Impact of Analog IC Impairments in SiPM Interface Electronics

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***Abstract*– The recent realization of Silicon Photomultiplier (SiPM) devices as solid-state detectors for Positron Emission Tomography holds the promise of improving image resolution, integrating a significant portion of the interface electronics, and potentially lowering the power consumption. Our lab has previously reported on novel board-level readout electronics for an 8x8 silicon photomultiplier (SiPM) array featuring row/column summation technique to reduce the hardware requirements for signal processing and is currently working on taking the next step by implementing a monolithic CMOS chip which is based on the row-column architecture. To date, relatively little modeling has been done to understand the impact of analog non-idealities associated with the front-end electronics, on SiPM-based PET systems. This paper focuses on various analog impairments associated with PET scanner readout electronics. Matlab was used as a simulation platform to model the noise, linearity and signal bandwidth of the frontend electronics with the measured SiPM pulses as the input.**

I. Introduction

THE recent realization of Silicon Photomultiplier (SiPM) devices as solid-state detectors for Positron Emission Tomography holds the promise of improving image resolution, integrating a significant portion of the interface electronics, and potentially lowering the power consumption. High quantum efficiency, high gain, operation at low bias voltages, insensitivity to magnetic fields, excellent timing resolution, robustness and compactness are some of the advantages offered by the solid-state solution in comparison to the traditional vacuum photomultiplier tubes (PMT) used for low-level light detection applications. In addition, this technology facilitates the interconnection between the detector and the read-out electronics.

With respect to the readout circuits for SiPM detectors in PET applications, a majority of the circuit solutions have been derived from the previous discrete or integrated implementations developed for PMTs [1-3]. Recently, there has been work on ASIC's dedicated for SiPM detectors in PET applications [4-6]. At the University of Washington, the Radiology Department working in conjunction with the Department of Electrical Engineering, has been exploring novel analog and mixed-signal electronic systems to simplify and reduce the required channels between the individual elements in the SiPM array and the backend digital electronics. Our lab has previously reported on novel board-level readout electronics for an 8x8 (SiPM) array featuring a row/column summation technique to reduce the hardware requirements for signal processing [7]. The goal now is to implement a monolithic chip for readout ASIC replacing the discrete board-level solution [8]. To date, relatively little modeling has been done to understand the impact of analog non-idealities on SiPM-based PET systems. This paper explores the impact of analog performance on the mixed-signal interface between SiPM devices and the digital electronics. The objective is to provide sufficient understanding of the effect of analog non-idealities on PET imaging systems, to be used as a part of a design methodology for the interface electronics. As a test bench to evaluate the relationship between analog performance and the overall image quality, this paper explores and models additive Gaussian noise, linearity with respect to harmonic and intermodulation distortion, and channel bandwidth. The interface between an 8x8 Silicon Photomultiplier (SiPM) array and our Phase II MiCES FPGA boards [9] is used as a test bench to understand the impact of analog circuit performance on the achievable energy resolution using the commonly accepted metric of Full Width at Half Maximum (FWHM).

This paper will first discuss the experimental setup for collecting the sample pulses from a photo detector. This is followed by a description of our Matlab simulation platform used to model the analog impairments. The next section describes each of the non-ideal blocks used in this study – non linearity, noise and channel bandwidth, followed by simulation results.

II. Methods And Materials

A. Experimental Setup

As a starting point, our Matlab model of analog impairments uses a set of measured SiPM pulses. 2000 SiPM pulses were taken from a Zecotek Photonics MAPD-3N1 using a 511 keV Ge-68 radiation source is an input..

B. Matlab Simulation Model

The Matlab simulation model for the front end electronics is illustrated in figure 1. The blocks inside the dashed lines are used to emulate various analog impairments associated with

Manuscript received November 15, 2011. This work was supported in part by NIH NIBIB EB001563, NIH NIBIB EB002117, NIH NCI CA136569, DOE DE-FG02-05ER15709, and Zecotek Photonics.

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the interface electronics including non-linearity, circuit noise and channel bandwidth.

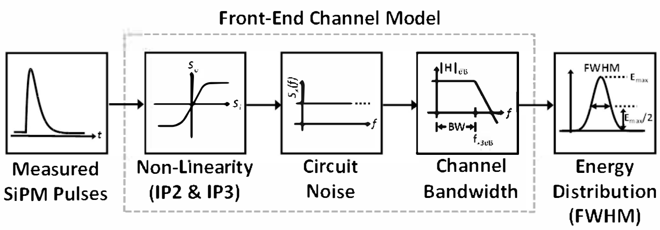

Fig. 1. Matlab Simulation Model

The analog impairments modeled here are associated with different performance parameters for an analog circuit. While analog circuits can be approximated by a linear model for small-signal operation, nonlinearities often lead to spectral regrowth and distortion in the time domain, that are not predicted by a linear small-signal model. Electronic noise from thermal, flicker and shot noise often limit the lower end of the dynamic range, thus limiting the minimum detectable signal. Channel bandwidth plays a critical role in determining the high-frequency behavior of the interface electronics as often times the sharp rising and falling edge of a SiPM pulse contains high-frequency information useful for timing and energy resolution. Each of the aforementioned non-idealities will now be described in more detailed with a discussion of the simulation results.

III. ANALOG NON-IDEALITIES

A. Linearity

The nonlinear behavior of a circuit can be viewed as variation of the small-signal gain with the input level. To model the nonlinearities of the channel, the circuit was assumed to be broad banded relative to the desired signal bandwidth. Stated differently, only resistive affects were considered and the circuit is assumed to be memory less. This allows an approximation of the circuit nonlinearities in the channel using a Taylor Series expansion [10] as follows,

$$\boldsymbol{y(t) = a_1 x(t) + a_2 x^2(t) + a_3 x^3(t) \ldots} \qquad (1)$$

For small $x, y(t) \approx a_1 x$, indicating that α_1 is the small-signal gain in the vicinity of x □ 0. The gain of the higher order terms can be related to common metrics of analog linearity performance in terms of the Input 2nd and 3rd order Intermodulation Intercept Point (IP2 and IP3) with the below expressions.

$$\boldsymbol{a_2 = \frac{a_1}{IIP2} \qquad a_3 = \frac{4a_1}{3IIP3}} \qquad (2)$$

The measured SiPM pulses were then applied to a Matlab model where the amplifier input referred linearity was defined using the above two expressions. The output of the amplifier blocks was then collected and energy resolution plots were constructed to help determine the FWHM as a function of linearity. The process was repeated with the IP2 and IP3 values swept from -30dBV to 0dBV.

Fig. 2 shows plots of FWHM as a function of the amplifier IP2 and IP3, respectively. IP3 is seen to have negligible impact on the FWHM of the pulses. In large part, this is intuitively pleasing as the effect of circuit nonlinearities is to generate new spectrum, this is commonly referred to as spectral regrowth in power amplifier used in communication applications. Although nonlinearities will create new spectrum, the total energy associated with the analog signal is preserved, thus having minimal impact on the FWHM performance of the analog portion of the SiPM channel. This suggests that digitization of signals early in the interface chain is possible in future architectures. However, 2nd order nonlinearities are seen to have an impact on the FWHM. This effect is still under evaluation but believed to be from DC components generated by the 2nd order.

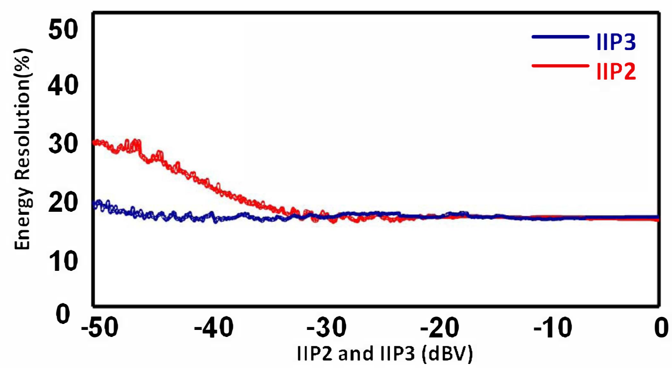

Fig. 2. Energy Resolution vs Input Intercept Point

B. Noise

Assuming CMOS technologies are used to realize the SiPM interface electronics, there are a number of noise processes which may interfere with a detection pulse including thermal channel noise and flicker noise. Electronic noise corrupts the signal level, thus changing the energy associated with the signal. Another challenge associated with the row-column summation approach used in [8] is the potential accumulation of dark noise produced by each of the detectors connected on a row, column, or diagonal line, in addition to the thermal noise generated by the associated interference electronics. For the purposes of these simulations, additive white Gaussian noise was assumed to be dominant. Scaling the noise floor in Matlab relative to the pulse amplitude was accomplished by estimating the signal power through simulation, then using the Signal-to-Noise Ratio (SNR) as a means to determine the variance of a noise source.

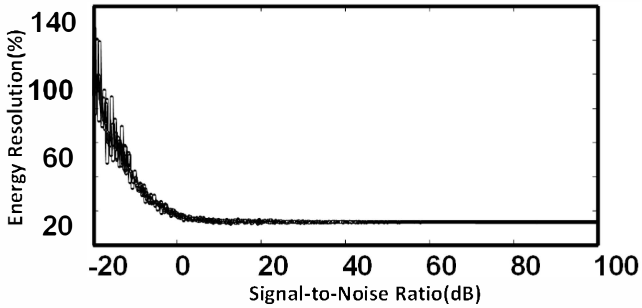

Fig. 3. Energy Resolution vs Signal-to-Noise Ratio

Fig. 3 shows the energy resolution as a function of the SNR (dB) scaled relative to the magnitude of the SiPM pulses. The energy resolution begins to degrade for SNRs < 5dB suggesting a relatively modest noise performance required of the front-end electronics.

C. Channel Bandwidth

Although achieving constant open-loop amplifier gain up to several GHzs is possible using modern silicon processes, realizing similar bandwidths using closed-loop amplifiers becomes challenging above several hundred MHzs. Moreover, understanding the required signal bandwidth becomes crucial from the perspective of optimizing overall power consumption of the front-end interface channel.

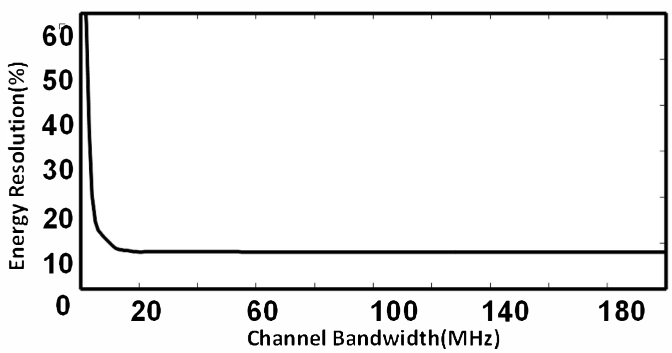

Fig. 4. Energy Resolution vs Channel Bandwidth

The rise time of the SiPM pulses can be as fast as 20 ns. To understand the impact on energy resolution versus channel bandwidth a 10^{th} order Butterworth filter was used in the Matlab simulation test bench. The channel bandwidth was swept and the impact on the energy resolution was recorded, Fig 4 shows that there is degradation in the energy resolution for cutoff frequency below 20 MHz. Although the bandwidth is relaxed for detecting the energy resolution, higher bandwidths are required to detect the timing information for the proposed ASIC architecture [5]. This is because the anodes of all the SiPM devices in the array are shorted to a common node. This common anode signal is used to derive the time of arrival information for each SiPM pulse. However, it is worth mentioning that only one common timing channel is required for the entire array.

IV. CONCLUSION

This work presents a study of the impact of analog non-idealities on interface circuits used at the front-end of PET imaging systems. The main characteristics of the waveform of the SiPM pulses have been conveniently related to common figures of merit for analog circuits. . The nonlinear behavior of the front-end electronics was evaluated in terms of the IP2 and IP3. 3^{rd} order non linearity is seen to have negligible impact suggesting the development of future architectures with digitization of signals early in the interface chain, but 2^{nd} order non linearity degrades the energy resolution, an effect that is still being evaluated. White Gaussian noise was added to a set of SiPM pulses and used to model the effect of electronic noise in the channel. The energy resolution degrades, as expected, when the Signal-to-Noise (SNR) decreases. Channel bandwidth of the front end electronics was modeled using a low pass filter where degradation in the energy resolution for cutoff frequency less than 20 MHz was found. The intent of this work was to develop MATLAB models which can be used to evaluate the system-level performance as a function of common analog building blocks. Some of these results can be used to aid designers to understand the relationship between analog design and PET system level performance.

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