), and position linearity of the detected events were evaluated [8, 12]. Also, the energy spectra of the individual crystals were obtained through the use of the crystal lookup tables which were generated semi-automatically by searching the local peaks in the flood image and calculating the minimum distance from the peaks. The energy resolution was computed as the full width at half maximum (FWHM) of the 511 keV photopeak. The time spectra were obtained in coincidence with a reference PET detector consisting of a 3.28 mm × 3.28 mm × 5 mm LYSO crystal and 3 mm × 3 mm GAPD photosensor (MicroFJ-SMPTA-30035; On Semiconductor, Phoenix, Arizona, USA) (Fig. 3).

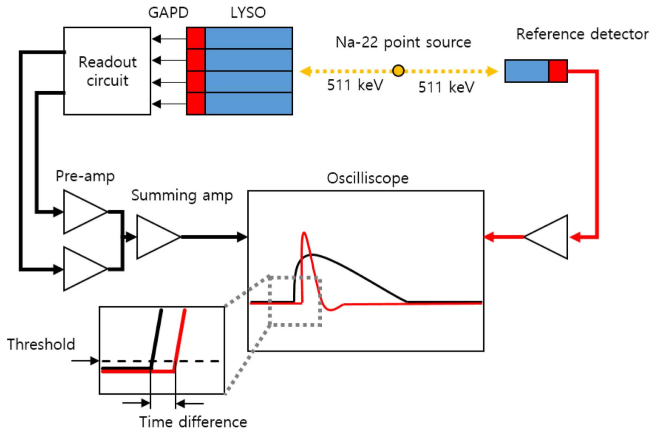

Fig. 3. (Color online) The basic experimental setup for coincidence timing measurements. MR-compatible LYSO-GAPD PET detector and reference detector are irradiated at the top of the crystal with annihilation photons from a Na-22 point source. The two detectors are separated by approximately 10 mm with the point source placed in the middle. The flight time difference of the two annihilation photons was acquired with oscilloscope.

3. Results and Discussion

Figure 4 shows representative output waveforms of the WTA, 2D-RCD and proposed hybrid RCD-WTA multiplexer. Visually, voltage and time information were changed considerably depending on the readout electronics. Rise time, fall time and pulse width of analog output wave-

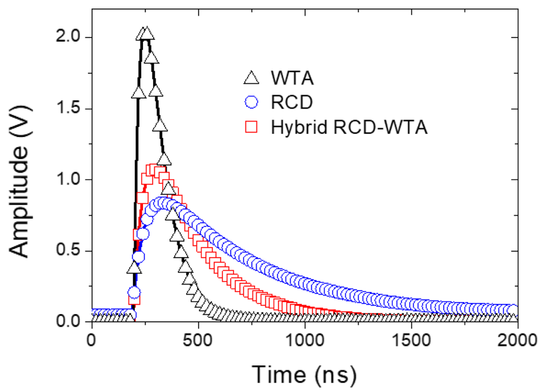

Fig. 4. (Color online) Representative output waveforms of PET detector with WTA (Δ), 2D-RCD (○), and hybrid RCD-WTA multiplexer (□). Voltage and time information were changed considerably depending on the readout electronics, while no unexpected noise sources, such as time jitter, baseline shift, and pulse oscillation, were observed with the WTA, 2D-RCD, and hybrid RCD-WTA electronics.

Table 1. Characterization of pulse waveforms.

Readout circuit Type	Rise time (10 %-90 %)	Fall time (90 %-10 %)	Pulse width (50 %-50 %)	Amplitude at 511 keV
WTA	30.8 ns	207.0 ns	141.4 ns	2.05 V
Hybrid multiplexer	55.0 ns	555.2 ns	301.2 ns	1.07 V
RCD	76.8 ns	783.4 ns	542.6 ns	0.73 V

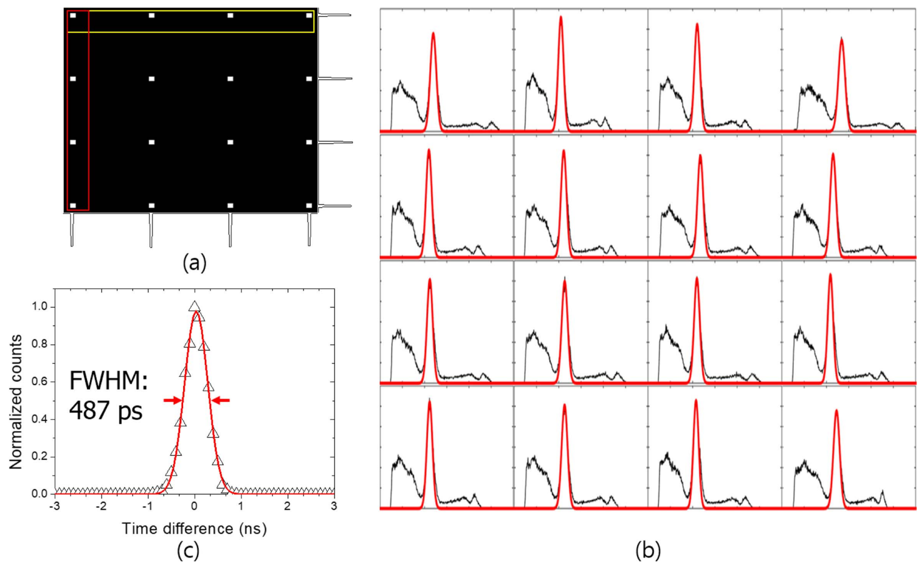

Fig. 5. (Color online) Flood histograms (a), representative energy spectra (b), and time spectra (c) obtained using WTA for 4 × 4 LYSO-GAPD PET detector. Ideal flood histogram providing good linearity and uniformity was acquired. The energy resolution (10.8%) and coincidence time resolution (487 ps) were relatively better.

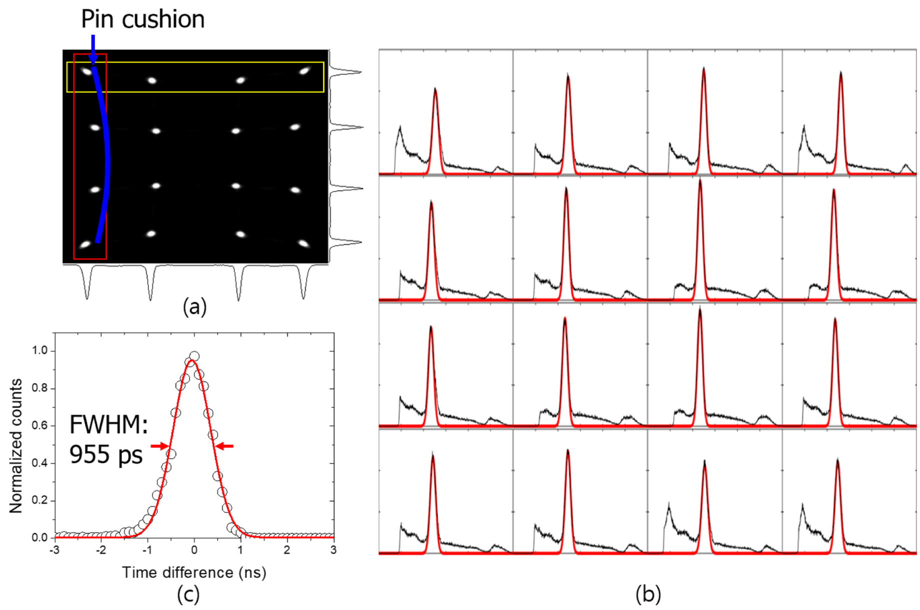

Fig. 6. (Color online) Flood histograms (a), representative energy spectra (b), and time spectra (c) obtained using 2D-RCD for 4 × 4 LYSO-GAPD PET detector. Pincushion distortion was observed in the flood histogram. The energy resolution (12.3 %) and coincidence time resolution (955 ps) were relatively poor.

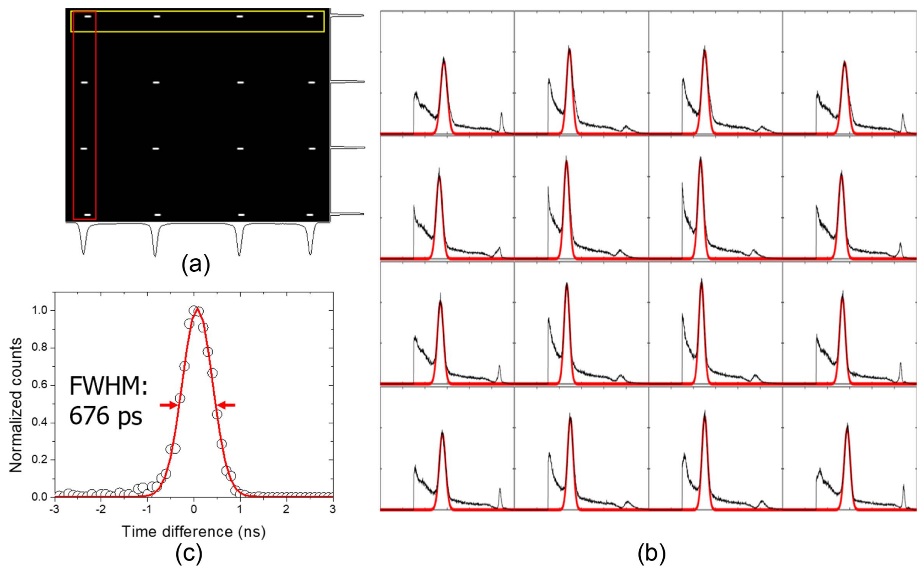

Fig. 7. (Color online) Flood histograms (a), representative energy spectra (b), and time spectra (c) obtained using hybrid RCD-WTA multiplexer for 4 × 4 LYSO-GAPD PET detector. No considerable distortion was observed in the flood histogram. Compared to 2D-RCD, the energy resolution (11.7 %) and coincidence time resolution (676 ps) were relatively improved.

forms were increased as number of register-connected GAPD pixels. Also, it could affect coincidence time resolution and count rate performance in PET detector. This was because input impedance of preamplifier increased with increasing relative resistance values in the resistive chain and they caused a decrease in amplitude, slow rise time and long fall time. Table 1 lists quantitative rise time, fall time, pulse width, and amplitude for 511 keV energy.

The 2D flood histograms, for WTA, 2D-RCD, and proposed hybrid RCD-WTA multiplexer, are shown in Fig. 5(a), Fig. 6(a), and Fig. 7(a), respectively. All 16 crystal elements were well separated for each circuit, while pincushion was observed in the flood histogram of 2D-RCD. Qualitatively, the performance of the three circuits was quite similar in crystal identification (PVR and DWR), spatial linearity, and energy resolution. Table 2 lists the quantitative performance comparisons including PVR, DWR, and spatial linearity for each readout circuit.

Figure 5(b), Fig. 6(b), and Fig. 7(b) show the energy spectra corresponding to each crystal position of the flood histograms. Moreover, the mean energy resolutions were 10.8 %, 12.3 %, and 11.7 % for WTA, 2D-RCD, and proposed hybrid RCD-WTA multiplexer, respectively. As shown in Fig. 5(c), Fig. 6(c), and Fig. 7(c), the time resolutions were 487 ps, 955 ps, and 676 ps for WTA, 2D-RCD, and proposed hybrid RCD-WTA multiplexer, respectively.

Compared to conventional RCD networks, the proposed circuit provides two advantages. First, the proposed design reduces the number of analog electric channels from N^2 to only 2 for an N by N photosensor array, while 2D-RCD network has to process four analog electric channels. The number of channels reduced to half, requiring only half the DAQ unit needed by the system. Second, the number of register connected between photosensor is reduced. This effectively decreases the total resistance and capacitance. Therefore, it is reasonable to suppose that the proposed hybrid multiplexer allows the improvements of time resolution for the development of PET detector module, as shown in Fig. 4. Also, the proposed hybrid multiplexer circuit requires only "N (No. column) × 2" preamplifiers and "N" comparators for N × N photosensor array, while WTA scheme need extra electronics as many

Table 2. Performance comparisons of three readout electronics.

Readout circuit Type	P/V ratio	DWR	Flood histogram linearity		Energy resolution	Time resolution
			X-axis	Y-axis		
WTA	∞	∞	1.0	1.0	10.8%	487.2 ps
Hybrid multiplexer	45.2 ± 5.0	13.5 ± 0.1	0.998	1.0	11.7%	676.4 ps
RCD	32.5 ± 0.3	12.7 ± 0.3	0.994	0.999	12.3%	955.1 ps

as the number of photosensor pixels (N^2). Having fewer electronics has several potential benefits as it affects the number of DAQ, system complexity, power consumption, and manufacturing cost. Moreover, the proposed multiplexer could provide high-resolution capability and system scalability, while WTA only allows one-to-one crystal sensor coupling.

4. Conclusion

In this study we examined the feasibility of a hybrid multiplexed readout circuit combing WTA and RCD for PET detector. Three readout circuits, including WTA, 2D-RCD, and proposed hybrid multiplexer were evaluated and various parameters (rise time, fall time, pulse width, amplitude at 511 keV, PVR, DWR, energy resolution, and spatial linearity) were characterized. The results of this study indicate that proposed RCD-WTA hybrid scheme could effectively reduce the number of analog electronic channels from N^2 to only 2 for an N by N array, while maintaining PET detector performance. This hybrid WTA-RCD multiplexed readout could be utilized in development of PET detector module with the improved spatial resolution and time performance. Nevertheless, further studies will be followed to characterize the count rate performance and imaging capability of the partial ring of the PET using hybrid multiplexer readout circuit for the development of MR-compatible PET system.

Acknowledgment

This research was a part of the project titled Smart Aquaculture Research Center, funded by the Ministry of Oceans and Fisheries, Korea.

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