FFT- and DWT-Based FPGA Realization of Pulse Shape Discrimination in PET system

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***Abstract*— In positron emission tomography (PET) scanners, the depth of interaction (DOI) is a great interest research area. To gain the DOI information, different pulse shape discrimination (PSD) techniques are used for crystal-identification of phoswich detectors. This paper evaluates two recent PSD algorithms due to their discrimination performance of two different pulses types. These pulses recorded from LSO and LuYAP crystals. The two evaluated PSD algorithms are based on the Fast Fourier Transform (FFT) and the discrete wavelet transform (DWT). The designs and FPGA implementations of the two algorithms are proposed and compared. For PET events measured with LSO-LuYAP phoswich crystals, the FFT-based and the DWT-based achieve a successful discrimination rate of 97.18%, and 99.3%, respectively. Based on Xilinx XCV800 chip, the DWT-based algorithm realization saves 26% of slices, and 10% of computation time with respect to the FFT-based realization.**

***Index Terms*— DOI, PSD, FFT, DWT, FPGA.**

I. INTRODUCTION

The Digital positron emission tomography (PET) scanner architectures offer high flexibility and reliability over analog ones [1], [2]. These scanners allow the development and experimentation of novel and complex algorithms that propose new solutions to current PET scanner problems such as parallax error, higher pixelization, and energy thresholding adjusted to crystal granularity [2]. An essential problem that limits the PET spatial resolution is the parallax error, caused by particles entering the detector with non perpendicular angle of incidence. This effect dominates in systems with detectors of high resolution and interaction depth and when the observed field of view is large with respect to the detector distance. However, the problem is eliminated when the depth of interaction (DOI) is known [3].

The use of a stack of two different scintillation materials optically coupled to a single photomultiplier tube (PMT), known as phoswich detector (shown in Fig. 1). Recent papers are dealing with different approaches to gain the DOI information. This can be realized by measuring the light spread on the detector [4], [5] or the ratio of light output on opposite ends of the scintillator crystal [6],[7].

Furthermore, Pulse shape discrimination (PSD) methods use temporal information of pulses [8]. Although they are quite easy to implement, they are also fairly sensitive to noise and, mostly limited to specific crystal pairs with rather different characteristics. On the other hand, performing frequency analysis or wavelet decomposition on the real-time signals is an alternative. In the following section, the system setup and the pulse recording are described. In section III, the two evaluated algorithms are presented and their performances are compared. FPGA realization is demonstrated in section IV. Finally, section V gives the discussions and conclusions.

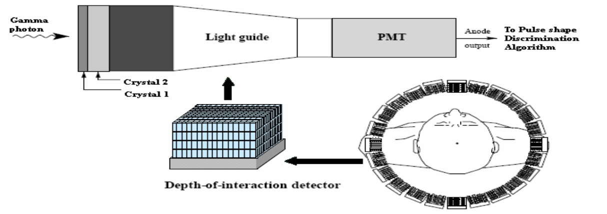

Fig.1. DOI (Phoswich) Detector

II. PULSE RECORDING

As a base for analyzing the properties of the light output a set of 10 000 pulses was recorded for the two crystals (LSO, LuYAP). The crystals are polished and of size 2X2X10 mm. They were positioned individually on a photomultiplier tube. Scintillation pulses were recorded by means of an acquisition board described in [9]. The interesting pulse signal is picked up at the last dynode of the PMT. The signal is amplified and has to pass a low-pass filter in order to satisfy the Nyquist theorem prior to digitization. For this purpose a passive second order LCR filter with a cut-off frequency at 3.6 MHz and an attenuation of 3 dB is used. Finally, each pulse is represented by 16 samples recorded at a sampling frequency of 40 MHz, thus covering a time window of 400 ns. In order to get an impression of the different pulse characteristics, Fig. 2 shows sample of the recorded data. It can clearly be seen that LuYAP has a significantly lower light output (lower energy) than LSO.

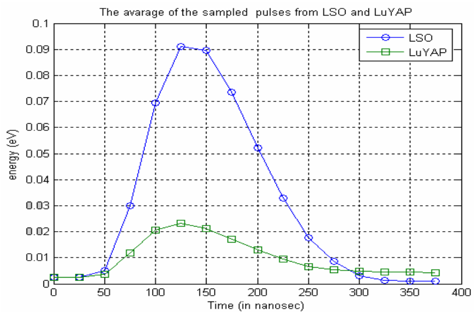

Fig.2. Filtered and sampled pulses at 40 MHz from LSO, LuYAP each averaged over all recorded events

III. PULSE DISCRIMINATION AND RESULTS

To implement a method that distinguishes pulses from LSO and LuYAP on FPGA, we first evaluated an algorithm that is based on spectral analysis of the pulse shapes "Fourier transform". Such a method is expected to be comparatively reliable and un-sensitive to noise because only a rather narrow bandwidth of the input signal is exploited.

In order to avoid the complexity of this algorithm we evaluate a second approach by using wavelets to discriminate the pulse shape. The performance of this algorithm is finally compared to that of the first one.

A. Fourier Transform Analysis

When performing a Fast Fourier transformation (FFT) to the 16 samples recorded at 40 MHz, the first spectral component will be at 2.5 MHz. Higher spectral components are weakened by the low-pass filter anyway. For being independent of the pulse height, the amplitude of this first component A_1 is normalized to the dc component A_o. Thus the normalized amplitude a_1 is obtained from the 16 pulse samples x_i by

$$a_1 = \frac{A_1}{A_o} = \frac{\sqrt{\left(\sum_{i=1}^{16} \alpha_i x_i\right)^2 + \left(\sum_{i=1}^{16} \beta_i x_i\right)^2}}{\sum_{i=1}^{16} x_i} \quad \text{with}$$

$$\alpha_i = \cos\frac{2\pi i}{16}, \ \beta_i = \sin\frac{2\pi i}{16} \qquad (1)$$

The values for 16 point FFT have been calculated for all recorded pulses of each of the two measured crystals. Then a barrier value is calculated. The mean FFT values are shown in Fig. 3 together with the barrier.

Obviously the spectral components will allow a clear separation of LSO from the LuYAP materials. So a barrier subtraction step is calculated to subtract from each normalized FFT component its barrier relative value. Then a weighting summation step is calculated, in which the results of the barrier subtraction step is weighted by a weight factors values (shown in Fig. 4) and summed up to get a result value of sum. Finally, a weighting summation greater-than-zero decision, (sum>0?), gives a discrimination answer of the two decay pulses. If sum > 0 then a slow pulse, otherwise a fast pulse [10],[11].

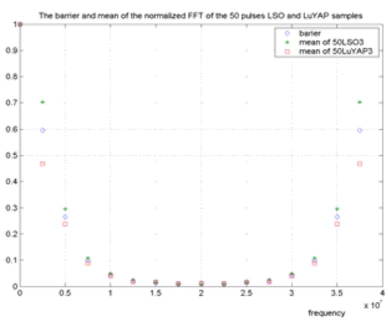

Fig.3. the mean of 16 point Spectral components for 50 pulses of the investigated crystals with magnitudes normalized to dc component.

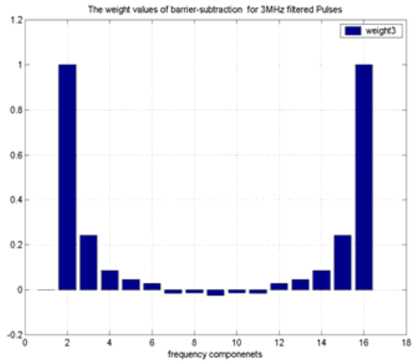

Fig.4 the weight values of the barrier between LSO and LuYAP types

The best result for distinguishing the LSO from the LuYAP pulses is a reliability of 99.3%; i.e. 9934 pulses out of 10000 are correctly discriminated into its type. The results of the proposed PSD technique for the 10K processed pulses (5000 pulses of each type (LSO and LuYAP) are shown in Fig. 5.

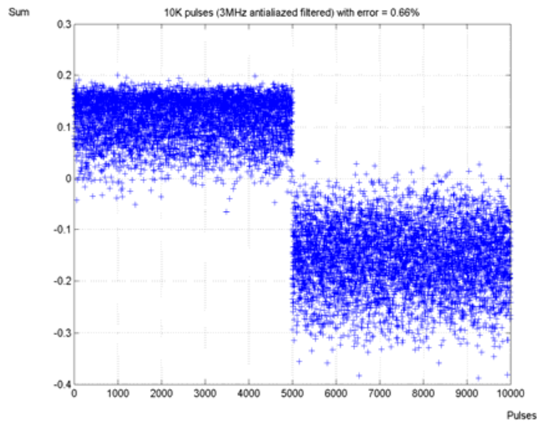

Fig. 5 the proposed FFT-based PSD technique applied to 5K pulses of each LSO and LuYAP pulses, respectively

B. Wavelet Transform Analysis

In spite of the satisfying results obtained by the spectral analysis, the complexity of (1) is challenging for a real time processing system at high count rates. The discrete Wavelet transform (DWT) [12] algorithm is desirable which can handle more pulses in the same time and therefore reduce the required calculation power. DWT involves decomposing signals into its constituent parts like the FFT does with a sum of sine. DWT offers advantages over other analysis methods, like FFT, for signals containing sharp transients and discontinuities like nuclear pulses issued from PET detectors. The analysis signal used in DWT is known as a wavelet describe by

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right), a \in R^+, b \in R \qquad (2)$$

where a represents the scale parameter and b the translation parameter. Unlike DFT, the wavelet is repeatedly shifted, scaled, and convolved with the analyzed signal to extract temporal and spectral component. Many wavelets have been proposed in literature [12], [13]. However, some are more popular than other for their characteristic or their performance. Fig. 6 depicts the daubechies wavelet function which is an example of the *wavelet* used in this simulation.

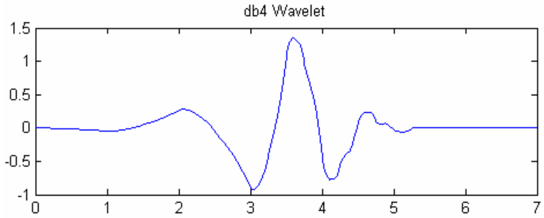

Fig. 6 Daubechies 4 Wavelet Function

Although good temporal and frequency resolution are obtained with Continues Wavelet Transform (CWT), it requires high processing time, memory usage, and, moreover, generates a huge amount of redundancy. For these reasons, the Discrete Wavelet Transform (DWT) is preferred for computation. The DWT minimizes the redundancy while retaining enough information for accurate analysis and synthesis of the signal [14]. The DWT generates the approximation coefficients $A_j[k]$ and detail coefficients $D_j[k]$ for the decomposition of the signal x_i(t) into its scaling function $\varphi(t)$ at scale j and wavelet function $\psi(t)$ at scale j

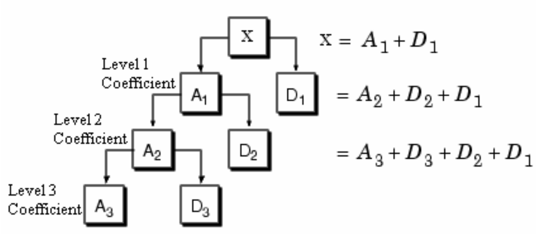

Fig. 7. The Discrete Wavelet decomposition tree

The DWT analysis operation is similar to a simple convolution and its implementation follows a recursive filter scheme known as a two-channel subband coder. The filter design, used at each decomposition stage, is based on wavelet functions (Fig. 6) chosen in the DWT analysis [12]. The algorithm scheme of discrete wavelet decomposition is shown in Fig. 7.

Although the DWT is a very powerful method used in the compression field, it can be used for crystal identification by decomposing the signal into its DWT coefficients. The wavelet coefficient at level 1,2,3 distribution from 10000 samples are reported in Fig. 8,9,10 respectively where crystal identification performance achieves nearly a perfect score. Then analyzing these coefficients to deduce the best one to be used for discrimination. Then a barrier (threshold) is calculated (shown in Fig. 8). Finally, a summation greater-than-zero decision, (sum>0?), gives a discrimination answer of the two decay pulses. If sum > 0 then a slow pulse (LuYAP), otherwise a fast pulse (LSO).

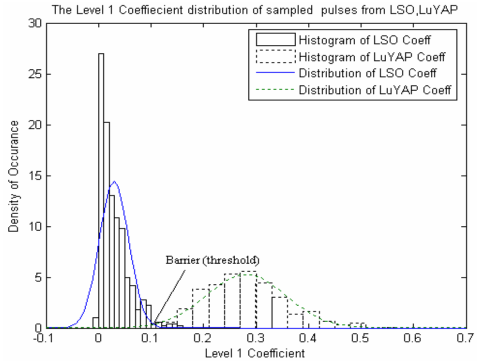

Fig.8 The Discrete Wavelet Level 1 approximation coefficient distribution of LSO and LuYAP

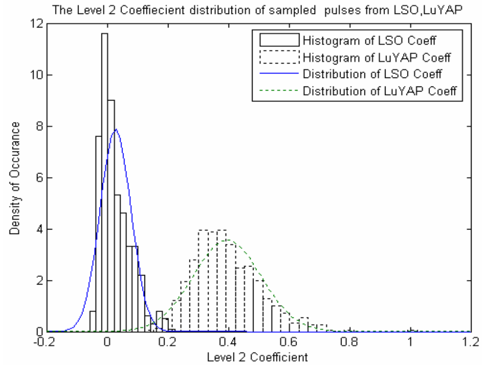

Fig.9. the Discrete Wavelet Level 2 approximation coefficient distribution of LSO and LuYAP

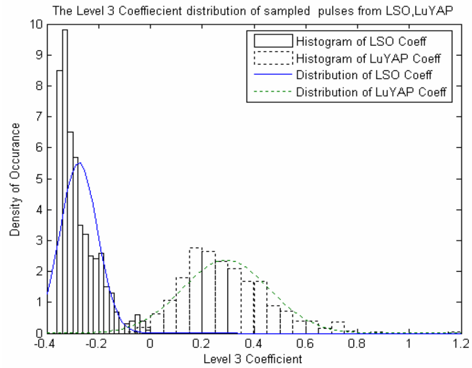

Fig.10. the Discrete Wavelet Level 3 approximation coefficient distribution of LSO and LuYAP

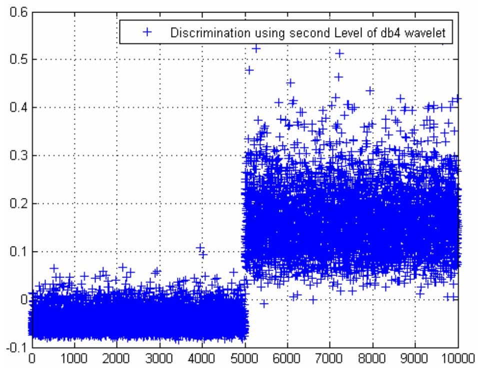

Fig.11 the proposed DWT-based PSD technique applied to 5K pulses of each LSO and LuYAP pulses, respectively

Fig. 11 shows the fraction of correct identifications for a range of tested samples. The best result for distinguishing the LSO from the LuYAP pulses is for reliability of 97.18% using the coefficient number nine of the second level of decomposition. For LuYAP 99.98% correct identifications were reached.

IV. FPGA RELAIZATION

As a prototyping platform, the *UniDAq* board with Xilinx XCV800 Virtex device is utilized for the DWT and FFT implementations. Table 1 shows the synthesis result of the DWT and FFT [10] module.

Table 1 Device Utilization Summary of XCV800-based implementation of DWT and FFT block

	DWT	FFT
Slices	100	135
Max. Frequency (MHz)	200	180

The DWT-based algorithm is realized on XCV800, in which a clock speed of 200 MHz is reached. The DWT consumes 100 of slices. The FFT clock speed is 180 MHz and consumes 135 of slices.

V. DISCUSSION AND CONCLUSION

The layer identification in a phoswich detector of two different short decay time scintillators can be simplified when one scintillator has an additional slow decay time component. The slow component can be easily detected and may also reduce the necessary hardware requirements compared to a system distinguishing two fast decay times. In the case of FFT and DWT based system a bandwidth of 3.6 MHz was sufficient, whereas discriminating the scintillators require sampling rate 40 MHz only.

Two different algorithms DWT and FFT based PSD for pulse distinguishing were tested and compared. The FFT-based PSD uses parallel 16-point serial-bit input and needs complex multiplications. On the other hand, DWT -based PSD algorithm uses 16-point pipelined and consumes less area and real multiplications. The FFT algorithm results for distinguishing the LSO from the LuYAP pulses is a reliability of 99.3% which is better performance than DWT result. DWT reliability is of 97.18% but avoids difficulty of FFT computation Difficulty. From a hardware point of view, the DWT performance is faster and saving chip area.

It should be noted that in this study only a limited number of crystals was tested. Whether the excellent result of only 1%–3% misidentified pulses can be maintained in a real PET system with several thousands of crystals depends very much on the variation of the slow component properties and will be subject of future investigations.

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