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A PULSE MODE GAMMA RADIATION MONITORING SYSTEM

Abstract: *In this paper a prototype of a pulse mode gamma radiation monitoring system has been presented. The proposed system is PC-based and is intended for the use with a PIN photodiode as a radiation detector. It is designed for real-time monitoring of low level (low dose rate) gamma radiation on the principle of counting the current pulses produced in the radiation detector as a consequence of interaction between the ionizing photons and the sensing material. The system is constructed with commercially available components and supports serial interface for communication with a personal computer. Experimental evaluation of the system performance was conducted by pulsed signal excitation and by radiation excitation with* ^{137}Cs *gamma radiation source. The pulsed signal excitation has been used for estimating the conversion gain and count rate capability, and the experimental results have shown that the conversion gain is preserved up to the count rate of 100k counts/sec. Excitation with radiation source has verified the system's ability to detect low level gamma radiation, but further research is necessary to obtain a more reliable design. During the test, a PIN photodiode PS100-6-CER2 PIN, from First Sensor, with active area of 100* mm^2*, was used as a gamma radiation detector.*

Key words: pulse mode, radiation monitoring, PIN photodiode.

INTRODUCTION

As a result of rapid advancement and expansion of nuclear technology in the past several decades, the risk of accidents induced by ionizing radiation, mainly by the gamma radiation which is particularly hazardous, has increased considerably. Therefore, the detection of low level gamma radiation has become a crucial aspect in the pre-emptive protection of human lives. In that sense, extensive scientific researches are aimed at the development of precise, reliable and cost effective low level gamma radiation monitoring systems.

Detection of low level ionizing radiation is achieved with pulse mode detectors. The pulse mode detectors operate on the principle of counting the interactions between the incident ionizing photons and the sensing material [1]. These interactions are manifested as the current pulses in the sensor, where the pulse count rate is proportional to dose rate, and the pulse amplitude corresponds to the photon energy.

The two major components of a conventional pulse counting radiation monitoring system are the radiation sensor and the processing electronics. The processing electronics provides conversion of radiation induced current pulses into voltage pulses and subsequent pulse processing. However, the design and the performance of the processing system are predominantly influenced by the type of the radiation sensor.

Among a large number of commercially available radiation sensors for pulse mode applications, the PIN photodiodes are particularly attractive because they offer unique advantages over other sensor types. Some of the most important features of the PIN photodiodes which qualify then as excellent pulse mode radiation detectors are: lower bias voltage compared to other pulse mode sensors, moderate cost, real-time read-out, relatively small dimensions, good mechanical stability and high quantum efficiency [2].

Basically, the PIN photodiodes can be utilized for radiation detection either as stand-alone sensors or in the form of optical coupling with a scintillator. The use of photodiode-scintillator coupling provides the benefit of higher sensitivity and efficiency, and this option is the best for spectrometric applications. On the other hand, the PIN photodiodes are suitable as stand-alone detectors in applications where it is required to detect the radiation or measure the absorbed dose.

The study presented in this paper was dedicated to the development of a low cost pulse mode radiation monitoring system. A prototype of the system was developed and tested. It was designed as a PC-based system and a commercial PIN photodiode was used as a radiation detector. The architecture of the developed system and the preliminary experimental results have been outlined in the following chapters.

SYSTEM DESCRIPTION

The proposed pulse counting system was designed as a PC-based real-time radiation monitoring system capable of measuring the pulse count rate and the total number of pulses in a preset time interval. It is made up

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of two main elements; (1) *Pulse processing unit*, and (2) *Pulse counting unit*.

The block diagram and the photograph of the pulse mode radiation monitoring system are illustrated in figures 1 and 2, respectively. The constitutive elements of the system, the pulse processing unit and the pulse counting unit, have been realized as two separate units to enable easier testing. The system is powered from a custom made power supply, and the connections with external elements (power supply and PIN photodiode) are achieved through coaxial cables. For interfacing with a PC, a standard RS-232 cable is used.

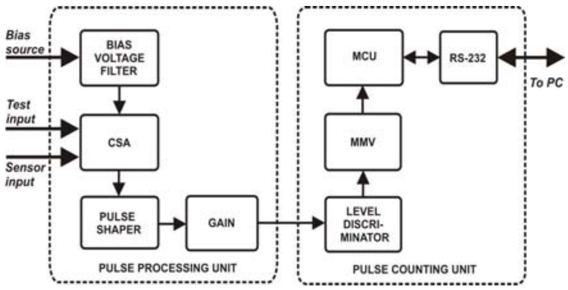

Figure 1. *Block diagram of the pulse mode gamma radiation monitoring system*

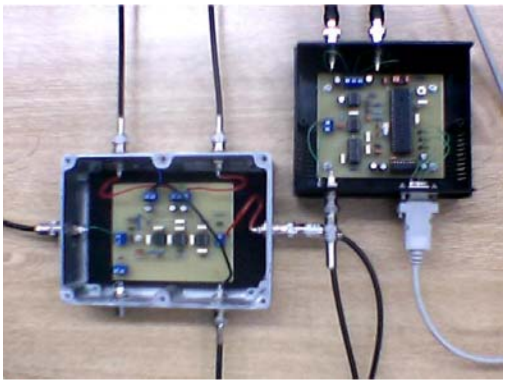

Figure 2. *Photograph of the pulse mode gamma radiation monitoring system (left – pulse processing unit, right – pulse counting unit)*

Pulse Processing Unit

The main function of the pulse processing unit is to convert the current pulses generated in the sensor as a result of radiation exposure into voltage pulses that can be easily discriminated and counted. It is composed of a charge sensitive amplifier (CSA), a pulse shaper, an additional gain stage, and a bias voltage filter.

The CSA performs the conversion of current pulses into voltage pulses. It is a charge integrating amplifier made up of an operational amplifier with a capacitor in the negative feedback and an appropriate logic for capacitor discharging. The gain G of the CSA is inversely proportional to the feedback capacitance C_f ($G = 1/C_f$) [3]. The coupling between the CSA stage and the detector can be either AC or DC, depending on the practical application requirements.

A critical issue in the CSA design is the choice of the operational amplifier. For best performance, a very low noise operational amplifier with low input bias current and low input capacitance is required. Beside that, the charge sensitive amplifier must be designed to sustain high count rate and preserve the conversion gain for a wide range of input charge. In this case, the CSA was constructed with a low noise operational amplifier OPA627, from Burr Brown, featuring 5 pA input bias current, 4.5 nV/Hz$^{1/2}$ noise level and 16 MHz bandwidth. A ceramic capacitor of 1 pF connected in parallel with 100 MΩ metal film resistor intended for discharging the capacitor are implemented in the negative feedback, between the inverting input and the output of the operational amplifier. The CSA stage is AC coupled to the input for interfacing the sensor, with a block capacitor of 1 nF.

Pulses generated by the CSA are inadequate for further processing because they are prone to noise and pile up at high count rates. Therefore, a second stage in the form of a pulse shaper is introduced to transform the slow decay pulses from CSA stage into short pulses that are suitable for further processing [4].

The pulse shaper is actually a band-pass filter that provides the pulse shaping according to the predefined timing requirements and the filtration of input noise to obtain a maximum signal to noise ratio (SNR). The pulse shaping can be accomplished in analog or digital domain. The main analog pulse shaping techniques are CR-RC, Semi-Gaussian (CR-(RC)^n) and delay line pulse shaping, while the triangular and trapezoidal shaping can be achieved by digital processing.

In the proposed solution, the pulse shaping stage is designed as a CR-RC shaper with a shaping time of 1 μs (CR = RC = 1 μs) [5]. A high speed dual operational amplifier LM6172, from National Semiconductor, with a 100 MHz bandwidth, is used as a unity gain buffer between the CR and RC sections.

Since the CR-RC pulse shaper is a passive element, it significantly attenuates the input signal, and therefore an additional gain stage should be implemented at the output of the pulse shaper to compensate for that attenuation. In this case, a voltage inverting amplifier is used to provide further gain. This stage is based on a Burr Brown dual operational amplifier OPA2111.

Most detectors employed for pulse mode radiation sensing require a stable reverse bias voltage. This is especially important for PIN photodiodes which must be reverse biased in order to obtain higher sensitivity. The bias voltage is fed to the sensor through a resistive-capacitive filter to eliminate the noise induced by the bias source. In this case, the filter is implemented in the system, while the bias voltage is provided from an external bias source.

For testing purposes, a separate input connection was implemented. This input is designated for injection of test charge directly at the CSA input through a built-in capacitor of 1 pF. During the normal operation of the system, the test input is not used.

Because low level radiation detection requires low noise amplification, the front-end amplifier stage must be operated in a completely shielded environment. To achieve this, the pulse processing unit was realized on a single printed circuit board and enclosed in a 16 cm × 12 cm × 5 metal case, as shown in figure 2.

Pulse Counting Unit

The pulse counting unit accepts the voltage pulses from the pulse processing unit, determines their rate of occurrence and transfers the information to the personal computer (PC). It consists of a level discriminator, a monostable multivibrator (MMV), a microcontroller (MCU), and a PC interface.

The level discriminator generates a square pulse for each input pulse (from pulse shaper) whose amplitude is above a predetermined threshold level [6]. The basic idea of the level discrimination is to enable detection of pulses which represent only the valuable information, i.e. the pulses that are produced in the photodiode as a result of radiation exposure, and to reject the pulses caused by noise or other undesirable signals. A dual voltage comparator LM393, manufactured by National Semiconductor, is utilized as a level discriminator. Its input is directly interfaced to the output of the pulse processing unit. The threshold level can be adjusted manually, from 100 mV to 2 V, with a potentiometer, enabling the detection of a wide variety of sources.

Since the pulses generated by the comparator have variable width which depends on the width of the input signal (the signal from the pulse shaper), they are not appropriate for processing in the MCU. For this reason, the output from the voltage comparator is fed into a MMV stage, realized with an integrated monostable multivibrator 74HC221, from Philips, which generates a fixed duration (10μs) pulse for each pulse from the comparator. The fixed width pulses from the MMV are delivered to the MCU for further processing.

The count rate of the pulses obtained from MMV is determined by a general purpose 8 bit microcontroller PIC16F887 from Microchip. Two timers integrated in the MCU, timer 0 and timer 1, are employed for this purpose. Timer 1 is configured as a counter, while timer 0 measures the preset counting period (1 sec or 1 min). The firmware implemented in the MCU controls the operation of both timers. After the end of preset counting period, MCU sends the number of pulses counted within that period to the PC.

The communication between the MCU and the PC is realized through a serial RS-232 interface. A level translator MAX232 provides the necessary conversion of voltage levels. The communication is full-duplex with a baud rate of 9600 bit/s.

A Windows PC application software, developed in Visual Studio 2005, is used for monitoring the system operation. This application enables display of the pulse count rate in two formats (counts/sec and counts/min) and the total number of pulses detected in a predefined time interval. All acquired results and the exposure time are stored in appropriate files.

The elements constituting the pulse counting unit are mounted on a printed circuit board and enclosed in a 15 cm × 10 cm × 5 cm plastic box with adequate interface connectors (figure 2).

PERFORMANCE EVALUATION

Evaluation with pulsed signal excitation

The pulsed signal excitation is used for determining the conversion gain and the count rate capability (maximum number of pulses per unit time that can be processed). It is performed by injecting a predefined test charge at the CSA input through a small capacitor (typically several pF).

The experimental setup is illustrated in figure 3. A signal generator model Keithley 3390, from Keithley, was used for charge injection while the output of the pulse processing unit was monitored in real-time on a dual-channel DPO4032 oscilloscope manufactured by Tektronix. The count rate was recorded with a PC.

In general, two types of pulses can be applied for charge injection; (1) the square pulses, and (2) the tail pulses with very fast rise time (< 20 ns) and slow fall time (> 100 μs). The amplitude of the pulse determines the injected charge according to the relation $Q = C \times V$, where Q is the injected charge, C is the test capacitance and V is the amplitude of the applied pulse.

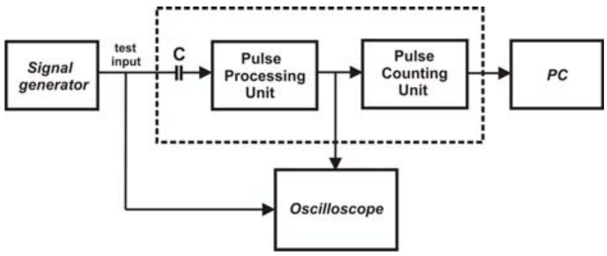

Figure 3. *Pulse excitation test setup*

The conversion gain was determined according to the procedure outlined in [7]. Namely, by injecting the pulses with different amplitudes, and hence different charges, and observing the output voltage, it is possible to determine the functional relation between the input charge and the output voltage, and from that relation the conversion gain can be easily extracted.

A square waveform from the signal generator was injected into the test input while the output of the pulse processing unit was observed on the oscilloscope. The typical response is illustrated in figure 4.

The result depicted in figure 4 shown that a 100 mV input pulse is converted into a 5.84 V shaped pulse, specified by the proposed design.

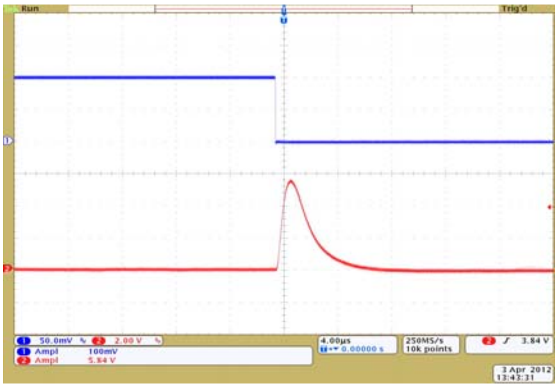

Figure 4. *Response of the pulse processing unit to the input step voltage*

To determine the gain precisely, the amplitude of the input test pulse was varied from 20 mV to 100 mV, with 10 mV increments. This range corresponds to the injected charge from 20 fC to 100 fC (for test capacitance C = 1 pF). The relation between the input charge and the output voltage is illustrated in figure 5.

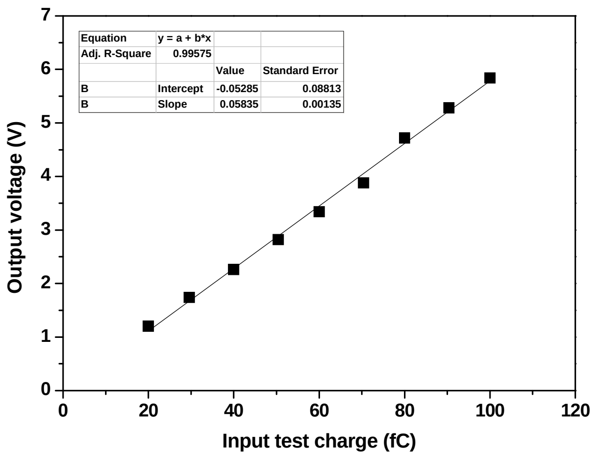

Figure 5. *Dependence between the input test charge and the output voltage of the pulse processing unit*

Applying linear fitting, it was found that the overall conversion gain of the pulse processing unit is 58.35 mV/fC. It can be seen from figure 5 that the conversion gain is stable in the whole range of applied test charge, with minor fluctuations which are the result of the pulse shaper imperfections.

The conversion gain can also be expressed in terms of energy using the procedure for converting the gain in mV/fC into the gain in mV/MeV [7]. The gain of the proposed system is 2.56 V/MeV.

To determine the count rate capability, i.e. the maximum number of pulses per unit time that can be processed, the system was subjected to a variable frequency square waveform and the response was monitored on the PC. It was observed that the system could process the signal with frequency up to 100 kHz (100 000 counts/sec), while preserving the conversion gain. For frequencies higher then 100 kHz, a decrease of the conversion gain was observed.

Evaluation with radiation excitation

For evaluation of the system's response to gamma radiation, a PIN photodiode PS100-6-CER2 PIN from First Sensor was chosen as radiation detector while the radiation excitation was achieved with a ^{137}Cs source (gamma photon energy peak at 662 keV). The test was carried out at room temperature (~ 25°C).

The PS100-6-CER2 PIN photodiode (figure 6) has an active area of 100 mm^2, a maximum dark current of 500 pA (at 100 V reverse bias), junction capacitance of 900 pF at zero bias, 200 MΩ shunt resistance and breakdown voltage of 100 V. This PIN photodiode was chosen primarily because of its large active area and low dark current, as these are desirable characteristics of radiation sensors employed for pulse mode gamma radiation detection.

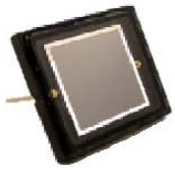

Figure 6. *PS100-6-CER2 PIN photodiode*

To provide good optical isolation, the photodiode was soldered on a small printed circuit board and wrapped with light proof tape and aluminium foil. The interface with the pulse processing unit is achieved through a BNC connector installed on the printed circuit board.

A programmable dual-channel source measuring unit model Keithley 2636A, from Keithley, was used for reverse biasing the PIN photodiode. The setup was constructed in such a way that the anode of the PIN photodiode was biased with positive voltage while the cathode was connected to ground potential (0 V). The PIN photodiode was reverse biased with 60 V during the experiment.

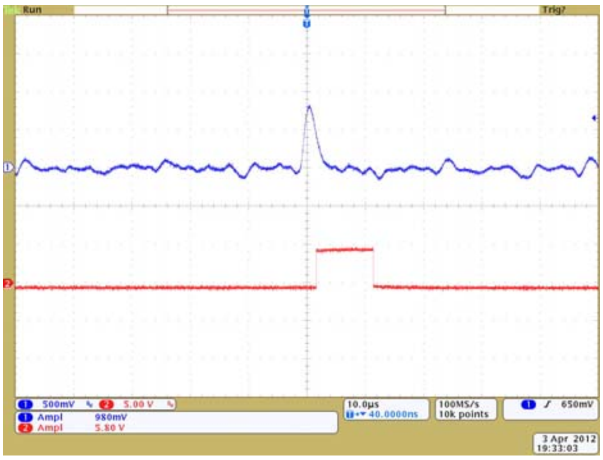

Figure 7. *Result of the excitation with* ^{137}Cs *source*

Due to very low activity of the used source, it was necessary to place the ^{137}Cs very close to the diode so that the system could detect the induced pulses. The typical waveforms illustrating the system's response to gamma photons from ^{137}Cs source are presented in figure 7. Upper waveform represents the output of the pulse processing unit, while the lower waveform is the 10 μs pulse generated by the MMV.

From figure 7 it can be observed that the system is capable of detecting the gamma photons emitted from ^{137}Cs source. For each pulse with amplitude above 650 mV (the threshold level) at the output of the pulse processing unit, a square pulse is generated by MMV and processed in the microcontroller. The amplitude of the detected pulse is 980 mV. However, this amplitude was not the same for all detected pulses – some of the pulses had lower amplitudes (around 850 mV) while other pulses had higher amplitudes (about 1.1 V). The reasons for this amplitude variations and their effect on the system performance will be thoroughly investigated in the future research.

The count rate of the pulses resulting from ^{137}Cs excitation was up to 78 counts/minute. With these results it is not possible to evaluate the dosimetric properties of the proposed system or the sensitivity of the chosen PIN photodiode. Therefore, a more through research must be conducted using radiation sources with higher activity (that can induce a larger number of pulses per unit time), different types of radioactive sources (with different energies), and a number of different types of PIN photodiodes. In addition, it is necessary to compare the performance of the developed system with some reference pulse mode detector.

CONCLUSIONS

Design and performance of a research grade pulse mode gamma radiation monitoring system have been described in this paper. The system was constructed with low cost commercially available components and is intended for dosimetric applications where the PIN photodiodes are used as radiation detectors.

Performance evaluation was performed by exciting the system with pulses from a signal generator and by exposing the system (with the photodiode) to gamma radiation from a gamma ray source. The pulsed signal excitation was used to determine the conversion gain and the maximum count rate that can be measured by the proposed design. The radiation exposure was used to test the system's response to gamma radiation, and in this case the First Sensor PIN photodiode PS100-6-CER2 PIN, with active area 0f 100 mm^2, was used.

The results obtained by the pulsed signal excitation have proven the gain stability, as well as the capability of detecting count rates up to 100k counts/sec. The excitation with low activity ^{137}Cs gamma radiation source has verified the system's ability to detect the low level gamma radiation. However, due to very low activity of the used gamma source, further research is necessary in order to obtain a more detailed overview of the system's performance.

Future work will be focused on the improvement of the proposed design, with the main aim to realize a system that can detect low level gamma radiation and measure the dose rate and the absorbed dose on the basis of the number of pulses detected in a preset time interval. Beside the PC-based version, the development of a stand-alone pulse mode radiation dosimeter will be a major subject of the future research activities.

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BIOGRAPHY

Marko Anđelković was born in Leskovac, Serbia, in 1982. He received a B.Sc. degree in electronics from the Faculty of Electronic Engineering, University of Niš. His main research areas include characterization of radiation dosimeters and development of read-out electronics for dosimetric applications. He is currently working as a researcher in the Applied Physics Laboratory, at the Faculty of Electronic Engineering Niš, Niš, Serbia.

SISTEM ZA PRAĆENJE GAMA ZRAČENJA NA BAZI IMPULSNOG ODZIVA

Marko Andjelković, Goran Ristić

Rezime: *U ovom radu je predstavljen prototip sistema za praćenje gama zračenja na bazi impulsnog odziva. Predstavljeni sistem je zasnovan na personalnom računaru i predviđen je za korišćenje sa PIN fotodiodom kao senzorom zračenja. Sistem je namenjen za praćenje niskih nivoa (niskih jačina doza) gama zračenja u realnom vremenu na principu brojanja strujnih impulsa koji se indukuju u senzoru zračenja kao posledica interakcije između jonizujućih fotona i senzora. Sistem je realizovan komercijalnim komponentama i podržava serijsku komunikaciju sa personalnim računarom. Eksperimentalna procena performansi sistema izvedena je impulsnom ekscitacijom i ekscitacijom pomoću izvora gama zračenja* ^{137}Cs. *Impulsna ekscitacija je korišćena za procenu pojačanja sistema i ukupnog broja impulsa u jedinici vremena koje sistem može da procesira. Rezultati testiranja su pokazali da sistem ima veoma stabilno pojačanje uz mogućnost detekcije do 100 000 impulsa/sek. Ekscitacija pomoću radioaktivnog izvora je potvrdila sposodnost sistema da detektuje izvore veoma male aktivnosti ali su neophodna dodatna istraživanja kako bi se dobilo pouzdanije rešenje. Tokom testiranja, kao senzor gama zračenja korišćena je PIN fotodioda PS100-6-CER2 PIN, firme First Sensor, sa aktivnom površinom od 100* mm^2.

Ključne reči: *impulsni odziv, praćenje zračenja, PIN fotodioda.*