Pulse Shaping Amplifier (PSA) For Nuclear Spectroscopy System

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ABSTRACT

Pulse Shaping Amplifier (PSA) is an essential component in nuclear spectroscopy system. This network has two functions; to shape the output pulse and performs noise filtering. In this paper, we describe procedure for design and development of a pulse shaping amplifier which can be used for nuclear spectroscopy system. This prototype was developed using high performance electronics devices and assembled on a FR4 type printed circuit board. Performance of this prototype was tested by comparing it with an equivalent commercial spectroscopy amplifier (Model SILENA 7611). The test results show that the performance of this prototype is comparable to the commercial spectroscopic amplifier.

ABSTRAK

Amplifier pembentuk denyut merupakan satu komponen penting dalam sistem spektroskopi nuklear. Rangkaian ini mempunyai dua fungsi; untuk membentuk isyarat denyut keluaran dan menuras hingar elektronik. Dalam kertas kerja ini, kami akan menerangkan prosedur reka bentuk dan pembangunan sebuah prototaip amplifier pembentuk denyut yang boleh digunakan untuk sistem spektroskopi nuklear. Prototaip ini telah dibangunkan dengan menggunakan peranti elektronik berprestasi dan dipasang pada papan litar tercetak jenis FR4. Prestasi prototaip ini telah diuji dengan membandingkan ia dengan spektroskopi amplifier komersil (*Model: Silena 7611*). *Keputusan ujian menunjukkan bahawa prestasi prototaip ini adalah setanding dengan spektroskopi amplifier komersil.*

Keywords: Pulse shaping amplifier (PSA), nuclear spectroscopy system.

I. INTRODUCTION

Pulse Shaping Amplifier (PSA) is an essential component in nuclear spectroscopy system. There are two types of PSA often used in nuclear spectroscopy; analog and digital PSA. Although the use of a digital PSA in commercial spectroscopy system is increasing but analog PSA is still relevant especially for a custom experiment or application. Theories regarding topologies and various types of PSA commonly used in nuclear spectroscopy have been discussed extensively in previous reports[1-3], unfortunately number of studies which specifically on design of an analog PSA is very limited. Furthermore, technical details of a commercial PSA are control by the manufacturer. This paper will not present any new findings in this field, but rather intended as a tool for knowledge sharing.

The remainder of this work is organized as follows. In Section II, the design and development procedure is discussed. In Section III, we report and discuss test results obtained from the newly developed PSA in comparison with a commercial spectroscopy amplifier. Finally, in Section IV, we present our conclusions.

II. METHODS

A pulse shaping amplifier called PSAMCA was developed as part of the FPGA-based digital MCA upgrading project. It was designed specifically to meet the requirement of the components /modules that will be used to complete the project i.e. the ADC chip and radiation detectors. Design procedure for the development of this PSAMCA is summarized in figure 1 and the design specification is shown in Table 1. Analog pulse shaping amplifier for nuclear spectroscopy system can be design either in time domain or frequency domain. In this works, we design the circuit in frequency domain because the required parameters can be obtained solely through mathematical method.

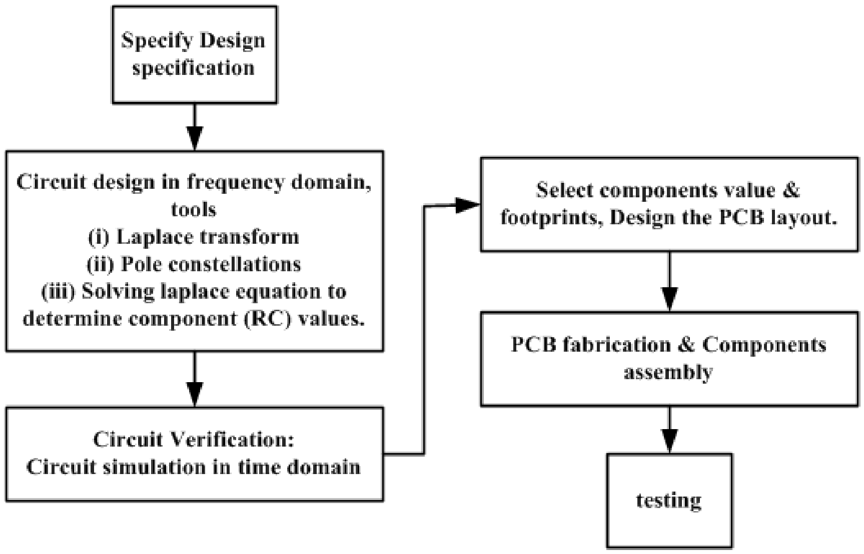

Figure 1: Flowchart describing the design procedure for development of the PSAMCA**.**

Table 1: Design specification of the PSAMCA**.**

Parameters	**Specification**
Input signal	Positive unipolar tail pulse, Range: 20-300 mV
Pole-Zero Circuit	Mandatory: Compensate long decay time constant of the preamplifier (∼100 μs)
Topology, order & Peaking time	Gaussian Approximated output, 5th order & τ_{CR_diff}=1.5 μs
Output signal & DC offset	Unipolar, Max = 2V, DC offset at minimum (BLR required)

a) Types of networks and theories used for designing the PSAMCA.

The block diagram for the PSAMCA is shown in Figure 2. It comprised of a single 1st order high pass filter (HPF) with pole-zero (PZ) cancellation networks, two 2nd order low pass filter networks in cascade and a baseline restorer (BLR) networks as DC offset controller. Basic circuits used for the construction of this PSAMCA are shown in Figure 3. The first section is based on inverting low pass filter networks whereas the two 2nd order low pass filter is a complex-pole LPF using Sallen-Key networks. The previous three sections is AC coupled, this will allows propagation of DC offset throughout the networks. In addition, sequential unipolar pulses will create additional DC offset. This DC offset will create shift in energy level in spectral distribution. A baseline restorer (BLR) added into the last section of PSAMCA chain to minimize this DC offset effect. The BLR circuit is not shown here but is was based on the BLR circuit proposed by Arnaboldi & Pessina [4].

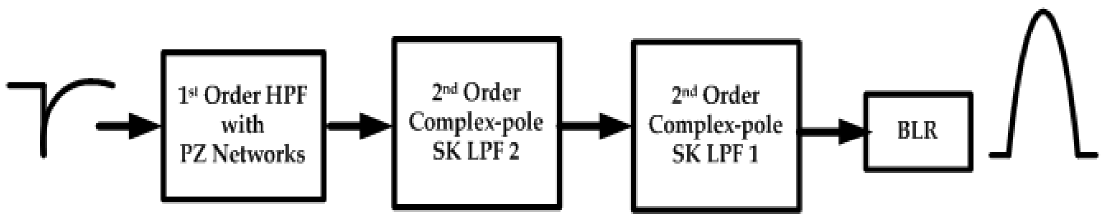

Figure 2: Block diagram of the PSAMCA.

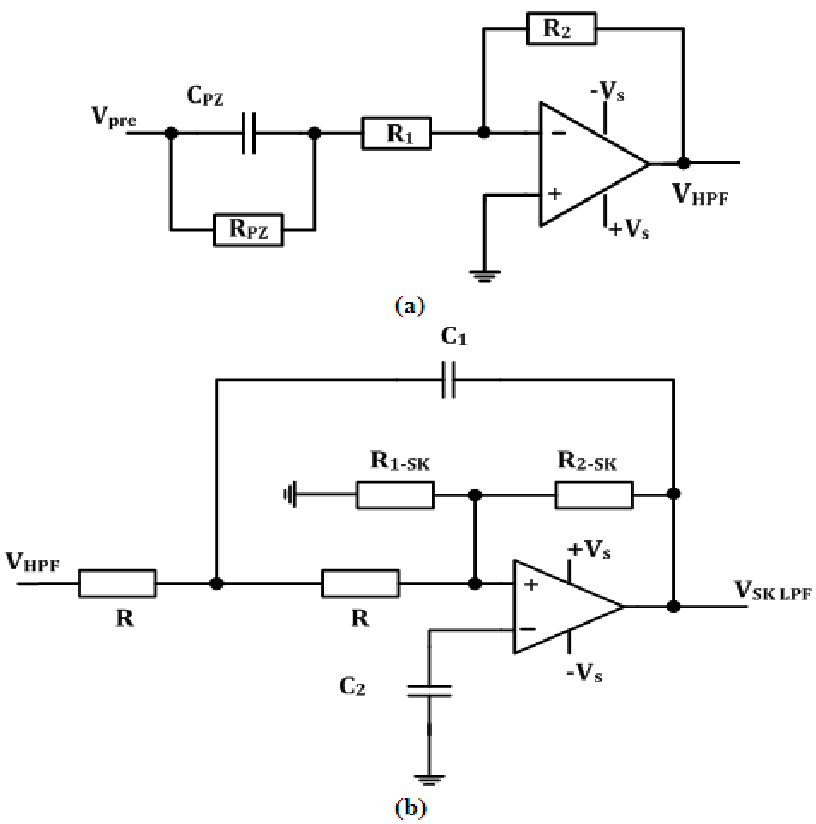

Figure 3: Circuits used for designing the PSAMCA, (a) 1st order high pass filter (HPF) with PZ cancellation networks and (b) 2nd order low pass filter (LPF) using Sallen-Key (SK) topology.

An interesting method proposed by Ohkawa et.al. [5] regarding design for a nearly Gaussian pulse shaping amplifier. They proposed that a Gaussian PSA is composed of an ideal differentiator followed by a network whose impulse response is a Gaussian waveform. The transfer function of this PSA is given by the following expression;

$$H(s) = \frac{A_0 \prod_{i=1}^{n} (A_i^2 + W_i^2)}{(\eta s + A_0) \prod_{i=1}^{n} \{(\eta s + A_i)^2 + W_i^2\}} \qquad (1)$$

Where,

$\eta = 1.0844\tau_{CR-Diff}$ is the normalization factor.

A_0 = Real pole of the ideal differentiator

A_i and W_i = Real and imaginary part of the complex-pole conjugate

$\tau_{CR-Diff}$=time constant of an ideal differentiator

Successful implementation of this method can be found elsewhere in [6, 7]. Poles constellation for 5th order PSA networks according to this method is shown in Table 2.

Table 2: Poles constellation of Gaussian PSA**[5] .**

Section	**Poles**	**n = 5**
HPF with PZ networks	A_0	1.4766878
SK LPF 1	A_1	1.4166647
	W_1	0.5978596
SK LPF 2	A_2	1.2036832
	W_2	1.2994843

Output signal of a charge sensitive preamplifier with resistor feedback reset can be expressed in Laplace transform form as

$$V_{pre}(s) = \frac{{-Q}/{C_f}}{\left(s + {1}/{\tau_{Preamp}}\right)}. \qquad (2)$$

By feeding this output into the input stage of the HPF in Figure 3 (a) and assuming that the preamplifier's pole is being cancelled by HPF Zero i.e. $\tau_{Preamp} = \tau_{HPF-PZ}$, the transfer function for the HPF with PZ cancellation networks become

$$H_{HPF\_PZ}(s) = \mathrm{A_{preamp}}.\,\mathrm{A_{HFP\_PZ}}.\frac{1}{\left(s + \frac{m}{\tau_{HPF\_PZ}}\right)}\ . \qquad (3)$$

The quantities $\mathrm{A_{Preamp}} = {}^{-Q}\!/_{C_f}$ and $\mathrm{A_{HPF\_PZ}} = {}^{R_2}\!/_{R_1}$ are DC gain for the preamplifier and HPF networks, whereas $m = {}^{R_{PZ}}\!/_{R_1} + 1$. From eq. (3), the network has a new time constant equal to;

$$\tau_{new} = \frac{\tau_{HPF-PZ}}{m} \qquad (4)$$

The new time constant in eq. (4) is equivalent to the time constant of an ideal differentiator. Using the relationship between equations (1), (3) and (4) yields;

$$\frac{A_0}{\eta} = \frac{m}{\tau_{HPF\_PZ}}$$

$$m = \frac{A_0 \tau_{HPF\_PZ}}{1.0844\tau_{CR\_diff}} \qquad (5)$$

The 2nd order complex-pole SK LPF shown in Figure 3(b) has a transfer function with a normalized corner frequency ($\omega_c = 1$) of;

$$H_{SK\_LPF}(s) = \frac{A}{1 + [2\tau_2 + (1-A)\tau_1]s + \tau_1\tau_2 s^2}\ . \qquad (6)$$

The DC gain of this network, $\mathrm{A} = 1 + {}^{\mathrm{R_{2\_SK}}}\!/_{\mathrm{R_{1\_SK}}}$ must be kept at low value (< 3) to prevent output pulse oscillation. The two time constants namely, $\tau_1 = \mathrm{RC_1}$ and $\tau_2 = \mathrm{RC_2}$ define the characteristic of this network. Expanding the second part of the right-hand side of eq. (1) yields a transfer function of a 2nd order complex-pole low pass filter given as:

$$H_{LP\_CP}(s) = \frac{A_i^2 + W_i^2}{\eta^2 s^2 + 2\eta A_i s + A_i^2 + W_i^2}. \quad (7)$$

Comparing the denominators of eq. (6) and (7) leads to the following conclusion:

$$\tau_1\tau_2 = \mathrm{R}^2\mathrm{C}_1\mathrm{C}_2 = \frac{\eta^2}{A_i^2 + W_i^2} \quad (8)$$

$$2\tau_2 + (1 - \mathrm{A})\tau_1 = \frac{2\eta A_i}{A_i^2 + W_i^2} \quad (9)$$

Re-arranging eq. (9) and replacing DC gain, $\mathrm{A} = (\mathrm{R}_{2\_SK}/\mathrm{R}_{1\_SK} + 1)$ yields;

$$\frac{\mathrm{R}_{2\_SK}}{\mathrm{R}_{1\_SK}} = \frac{2\mathrm{C}_2}{\mathrm{C}_1} - \frac{2\eta A_1}{\mathrm{RC}_1(A_1^2 + W_1^2)} \quad (10)$$

b) Procedure for designing the PSAMCA

The procedure for designing this PSAMCA can be summarized as follows;-

i. Designs the HPF with PZ networks section by selecting an appropriate C_{PZ} and R_{PZ} values to match the time constant of the preamplifier. Calculates the unknown R_1 using eq. (5) then selects value for R_2. Value for this DC gain resistor must be carefully chosen; higher gain value is not recommended.

ii. Designs the SK LPF 1 section using poles specified in Table 1. It is better to select standard value capacitors then calculates the unknown resistor values. Capacitor's values must be carefully chosen so that the root of the denominator in eq. (6) will be a complex-conjugate. The unknown resistor R and resistors which made the DC gain networks (R_{1_SK}, R_{2_SK}) can be calculated by using eq. (8) and (10) respectively.

iii. Repeat (ii) for designing the SK LPF 2.

iv. Designs the BLR section, details for this networks is found in [4].

v. Designs the printed circuit board (PCB) which suit the PSA circuit.

c) Circuit verification and PSAMCA performance evaluation

We performed a circuit simulation in time domain using circuit simulation software, Multisim 11.0 before proceeding with full circuit assembly on printed circuit board. This is necessary to verify the circuits and also help to optimize the components value. Parameters and list of electronics components/devices for designing the PSAMCA are listed in Table 2.

Table 3: Parameters and list of components/devices for designing the PSAMCA

Section	Parameters	Values	Active Devices
HPF with PZ networks	R_{PZ}, C_{PZ}	120 kΩ, 820 pF	OPA656
	τ_{CR_diff}	1.5 μs @ $\tau_{Preamp} = 100$ μs	
	R_1, R_2	1.8 kΩ, 3,3 kΩ	
SK LPF 1	C_1, C_2	470 pF, 680 pF	
	R	3.3 kΩ	
	R_{1_SK}, R_{2_SK}	330 Ω, 330 Ω	
SK LPF 2	C_1, C_2	330 pF, 560 pF	
	R	2.2 kΩ	
	R_{1_SK}, R_{2_SK}	330 Ω, 430 Ω	

In order to evaluate the performance of this PSAMCA, we performed a various test in comparison with a commercial spectroscopy amplifier (Silena 7611/L). The test includes, measuring charge sensitivity and linearity, electronics noise and spectroscopic performance. The first three tests were carried out using instruments setup depicted in Figure 4. Similar setup is used for testing the spectroscopic performance but a real radioactive source is used to replace the nuclear pulser and the detector is biased with high voltage. List of test instruments and apparatus used during this test is shown in Table 4.

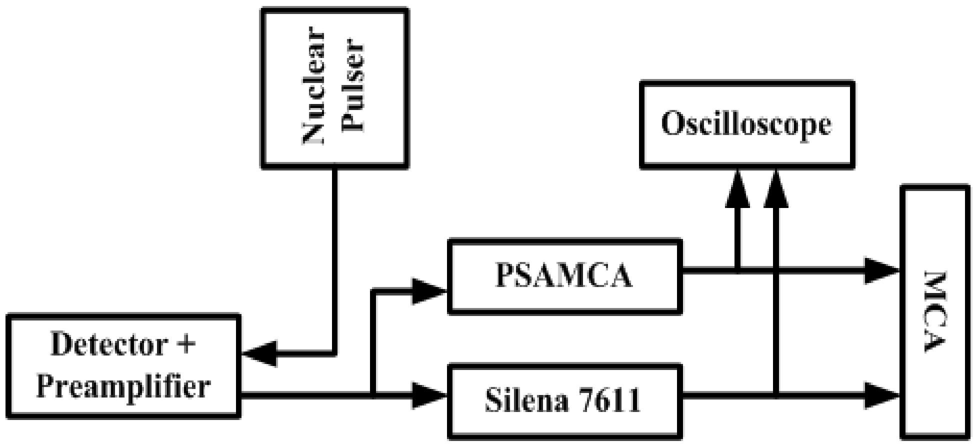

Figure 4: Instruments setup for measuring the PSAMCA performance**.**

Table 4: List of instruments & apparatus used during testing.

Instruments/Apparatus	**Description**
Oscilloscope	LeCroy, Model:Wavejet 334A
MCA	Ortec, Model: ASPEC-927
MCA emulator	Ortec, GammaVision 7
NimBin	Canberra, Model:2000
HVPS	Canberra, Model:3002D
Power Supply	Instek, Model GPC-3030DQ
Nuclear Pulser	BNC, Model: PB-5
Scintillation Detector & Preamplifier	Canberra, Model: 802-2X2, Preamplifier: 2007P
Radioactive Sources	Na-22 & Mn-54

III. RESULT AND DISCUSSION

The finished PSAMCA is shown in Figure 4, it was designed mostly with surfaced mounted component/devices and assembled on a 5 x 3 inch square FR4 PCB. It also equipped with ± 6V power management system to power the active devices. Simulated output and real output of the

PSAMCA is shown in Figure 6 (a) and (b). This figure indicates pulse parameters such as shape, peaking time and width for real PSAMCA output and time domain simulation response is comparable. The real output however has a lower gain due cable termination effect in the nuclear pulser, model 2007P preamplifier and PSAMCA interconnections. Figure 6 (b) also shows comparison between the output of the PSAMCA and a commercial spectroscopy amplifier, model Silena 7611. In this measurement, the shaping time of the Silena 7611 is set at 2 μs and therefore, the pulse width is much wider compared to the PSAMCA pulse. The shaped of the output is however identical.

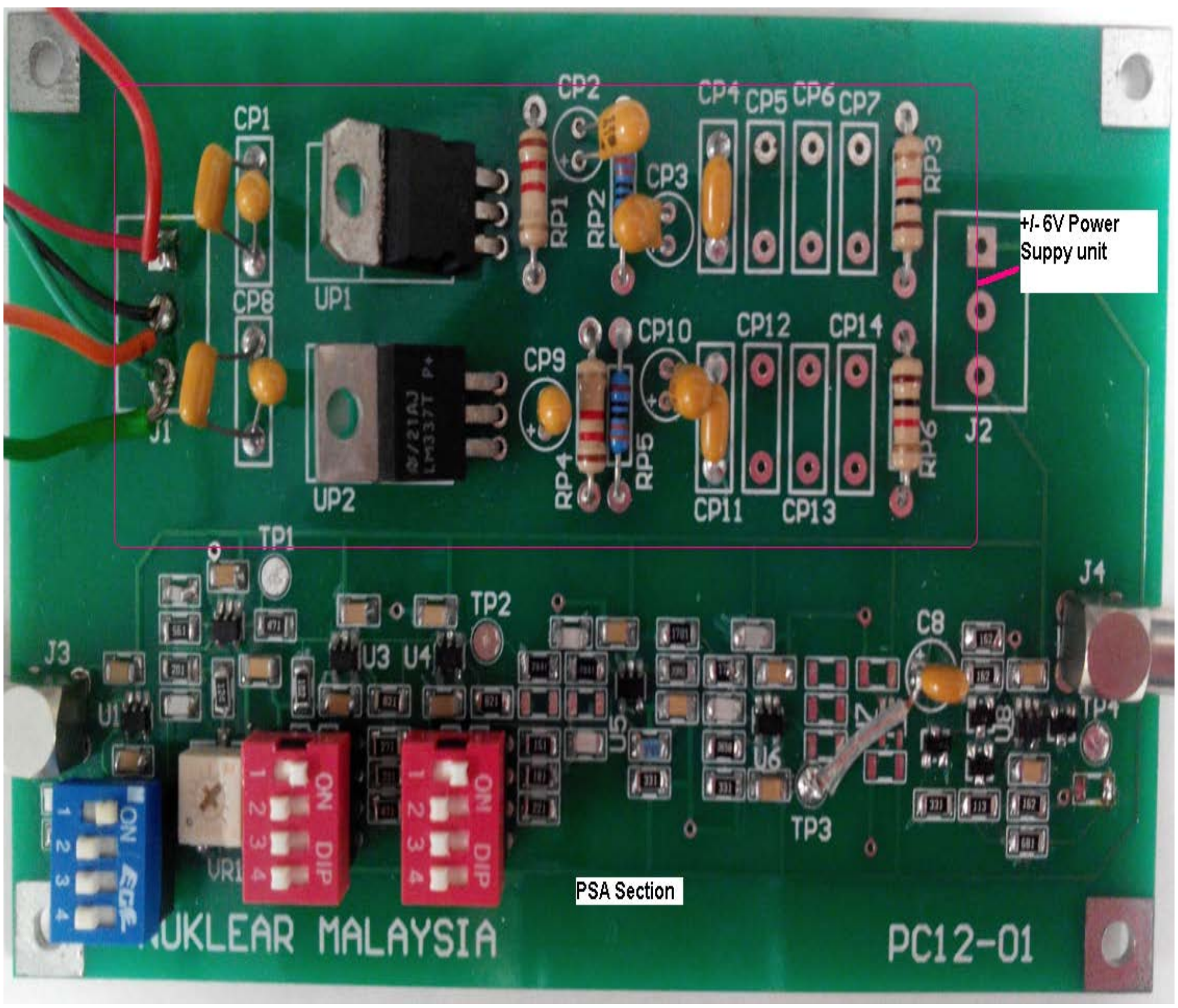

Figure 5: PSAMCA prototype**.**

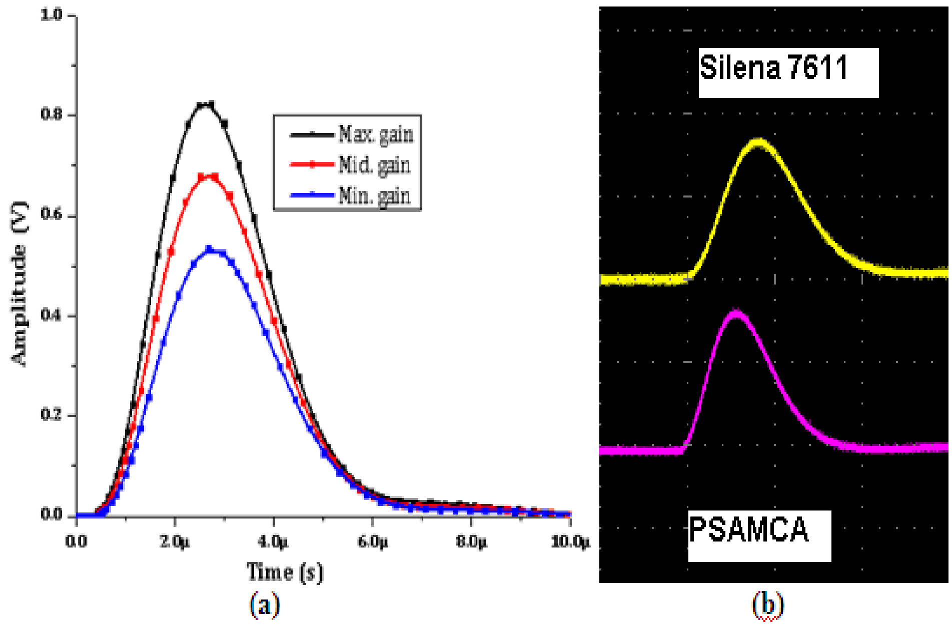

Figure 6: Response of the PSAMCA, (a) time domain simulation for various attainable gain at 50 mV pulser input signal and (b) oscilloscope capture of PSAMCA (pink trace) and commercial spectroscopy amplifier Silena 7611(yellow trace) outputs, both vertical and horizontal axis scale at 200 mV/div and 5 µs/div.

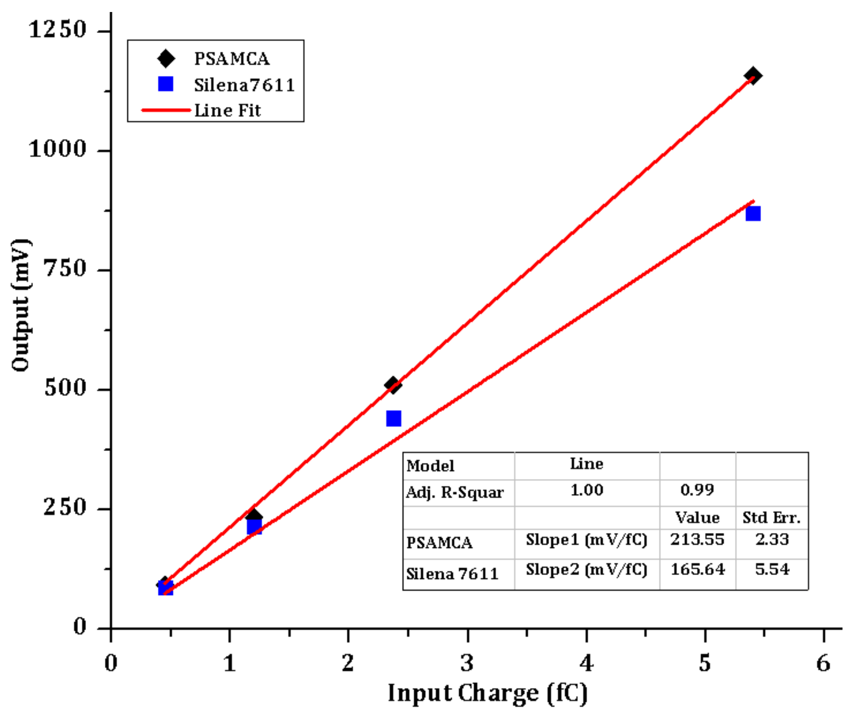

Figure 7: Charge sensitivity plot for both PSAMCA and Silena 7611 spectroscopy amplifier.

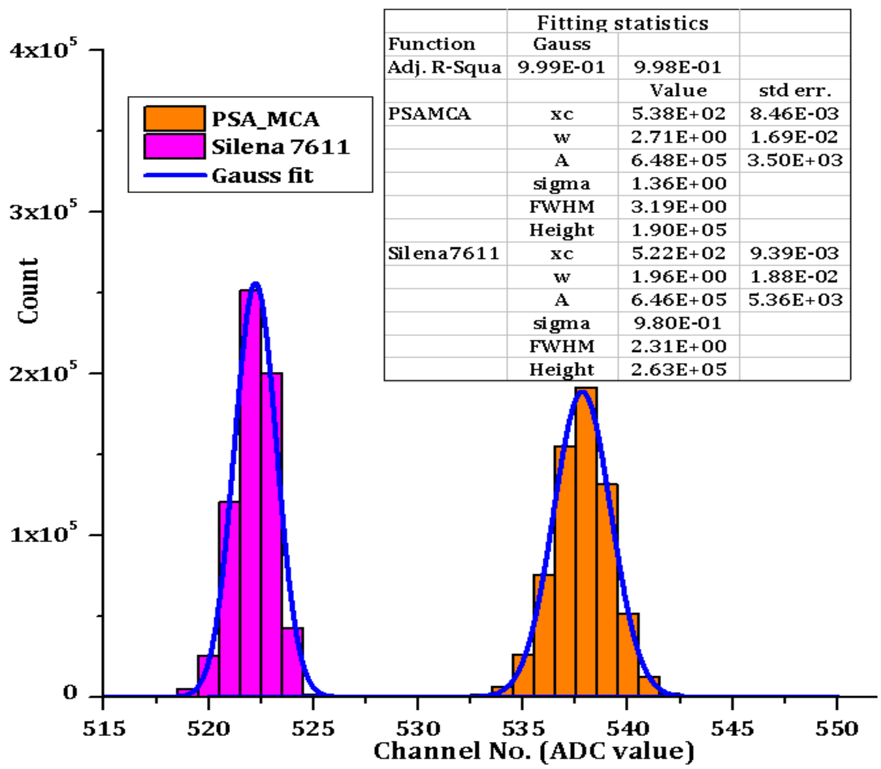

Figure 8: Spectral distribution of 50mV pulser signal obtained with PSAMCA and Silena 7611 spectroscopy amplifier.

As shown in Figure 7, the PSAMCA has much higher charge sensitivity (214 mV/fC) and better linearity than the commercial amplifier. Contribution of electronic noise from the PSAMCA and Silena 7611 Effect to the energy spectral distribution are shown in Figure 8. It is shown from the fitting statistic that the contribution of electronic noise for spectroscopy system connected to the PSAMCA is higher (0.6% @ 538 ADC value) compare to the Silena 7611 (0.4% @ 522 ADC value). This noise however is too small compare to the uncertainty produced by the radiation detector itself and therefore will not contribute significantly in total energy spectroscopy uncertainty. The spectroscopic performance of both PSAMCA and Silena 7611 tested with radioactive sources Na-22 and Mn-54 is shown on energy spectral distribution in Figure 9. These spectra were acquired from Ortec ASPEC-927 dual input Multi Channel Buffer (MCB), PSAMCA is connected into the MCA input 1 and Silena 7611 on input 2. Both MCB has different channel calibration factor because these PSA has a different charge sensitivity. Spectroscopic performance for both PSA is summarized in Table 5. This result however does not prove that the PSAMCA is superior because it has a lower channel-energy conversion factor.

Table 5: Spectroscopic performance of the PSAMCA and Silena 7611 tested with radioactive sources.

Energy Peaks	Resolution (%)	
	PSAMCA	Silena 7611
Na-22 @ 511 keV	8.97	8.85
Na-22 @ 1274.5 keV	5.13	6.03
Mn-54 @ 835 keV	6.21	7.16

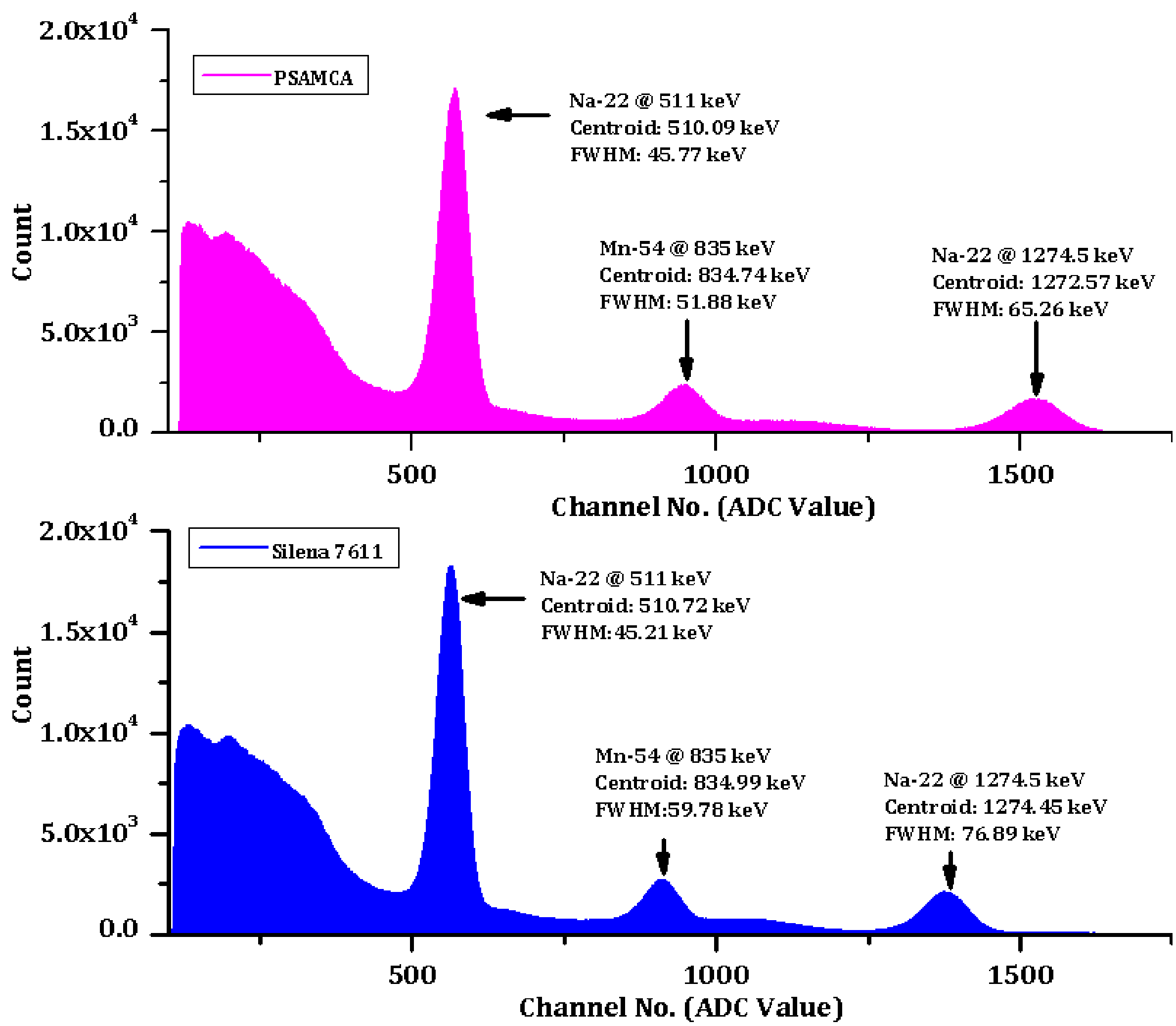

Figure 9: Spectral distribution of Na-22 and Mn-54 obtained with PSAMCA and Silena 7611 spectroscopy amplifier. The peaks information was extracted from a calibrated GammaVision 7 ROI file.

IV. CONCLUSION

We have successfully developed a pulse shaping amplifier called PSAMCA suitable for used for nuclear spectroscopy. Design procedure for designing this pulse shaping amplifier is discussed in details and systematic. Test result shows that the performance of this PSAMCA is comparable with a commercial spectroscopy amplifier.

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