Pulse Width Modulation: a Novel Readout Scheme for High Energy Photon Detection

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Abstract—In standard PET scintillation detection, the energy, timing, and location of the incoming photon are recovered using analog signal processing techniques. The energy and location information are processed using an analog-to-digital (ADC) converter that samples an analog value that is proportional to the integral of the charge created by the scintillation event. We propose to change the paradigm and modulate the width (rather than amplitude) of a digital pulse to be proportional to the integral of the charge created. The analog value of the outgoing digital pulses is recovered by using a time-to-digital converter (TDC) in the back-end electronics, without the need for an ADC. Note that in this new scenario the same TDC used to record the time of the event is used to recover the amplitude. The main performance parameter that must be optimized is the dynamic range versus the dead-time of the front-end detector. The goal is an 8-bit dynamic range for this pulse-width modulation (PWM) scheme, which is adequate for high resolution PET systems based on semiconductor detectors such as avalanche photodiodes (APD) or cadmium zinc telluride (CZT). A novel circuit has been designed, fabricated, and tested for the proposed PWM readout scheme. This circuit is different than previously developed time over threshold pulse width modulation circuits used in high energy physics. PWM techniques simplify the routing to the back end electronics without degrading the performance of the system. A readout architecture based on PWM processes digital rather than analog pulses, which can be easily multiplexed, enabling one to achieve very high channel density required for ultra-high resolution, 3-D positioning PET detector systems.

INDEX TERMS—PET, Semiconductor detectors, PWM, Pulse width modulation, Time over threshold, Wilkinson ADC

I. INTRODUCTION

In standard high energy photon (e.g., gamma ray or annihilation photon) detectors, information from individual interactions are recorded, such as the time of the event, the energy of the event, and the location of the event. These parameters are determined through certain processing algorithms applied to the analog signals that the detector generates. In evaluating the best architecture to implement very high channel count PET data acquisition systems, pulse width modulation (PWM) has significant advantages over previous generations of readout architectures (see Fig. 1). PWM architectures eliminate ADCs and dense analog buses. We are studying a PWM scheme (see Fig. 2) that encodes the time, energy, and location of each high energy photon interaction in a detector using the
different arrival times of various edges of a digital signal, rather than in the amplitude of an analog signal. This PWM scheme marries the fast CFD timing needed for PET and the time counter principles behind the Wilkinson ADC conversion technique for encoding amplitude. Because it is relatively simple to implement a very high degree of multiplexing using digital pulses, the proposed PWM readout architecture can potentially readout more channels than a high density analog readout architecture without using ADCs. With the advent of very high channel count FPGAs synthesized into very high performance TDCs [3], [4], the digital back-end readout of PWM architectures, even with thousands of readout channels, can be easily realized using off the shelf components and simple high density digital buses.

A. Time over Threshold

PWM circuits utilizing time-over-threshold (TOT) were some of the first methods to digitize amplitude information of nuclear decay and drift chambers [5], [6]. By setting a threshold voltage above zero, an amplitude dependent pulse width can be generated from a Gaussian, or other CR-RC type shaped pulse. The noise of time-over-threshold depends on the shaping circuits used and strongly depends on the inherent non-linearity of the width versus amplitude dependence. Since the decay of a Gaussian-shaped pulse falls off exponentially with the time$^2$, it does not provide the good delay linearity needed for a robust PWM scheme. The data acquisition architectures of TOT are used in very high channel count physics experiments using silicon vertex trackers and calorimeters [8], [9], [10]. New high resolution PET systems have similar high channel count needs as these high energy physics experiments. Recently, two groups have developed TOT ASICs for PET applications [11], [12], but their choice of pulse shaping leads to deficiencies, as explained in the next section.

II. PULSE WIDTH MODULATION CIRCUIT

In this work, we tried to improve two aspects of these previous implementations of TOT for PET (see Fig. 2). In the first modification, a CFD encodes the arrival time and reduces time walk. Secondly, a peak detector captures the maximum signal from a Gaussian shaped signal and generates a ramp function that linearly decays to zero. By splitting the signal into two paths, the SNR of coincidence timing can be optimized at the same time as the SNR of the energy signal. One of the TOT ASICs developed in the past [11] either uses little or no shaping to attain the best timing performance, but this severely degraded the SNR of the energy channel. The second TOT ASIC [12] uses Gaussian shaping with good SNR for energy performance, but this slow shaping significantly degraded timing performance.

A. Pulse width modulation and CFD timing

In standard PET data acquisition, timing is performed by a constant fraction discriminator (CFD) to reduce the amplitude dependent time walk. In the proposed PWM circuit design, the scintillation pulse is driven into a CFD that sets a latch started at the rising edge. The scintillation signal may have some small amount of fast shaping to optimize the timing resolution. In terms of time pickoff, the proposed design is identical to and will have the same performance as standard PET electronics. Thus, this paper will only focus on studying the proposed PWM scheme energy resolution performance.

B. Peak detection and linear ramp

The pulse width modulation circuit can be seen as an ADC operating on the energy portion of the scintillation pulse. The scintillation signal is first shaped by a Gaussian shaper set with a time constant to maximize SNR. Because the Gaussian shaper is a linear transform of the scintillation signal, the time between the start of the pulse and the peak...
Fig. 4: An input scintillation signal (black) enters a peak-detector with a linear ramp discharge (green). The blue dotted line represents the maximum of the signal and is proportional to maximum value of a Gaussian shaped signal. The red dotted line represents the threshold for firing the trigger.

Associated electronics to fire a sample-and-hold precisely at the peak of the signal. The peak detector has a capacitor to store the value. With a simple resistor, an approximately linear discharge current can be generated that decays based on a RC product. The peak detector will begin to decay as soon as the output of the Gaussian shaper falls below the value of the storage capacitor. On the other hand, a sample-and-hold circuit would not have this limitation and could begin decaying immediately after sampling the value. Therefore, for an ASIC implementation, a sample-and-hold circuit would be preferred over a peak detector because the ramp could decay faster than the falling edge of the Gaussian shaper, which would improve count rate performance.

C. High speed comparator

The output of the PWM with a linear ramp discharge is fed into a high speed comparator with an adjustable threshold. The output of the comparator fires the reset of the latch. The final digital signal has the rising edge encoding the arrival time of the scintillation pulse and the falling edge encoding the width of the pulse. Other information can be tacked onto the end of the pulse such as channel id [12], but these can come with a large penalty to the maximum count rate.

III. Noise Analysis

The PWM circuit can be analyzed to understand its impact on energy resolution for a scintillation detector. Other figures of merit, including spatial resolution, can be easily derived from this framework. First, the variance of the PWM in time must be derived:

$$\sigma_{PWM}^2 = \sigma_{CFD}^2 + 2\sigma_{COMP}^2 + 2\sigma_{TDC}^2 + \sigma_{CAP}^2 + \sigma_{Vc}^2 + \sigma_{Vt}^2 \frac{\partial V}{\partial t}$$ (1)
The slope of the discharge is related to the value of the resistor R1 and capacitor C1 (see Fig. 3), and the negative supply voltage. The discharge is made more linear by connecting the terminal of the resistor to VEE. The slope is:
\[
\frac{\partial V}{\partial t} = \frac{V_i - VEE}{RC} \\
\approx \frac{VEE}{RC} \quad \text{because } V_i \ll VEE
\]  
(2)

The variance of the PWM can be converted into energy resolution by optimizing the voltage headroom of the circuits \(\sigma_{PWM}^2 = \frac{V_{EE}^2}{RC} \) (max\(\left\langle V_i \right\rangle \approx \frac{VEE}{2}\), and \(\sigma_{PWM}^2 \approx \) because it accommodates the 511keV photopeak pulse height).

\[
\frac{\sigma_{PWM}^2}{\max\left\langle V_i \right\rangle} = \frac{1}{2} \sqrt{\frac{\sigma_{CFD}^2 + \sigma_{COMP}^2 + 2\sigma_{TDC}^2}{\sigma_{PWM}^2 + \sigma_{VCAP}^2 + \sigma_{V_i}^2}}
\]  
(3)

There is a clear tradeoff in choosing the \(RC\) constant. The longer the \(RC\) constant, the better the energy resolution (ie better SNR), but this will come with a penalty in dead-time. The dead-time of this PWM is different from ADC based converters. The dead-time of this PWM circuit is the same as that for a Wilkinson ADC, because the time to convert the amplitude is linearly related to the amplitude. For Wilkinson ADC or PWM circuits [14], the non-Poisson nature of the dead-time has been derived. The noise voltage terms of equation (3) should be made small relative to the input amplitude \(V_i\). The noise \(V_{cap}\) is simply the \(\frac{kT}{C}\) noise of the storage capacitor. Usually, the noise of the front end detector is much larger than the noise of these simple elements.

IV. MATERIALS AND METHODS

A discrete PWM test board (Figure 5) was fabricated and evaluated for energy resolution performance versus a standard peak-sampled ADC (see Fig 5). The PWM circuit comprises a peak-detector with a linear ramp discharge (see Fig. 3) and a high speed LT1171 comparator. The R was set at 10k and the C at 100pF giving a slope of 50 \(\frac{V}{\mu s}\). Linearity of the test board was tested by driving a pulser signal into the input preamplifier and measuring the output voltage after TAC. For our tests the TAC followed by an ADC will mimic the TDC that is intended to be used in this PWM scheme (see Figure 2). After pulser linearity tests, a 10 \(\mu Ci\) \(^{22}\)Na source irradiated a 3 mm x 3 mm x 20 mm LYSO crystal connected to a single 3 mm x 3 mm solid state photomultiplier (SSPM) pixel of the SENSL 4x4 SPMArray 3035G16. The test board contained a fast trans-impedance amplifier (500 Ohms) to amplify and invert the input signal for the input to an Ortec CFD-935. A CFD is key to the fast timing for the proposed PWM scheme (see Fig. 2). The output of the CFD was the start for the Ortec 567 TAC/SAC. For the energy channel, the signal was shaped by a Cremat-200 100ns Gaussian shaping amplifier. The shaped signal was input to both the discrete PWM circuit and to a Ortec 427A delay amplifier. The latter channel enables comparison to the standard analog modulated processing chain. After level shifting to negative NIM voltage standard, the PWM signal was sent to the stop of the Ortec 567 TAC/SAC. The output of the delay amplifier and the TAC went to a NI-1110 peak-sampling ADC. The Ortec 567 TAC/SAC is being used to convert the pulse width back into an amplitude for digitization to mimic the function of the TDC and generate the PWM equivalent of a pulse height spectrum. The \(^{22}\)Na energy spectrum was acquired for both the standard analog-modulation, peak-sensing ADC chain and the PWM processing chain.

V. RESULTS

The linearity of the PWM circuit (see Fig. 6) fits very closely to a second order polynomial over the dynamic range of the PWM. This second order behavior is solely determined by the discharge of the capacitor in the peak-detector using

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<th>TABLE I: Definitions</th>
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<tr>
<td>(\partial V/\partial t)</td>
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<tr>
<td>(\sigma^2_V)</td>
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<tr>
<td>(\sigma^2_{V_i})</td>
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<td>(\sigma^2_{VCAP})</td>
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<td>(\sigma^2_{CFD})</td>
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<td>(\sigma^2_{COMP})</td>
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<td>(\sigma^2_{PWM})</td>
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<td>(\sigma^2_{TDC})</td>
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<td>max(\left\langle V_i \right\rangle)</td>
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<td>VEE</td>
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<td>RC</td>
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VI. DISCUSSION

The circuit evaluated in this paper is a very simple discrete prototype that was used as a proof of concept. There are many better, but more complicated, linear ramp circuits that could easily be implemented in ASICs or more discrete components could have been used to achieve much better linearity. The peak-detector with resistive discharge could easily be replaced by a sample-and-hold with current source discharge architecture in an ASIC design. This would remove the non-linearity for small signals that the peak-detection method may suffer from with small RC constants used to improve dead-time performance. However, we do not expect this small low-amplitude non-linearity to be a significant detriment to the method.

VII. CONCLUSION

A proof of concept, discrete pulse width modulation circuit for PET has been analyzed and built. This PWM circuit provided a simple method to study the trade off of dynamic range and linearity versus dead-time by adjusting the slope of a ramp reset circuit. We achieved a dynamic range, linearity and SNR with a very simple circuit that can meet performance parameters needed in PET data acquisition designs. The proposed scheme preserves the low jitter of CFD based triggering while deriving a pulse width from an optimally shaped signal achieving a high SNR energy signal.
The energy resolution of the two conversion schemes is correlated very well with the analog-modulated scheme (b).

Fig. 8: (a) The PWM energy $^{22}$Na energy spectra results correlated very well with the analog-modulated scheme (b). The energy resolution of the two conversions schemes is identical at $19.3\pm0.4\%$ FWHM at 511 keV. There is some non-linearity for small amplitude signals from the PWM circuit that can be seen in (a) and (b).