TWO DIMENSIONAL ARRAY OF MULTI-PIXEL PHOTON COUNTER AND CESIUM IODIDE CRYSTAL (THALLIUM ACTIVATOR) FOR RADIATION MONITORING PROTOTYPE

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DEDICATION

This thesis is dedicated to . . . ..

MYSELF To Become Better

Ayah Ma; Jasni bin Nawi, Aini binti Che Isa

Hubby; Muhammad Nursyadiq bin Saian.

Siblings; ‘Aifaa binti Jasni, ‘Ayunni binti Jasni, Athirah binti Jasni, Azfar bin Jasni

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ABSTRACT

An efficient radiation and position monitoring system is useful for preliminary security inspection as well as for radiation emergency preparedness and response. For these applications, a high sensitivity and efficient monitoring system is required. Two position-sensitive prototypes were proposed using solid state detector (multi-pixel photon counters, MPPC) and inorganic scintillator (cesium iodide with thallium activator, CsI(Tl)). 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 2.0×2.4 cm^2 and 2.5×4.5 cm^2. These prototypes were read out using EASIROC-NIM module and tested with beta (Tl-204; 763.76 keV) and gamma (Co-60; 1.1732 keV) radioactive sources at different positions. The experiments showed that both prototypes were sensitive to both beta and gamma radiation and was able to determine the positions of the sources accurately. The prototype 2 was found to have a better resolution in terms of pixel that is only limited by resolution of the calculation, which is 250 steps in this setup whereas prototype 1 only have 8 pixels. In addition, the experimental efficiency for both prototypes were calculated and compared. The prototype 1 has better efficiency (with beta, 8.86 % and gamma, 18.15 %) than the prototype 2 (with beta, 1.65 % and gamma, 2.07 %). The setup in this study can be further enlarged to be adapted in industries such as security and medical sectors.

ABSTRAK

Sistem pemonitoran kedudukan dan sinaran yang cekap adalah penting untuk pemeriksaan keselamatan awal serta untuk kesediaan dan respon kecemasan sinaran. Untuk aplikasi-aplikasi ini, sistem pemantauan berkepekaan tinggi dan cekap diperlukan. Dua prototaip sensitif-kedudukan telah dicadangkan dengan menggunakan alat pengesan keadaan pepejal (pembilang foton multi-piksel, MPPC) dan pengelip inorganik (sesium iodida dengan pengaktif thallium, CsI (Tl)). Pengelip inorganik ini dipilih disebabkan keserasian panjang gelombang keluarannya dengan MPPC, sedikit higroskopik, transmisi foton yang tinggi, dan tenaga input. Untuk kedua-dua prototaip, lapan MPPC dengan konfigurasi yang berbeza digunakan untuk mendapatkan kawasan aktif iaitu 2.0×2.4 cm^2 dan 2.5×4.5 cm^2. Prototaip-prototaip tersebut dibaca dengan menggunakan modul EASIROC-NIM dan diuji dengan sumber radioaktif beta (Tl-204; 763.76 keV) dan gama (Co-60; 1.1732 keV) pada posisi yang berbeza-beza. Eksperimen-eksperimen ini menunjukkan bahawa kedua-dua prototaip adalah sensitif terhadap sinaran beta dan gamma dan dapat menentukan kedudukan sumber punca dengan tepat. Prototaip 2 didapati memiliki resolusi yang lebih baik dari segi piksel yang terbatas oleh resolusi pengiraan, iaitu 250 piksel dalam persediaan ini sementara prototaip 1 hanya memiliki 8 piksel. Di samping itu, kecekapan eksperimen untuk kedua-dua prototaip telah dikira dan dibandingkan. Prototaip 1 mempunyai kecekapan yang lebih baik (terhadap punca beta, 8.86 % dan gama, 18.15 %) daripada prototaip 2 (terhadap punca beta, 1.65 % dan gama, 2.07 %). Persediaan dalam kajian ini boleh dikembangkan lagi untuk diadaptasi dalam industri seperti sektor keselamatan dan perubatan.

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LIST OF ABBREVIATIONS

ABS	-	Acrylonitrile Butadiene Styrene
APD	-	Avalanche photodiode
BaF_2	-	Barium fluoride
BGO	-	Bismuth germanate
$CdWO_4$	-	Cadmium tungstate
Ce:LYSO	-	Cerium doped lutetium
Co-60	-	Cobalt-60
CsI(Tl)	-	Cesium iodide with thallium
DAC	-	Analog-to-digital-converter
DAQ	-	Data Acquistion
DOI	-	Depth of interaction
EASIROC	-	Extended Analogue SiPM Integrated ReadOut Chip
FEP	-	Full energy peak
FWHM	-	Full width at half maximum
GAGG	-	Gadolinium Aluminum Gallium Garnet crystals
GOS	-	Gadolinium oxysulfide
ILC	-	International Liner Collider
J-PARC	-	Japan Proton Accelerator Research Complex
LED	-	Light-Emitting Diode
MPPC	-	Multi Pixel Photon Counters
MRI	-	Magnetic resonance imaging
MuRAY	-	Muon Radiography
Nal(Tl)	-	Sodium Iodide doped with thallium activator
$PbWO_4$	-	Lead tungstate
PDE	-	Photon detection efficiency
PEB	-	Positron Electron Balloon Spectrometer

PET	-	Positron Emission Tomography
PMT	-	Photomultipliers tube
QE	-	Quantum efficiency
RQ	-	Quenching resistor
SiPM	-	Silicon photomultipliers
SNR	-	Signal-to-noise ratio
SPIROC	-	SiPM Integrated Read-Out Chip
Tl-204	-	Thallium-204

LIST OF SYMBOLS

γ	-	Gamma
β	-	Beta
σ	-	Full width half maximum
V	-	Voltage
ΔV	-	Overvoltage
V_{BIAS}	-	Reverse-biases voltage
V_{BR}	-	Breakdown voltage
V_{op}	-	Operation voltage
$f(g)$	-	Fill factor
Pa	-	Avalanche probability
l	-	Attenuation length
x	-	Path length
l_0	-	Initial light intensity
N_1, N_2	-	Number of photons signal

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Radiation monitoring is used widely in various applications such as medical procedures, homeland security and safety, food irradiation, environmental monitoring and industral applications. Radiation monitoring is important for preventive measure and planning of emergency reponse to a radiation incident. Current existing systems rely on the use of sensors capable of detecting radiation such as photomultiplier tubes (PMT) or avalanche photodiodes (APD).

PMT for radiation monitoring is a photon detector consisting of a scintillator, photocathode and electron multiplier anode. The scintillator converts incident ionizing photons into light which in turns ejects the electrons at the photocathode through photoelecric effect. The electron multiplier anode then amplifies the weak signal into a measurable electrical signal. On the other hand, an APD is a highly sensitive semiconductor photodiode which has the same function as the photocathode in the PMT. Therefore the APD still requires a scintillator to convert the incident ionizing photons. Unlike the PMT, the APD has higher detection efficiency (within 400 nm to 1100 nm wavelength range) [1], is smaller and does not require high voltage since it does not use an electron multiplier anode.

The APD detector is made of germanium or silicon which uses photovoltaic effect when light is flashed onto the semiconductor material [2]. For silicon, the suitable wavelength range for Si is 1.1 μm. Therefore, it suitable to detect visible light, but is unsuitable for detecting infrared. Today, such photodetectors are manufactured for the ultraviolet, visible and infrared wavelength bands. Another type of solid state detector is Multi-Pixel Photon Counter (MPPC), which a type of Silicon Photomultipier (SiPM). It is solid state detector that uses several APDs combined together as pixel which operates in Geiger mode. MPPC is sensitive enough to detect single photons for photo counting at even low light [3].

Besides a sensitive detector, a good scintillation material is required to get a high detection efficiency. There are several types of scintillation materials which are mainly solid crystals, but can also be made of liquid or gas [4]. For solid scintillators, there are two common types: organic and inorganic scintillators. Inorganic scintillators are suitable for high detection efficiency and low energy X-ray or gamma-rays whereas, the organic scintillators are fragile, have low detection efficiency and poor resolation [5].

For some applications, a simple radiation monitoring system is insufficient. Additional information such as the position of the radiation source is imperative and this 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 to determine the origin of the signal. This technique is useful for many applications such as vibration, heat and light measurement. For radiation monitoring, the relative magnitude of photocurrent signals can be used to determine the position of the radiation source in real time.

1.2 Problem Statement

Radiation monitoring system nowadays is inefficient and slow [6]. The radiation distribution in the monitored area can be detected and calculated by using a highly efficient position-sensitive device. Such a device must able to detect radiation at high and low intensities effectively in a short time and provide spatial information.

Current commercial instruments use photomultiplier tubes to detect radiation emission. The APDs are silicon photodetectors that have higher detection efficiency than PMTs over 400 nm to 1100 nm wavelength range [7]. For PMT and APD detectors, there are some disadvantages that make them undesirable. PMTs need a stable high voltage to operate and cannot be used in a strong magnetic field [8]. On the other hand, APDs have the advantage of a higher photon detection efficiency (PDE) than PMTs which can be >65 % and also a compact in size, ruggedness, and insensitivity to magnetic fields [9].

SiPM is similar to PMT in that it has high gain, good intrinsic timing resolution (< 200 ps) and enough PDE (more than 20 %), but it also has the physical advantages of compactness, ruggedness, and magnetic insensitivity that the APDs have. SiPM offers the best optimize solutions considering better energy resolution (8.8 %) and costs effectiveness and low operating voltage aspects compared to PMT [10]. Any Silicon Photomultiplier-Positron Emission Temography (SiPM-PET) system has a better timing resolution of (around 390 ps) than a traditional Photomultiplier Tube-Positron Emission Temography (PMT-PET) system [11, 12].

In addition, PMTs are mechanically fragile, very costly despite having lower quantum efficiency and large in size [1, 8]. The APDs are linear devices and have moderate gain (50-100) but are unable to measure low energies (<50 keV) [13]. 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).

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 operates at low bias voltage operation (typically 70 V) with high gain almost comparable to conventional PMT [14, 15]. MPPC is also good in signal multiplication and has higher photon detection efficiencies [16] despite having higher dark count rates compared to PMT (detection of weak scintillation light signals is difficult due to the several contamination of dark counts) [15]. Even though the active area of MPPC is much smaller compared to PMT and APD, it can detect scintillation light signals individually. It can also be used under a strong magnetic field range (up to 12 Tesla) [17]. MPPC is also affordable and durable compared to PMT [15] while having better energy threshold than APD since MPPC have better timing resolution and higher gain [1]. Its versatility allows it to be used in many photon detector experiments such as for Positron Electron Balloon Spectrometer (PEBS), Muon Radiography (MuRAY), Japan Proton Accelerator Research Complex (J-PARC), Positron Emission Tomography (PET) and medical imaging [18, 19, 20] but as far as we know, it is not yet used in inspection systems in safety and security applications.

Usually semiconductors detectors are used to measure radiation intensities in term of photon counts. In order, to get high performance photon counting and to allow maximum scintillation light transmission, the semiconductor detector is coupled with a scintillation material. Because solid scintillators are much denser than gases types, they have much better stopping power and are much more efficient detectors for X-rays and gamma rays [21]. The ionizing photon penetration depends on the atomic number, density and thickness of the material [22].

In this research, inorganic CsI(Tl) crystal was chosen as the scintillation material due to its excellent photo-fluorescent which can maximise scintillation light generation. Inorganic scintillators are used mostly because they are better at detecting gamma and X-rays. Because of their high density and atomic number, they have a high electron density. The higher the chance of this happening, the more electrons there are for the incident photons to collide with [22]. CsI(Tl) offers a high effective atomic number and consequently large cross-section of the radiation photo absorption [23]. Although, sodium iodide with thallium activator NaI(Tl), gives better light transmission, but NaI(Tl) is hygrocopic [24] and is easily tampered by humidity especially in Malaysia. CsI(Tl) is only slightly hygroscopic than NaI(Tl) [5] and CsI(Tl) has good radiation hardness (103 rad) that ideal for high-energy physics studies [20].

Thus, a position-sensitive radiation detection system was developed using MPPC and CsI(Tl) in this study. Two proposed systems, each with different array configuration was tested with different sources to determine the designs' accuracy and position resolution.

1.3 Objective of Study

In this work, two types of prototype are investigated:

i. To design and construct two prototypes of MPPC with different array module configuration.

ii. To determine the detection sensitivity in 2-D map for beta and gamma radiation for both prototypes.

iii. To determine the position resolution in 2-D map and detector counting efficiency for both prototypes.

1.4 Scope of Study

This study will cover two prototypes based on MPPC array. Prototype 1 has a dimension of $(3.0 \times 7.0 \times 6.6)$ cm^3 and prototype 2 has a dimension of $(8.9 \times 2.0 \times 5.9)$ cm^3. Both prototypes consist of 8 MPPCs and CsI(Tl) scintillators with different array configuration. Both prototypes are placed in a black box to avoid external background detection. The position measurements are examined with the Co-60 and Tl-204 at different positions.

The readout system used in this study is EASIROC-NIM module. It is an optical measurement for SiPM detectors and is able to count photons, has low electronic noise and low cross talk. This module contains of the parts such as amplifier, discriminator and power supply. The details of the measurement are then analyse by using ROOT software. The 2-D mapping for radiation position and efficiency of the prototypes are calculated.

1.5 Significance of Study

The finding of this study will be used to create a position-sensitive radiation monitoring and will contribute to the vast knowledge in relation to safety in inspecting and identifying goods in industry. The coupling between scintillation material and photon-counting device will provide the information on amount number of photon counts detected. It is very useful to differentiate between high and low radiation intensities. This new development of scanning system by using MPPC as detector is improve the position resolution for radiation intensity. It may help user to conduct inspections in difficult situations happens.

1.6 Thesis Outline

This thesis is organised as follows. The review on the previous study of the development radiation monitoring system and properties of scintillators are presented in Chapter 2. Chapter 3 provide a details explanation of methodology in this research which includes the experiment setup and apparatus used to achieve the objectives. The results are discussed in Chapter 4 to give a brief idea of data interpretation for both prototype designs. The summary of the research and recommendation of future studies will be discussed in Chapter 5.

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LIST OF PUBLICATIONS

Non-Indexed conference proceedings

1. **A.A.Jasni**, Y.S.YAP, I.H.Hashim & N.E.Ahmad (2019). Study of two dimensional array of MPPC by using EASIROC-NIM module. In *7th International Conference and Workshop on Basic and Applied Sciences* (*ICOWOBAS 2019*) (pp 58). https://science.utm.my/icowobas2019.

2. **A.A.Jasni**, Y.S.YAP, I.H.Hashim, N.E.Ahmad & N.Ramlee (2021). Two dimensional array of MPPC and CsI (Tl) for radiation monitoring prototype. In IOP Conference Series: Materials Science and Engineering (Vol. 1106, No. 1, p. 012028). IOP Publishing.