Two dimensional array of MPPC and CsI(Tl) for radiation monitoring prototype

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Abstract. An efficient radiation and position monitoring system is useful for preliminary security inspection and radiation emergency preparedness and response. A high sensitivity and effective monitoring system is needed for these applications. In this study, two position-sensitive prototypes were proposed by using of 8 Multi Pixel Photon Counters (MPPC) and coupled to the cesium iodide with Thallium (CsI(Tl)) scintillator. This inorganic scintillator was chosen for its output wavelength compatibility with MPPC, slightly hygroscopic, high photon transmission, and input energy. For both prototypes, eight MPPCs with different configurations were used to obtain active areas of \(2.0 \times 2.4 \text{ cm}^2\) and \(2.5 \times 4.5 \text{ cm}^2\), respectively. The prototype has been tested with radioactive (Tl-204 and Co-60). The intensity received by each MPPC's readout will be recorded using Extended Analogue SiPM Integrated ReadOut Chip (EASIROC) module. Our test showed that both prototypes were sensitive to both beta and gamma sources and were able to reliably determine the sources' positions. It was shown that the first prototype had greater resolution and performance than the second prototype. This studies may help to improve radiation detection system which is suitable for homeland security, medical field and scanning system.

1. Introduction

Radiation monitoring is important as a preventive measure before an accident occurs as well as to respond to a radiation incident. Current systems rely on the use of sensors capable of detecting radiation, such as photomultiplier (PMT) tubes or avalanche photodiodes (APD).

PMT for radiation monitoring is a photon detector containing of a scintillator, photocathode and electron multiplier anode. Incident ionising photons are transformed into light by the scintillator, which in turn ejects electrons by photoelectric effects at the photocathode. The electron multiplier anode then amplifies the weak signal into a measurable electrical signal.

An APD is a highly sensitive photodiode semiconductor that has the same feature as the photocathode in the PMT. To transform the incident ionising photons, the APD still needs a scintillator. The APD has higher detection efficiency (400 nm to 1100 nm wavelength range) [1], smaller and does not require high voltage since it does not use an electron multiplier anode compare to the PMT.

There are several disadvantages that make them undesirable for PMT and APD detectors. PMTs need a stable high voltage to operate and cannot be used in a strong magnetic field [2]. In addition, PMTs are mechanically fragile, very costly despite having lower quantum efficiency and large in size [2, 1]. The APDs are linear devices and have moderate gain (50-100) and unable to measure low energy (<50 keV)
[3]. As such, a suitable type of detector is needed for an efficient position-sensitive radiation monitoring system.

In this study, PMT and APD are replaced with a semiconductor detector with excellent photon counting capability known as Multi-Pixel Photon Counter (MPPC). It is a solid state detector using multiple combined APDs as a pixel operating in Geiger mode. The MPPC is sensitive enough to detect single photons for photo counting at low light [4]. MPPC is a type of silicon photomultiplier. The main features of MPPC are high resolution for single photon detection, small in size, insensitive to a magnetic field and low operating voltages.

The MPPC is a type of photomultiplier of silicon. High resolution, small in size, magnetic field resistant and low operating voltages are the key characteristics of the MPPC for single photon detection. The MPPC operates at low bias voltage operation (typically 70 V) with high gain almost comparable to conventional PMT [5][6]. MPPC is also good in signal multiplication and has higher photon detection efficiencies [7] despite having higher dark count rates compared to PMT (that the detection of weak scintillation light signals is difficult due to the many contamination of dark counts) [6]. Although the active area of MPPC is much smaller compared to PMT and APD, scintillation light signals still can be observed separately. It can also be used under a strong magnetic field range (1-12 Tesla) [8]. MPPC is also affordable and durable compared to PMT [6] while having better energy threshold than APD because of MPPC have better timing resolution and higher gain [1].

Besides a sensitive detector, a good scintillation material is needed to get a high detection efficiency. There are many types of scintillation materials which are primarily solid crystals, but can also be made of liquid or gas [9]. For solid scintillators, there are two common types: organic and inorganic scintillators. For high detection performance and low energy X-ray or gamma-rays, inorganic scintillators are suitable. The organic scintillators, however, are fragile, have low efficiency of detection and poor resolution [10].

In order to maximise the generation of scintillation light, an inorganic CsI(Tl) crystal was selected as the scintillation material to provide excellent photo-fluorescence. The CsI(Tl) offers a high effective atomic number and the consequently large cross-section of the radiation photo absorption [11]. Although, sodium iodide with thallium activator, NaI(Tl) gives a better light transmission, but NaI(Tl) is hygroscopic [12] and easily tampered by humidity especially in Malaysia. CsI(Tl) is only slightly hygroscopic than NaI(Tl) [10] and has good radiation hardness (103 rad) that suitable applied in high-energy physics experiment [13].

Additional information such as the position of the radiation source is imperative and can be determined using position-sensitive detection. In general, a position-sensitive detection is a measurement technique in 2 or 3 dimensions from a reference point, in order to determine the origin of the signal. This technique is useful for many applications such as vibration, heat and light measurement. Thus, in this research, a position-sensitive radiation detection device was built using MPPC and CsI(Tl). In order to assess the precision and resolution of the prototypes, two proposed systems, each with different array configurations, were tested with different sources.

2. Experimental setup

In this study, a new system position-sensitive monitoring was developed to identify the position of the radiation. There were two type of prototype were tested by using EASIROC-NIM for the performance of prototype of MPPC array. Therefore, each MPPC (S10362-11-50C) will be coupled to CsI(Tl) scintillator. Each pixel of them MPPC has a photosensitive area of 1.0 × 1.0 mm² and is composed of Geiger-mode APDs arranged at a pixel pitch of 100 μm. The surface of CsI(Tl) scintillator will be polished using sandpaper to make sure the surfaces were smooth and clear. Then, the CsI(Tl) scintillator was cleaned using 2-propanol. The silicone oil was used to coupling between CsI(Tl) scintillator and MPPC so it can allow propagation of photon signal from scintillator to the MPPC. The refractive index of silicone oil and MPPC are 1.405 and 1.41 respectively [4][14]. The density of CsI(Tl) is 6.01 g/cm³.

The prototype 1 housing is as shown in Figure 1. The prototype 1 outer dimension was around (3.0 × 7.0 × 6.6) cm³ where 8 CsI(Tl) filled up the insides of the housing with a total volume of (2.4 × 2.0 × 7.0) cm³.
There are contains four CsI(Tl) for each layer. Then each MPPC was coupled to CsI(Tl) crystal and all the MPPC were in contact with the surface of the CsI(Tl) crystal by using silicon oil. A radiation source was placed directly to prototype 1. The scintillation photons signal information was recorded by each MPPC that coupled to a single CsI(Tl) scintillator.

![Figure 1. The design of Prototype 1 housing for (a) female and (b) male part.](image)

Figure 1 shows the design of prototype 1 for female part and male part for prototype 1. The prototype 1 outer dimension was around $(8.9 \times 2.0 \times 5.9)$ cm$^3$, where 4 CsI(Tl) filled up the insides of the housing with a total volume of $(4.5 \times 2.0 \times 2.5)$ cm$^3$. Similar to prototype 1, all of the MPPC were coupled to the CsI(Tl) crystals with silicon oil. A radiation sources were placed in the middle of the CsI(Tl) scintillator. Then, the scintillation photons signal information were towards to both ends of MPPCs and recorded the position information.

![Figure 2. The design of Prototype 2 housing for (a) female and (b) male part.](image)

Figure 2 shows the design of prototype 2 for female part and male part for prototype 2. The prototype 2 outer dimension was around $(8.9 \times 2.0 \times 5.9)$ cm$^3$, where 4 CsI(Tl) filled up the insides of the housing with a total volume of $(4.5 \times 2.0 \times 2.5)$ cm$^3$. Similar to prototype 1, all of the MPPC were coupled to the CsI(Tl) crystals with silicon oil. A radiation sources were placed in the middle of the CsI(Tl) scintillator. Then, the scintillation photons signal information were towards to both ends of MPPCs and recorded the position information.

The distance of prototype from radiation source is kept constant but was varied the position of source to the prototype in order to observe the photons detected by all MPPCs. The schematic experiment setup is as shown in Figure 3. The photoelectron threshold was set from 0.5 p.e. A software that is interfacing with EASIROC module had been developed by Omega [3]. EASIROC-NIM module is connected to MPPCs using rainbow cable as stated in the user guide. The output of MPPC is a high-speed pulse signal and need to delay the signal for detection by 50 ns. In this system, the optimum delay was 50 ns and 5 meter of lemo coaxial cable 50 were used according RS component guide [15]. Operating voltage for each MPPC was varied within its range given by supplier. If the operating voltage
applied to the MPPC is significantly higher than the recommended operating voltage, noise components such as afterpulses and crosstalk will increase and make accurate measurement impossible.

Figure 3. The schematic diagram for the experiment.

3. Result
In order to observe the amount of counts events, the data was analyzed using ROOT software. The number of photon distribution detected by MPPs was calculated based on area under of histogram obtained.

The detector response function gives spectrum of signal amplitudes by a particle of defined energy. Photons with definite energy may interact with the detector which results into a broad spectrum of deposited energies due to the subsequent interaction of the recoil electrons. Charged particles with definite energies which are stopped within the detector material will follow Gaussian distribution of signal amplitudes [16].

The output charge radiation distribution was calculated using full energy peak (FEP) event formula [17]:

$$FEP = \tilde{x} \times \sigma \times \sqrt{2\pi}$$

where the $\tilde{x}$ is the highest peak for 1 p.e. and $\sigma$ is the FWHM.

In both prototype, scintillation photon will travel within the CsI(Tl) and MPPS located at the fo the scintillator. However, loss of the scintillation light can occur in two ways which are escape through scintillator boundaries and absorption due to the scintillator materials itself [16].

Only scintillation photon that reaches the MPPC will be converted into signals. As such, the light intensity observed by each MPPC corresponds to a fraction of the light emitted by the scintillation process due to attenuation along the scintillator. The light intensity as a function of length can be described as:

$$I(x) = I_0 e^{-\frac{x}{l}}$$
where \( l \) is the attenuation length, \( x \) the path length travelled by the light and \( I_0 \) is the initial light intensity.

The scintillation light that are converted into electrical signals are then counted to form the histogram. Once the histogram was plotted, the number of photon counts can be processed to form spatial images.

For prototype 1, this information can be used directly since each MPPC was connected to a single CsI (Tl) scintillator (refer in Figure 4) and a spatial image with intensity (photon count) can be plotted.

\[
I(x) = I_0 e^{-\frac{x}{l}}
\]

Thus, the number of photons in each CsI(Tl) scintillator was calculated by taking root of the product the number of photons signal N1 and N2 [18] is,

\[
N = N_1 \times N_2 = \sqrt{\frac{4N_1 N_2}{e(-1)}}
\]

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Number of scintillation photon detected by MPPC for prototype 1.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Number of scintillation photon detected by MPPC for prototype 2.}
\end{figure}

However, for the prototype 2, some processing is required to extract information to form the spatial image. In this design, the scintillation photon will move within the CsI(Tl) to both MPPCs, located at both ends of the scintillator. According to the Figure 5, the number of photons signal N1 and N2 of the left and right MPPCs located at the respective ends of the scintillator are [18]:
In order to evaluate the 2-D plane position monitoring, the mapping of photons count has been done by using Gnuplot software as shown in Figure 6. The contour plot of these 2-D images will represent different scintillation light intensities. These heat maps or contours are expected to be in agreement with the areas of high incident radiation photons where a colour map can represent areas of higher or lower radiation photon counts. As such, the position and spatial resolution of both prototypes can be determined. These parameters are important to determine the quality of the position-sensitive radiation monitoring system.

Figure 6. The 2-D plane profile monitoring for prototype 1 and 2.
4. Conclusion
In this study, the 2-D plane location monitoring indicates that both prototype arrays are feasible in the radiation position seen for both sources. The 2-D plane position monitoring is capable of separating high and low radiation counts for both prototypes. On both prototypes, the intensity photons of Tl-204 are higher compare to Co-60. This is because the energy deposited by the beta source is greater than the source of gamma. Plus, beta radiation has high ionizing compared to gamma radiation. In this case, the particle will decelerate when the ionising phase happens as beta particles travel into the scintillator. While the gamma emission brings the photon down to a more stable energetic state (lower state) and produce little ionization.

In this research, even change the position of source, it gets the same outcome depending on the position that has been placed. This proves that, in beta radiation, the MPPC has high-energy sensitivity and specifically separates between high and low radiation energy. The non-uniform photons distribution could be caused by the background noise and ambient fluctuation. The pattern for the highest count is the same from this study for positioning the source and dependent on photon distribution. The pattern found from this study is the same as the previous Wee et al. study [19] study the flexible temperature sensor array with different heat sources from different shape.

In terms of photon distribution, the position sensitivity response was calculated in order to obtain a 2-D plane profile. The number of photon events reported by the MPPC was specified on each channel by colours. The stability between the EASIROCNIM module MPPC and CsI(Tl) was observed by understanding the actual position of the MPPC detector that detects multiple source positions. The differences between high and low intensity radiation can be easily seen from the plane profile. Testing at different locations found that good agreement between the position allocated and detected position contributed to good position monitoring.

In this research, the absolute efficiency of the detector was calculated [20]. These measurements are the percentage of radiation that detect overall yield that emitted from the source to the detector. The total efficiency of prototype 1 with beta and gamma source is 8.86 % and 18.51 % while prototype 2 is 1.65 % and 2.07 %, respectively. Therefore, in terms of detection efficiency, prototype 1 was greater than prototype 2, since prototype 1 directly detected the distribution of scintillation photons compared to prototype 2.

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