Performance of CsI (Tl) photodiode with optic fiber wire for Gamma-rays and X-rays detection

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Abstract. In this paper, we explored the feasibility study of using the optic fiber wire to be a light transmitter for crystal scintillation material in the radiation measurement. The high-density material; thallium doped cesium iodide CsI (Tl) are widely used as converters for Gamma-rays and X-rays into visible light. Optic fibers are applied in the various applications such nuclear facilities, future fusion installations, medical treatment and diagnostic premises etc. The major advantages to be considered in optic fibers for radiation detection because their characteristics such as: capacities to work under electromagnetic fields; possibility to carry the wavelength signals; small size and low mass including possibility to monitor parameters from the sites far away from the controller. In this work, the cylindrical crystal CsI (Tl) material was connected with the single-clad optic scintillating fiber which transmitted the light signal to photodiode. Gamma-rays and X-rays sources had been investigated the measurement. The optic scintillating fibers have a good response with Cs-137 gamma radiation source at 662 keV. X-ray radiation that was generated from the X-ray tube was determined with the different operating voltages. The obtained results show this device can measure the X-ray radiation with energy range from 39 to 309 keV. CsI (Tl) photodiode detector with optic fiber wire can be applied to measure gamma radiation and X-ray radiation as well as being able to the further work in the nuclear and radiation fields.

1. Introduction

Nowadays, the radiation has been applied in many fields such as medical, environmental, industrial including research work. Radiation is divided into 2 types which are ionizing and non-ionizing radiation. In this work, we focused on the ionizing radiation. Ionizing radiation is separated to two groups. The one is particles that consists of alpha, beta, neutrons, and proton. Another one is electromagnetic waves that are X-rays, Gamma rays, etc. Synchrotron radiation is a type of electromagnetic wave which is emitted from the electron charged particles. The spectrum of synchrotron radiation is widely covered the range from infrared to X-rays. Photon is a particle of light. Gamma rays and X-rays are high energy photons. X-rays are emitted by electron outside the nucleus, while Gamma rays are emitted by the unstable nucleus. Photons have no rest mass and no electrical charge. Gamma rays and X-rays are high penetrating matter which might be affected with the human health. If lack of the adequate radiation protection. The interactions between Gamma rays and X-rays with material can be described through three mechanism processes which are photoelectric effect, compton scattering, and pair production.

Gas-filled detectors, solid state detectors, and charged coupled detector are the types of detector. The key factor to determine to use the radiation detector depends on the type of radiation, energy range, and
your specific applications. Gas-filled detectors and solid-state detectors are mostly applied to measure the Gamma rays and X-rays which the radiation detection are high efficiencies. Although the Gas-filled detectors has good uniformities but there are many disadvantage points such as gas leakage, highly sensitive with temperature, expensive cost, etc. While the Solid-state detectors have the uniformities problem, but these types are low weight, cost-effective [1], [2].

Optic scintillating fibers have been incorporated into the various types of sensors and applied in many fields. The study to develop the radiation sensors or detectors which composed of scintillator and optic fiber to detect the radiation [3], [4]. These research studies have the contributions to help the radiation measurement in the specific areas and applications. Due to the optic scintillating fibers have the advantages of low attenuation, prevent shock electrical, light weight and small size especially capabilities to work under electromagnetic fields which is suitable to apply with electromagnetic radiation area.

In this study, the optic scintillating fiber was assembled with the crystal scintillator and light sensor in order to measure the Gamma rays and X-rays from Gamma ray sealed source and X-ray machine. And we have measured linear responses of energies and dose rates of these instruments to determine the performance of their radiation detection.

2. Materials and Methods
This radiation instrument in this work is composed of six parts: radiation source, scintillator, light transmitter, photodetector, amplifier, and data acquisition. The detailed of materials and experimental set up were described below.

2.1. Crystal scintillator
Crystal scintillator and optic scintillating fiber. In this work, cesium iodide thallium; CsI (Tl) is a good candidate to be a scintillator material with high gamma ray stopping power due to its relative high density and atomic number. The CsI (Tl) had been applied in the widely energy range from lower 20 keV to upper 5 MeV. The maximum broad emission is situated at 550 nm and light yield is 66,000 photons per MeV. A principle of inorganic crystal scintillator, that is the electrons are elevated from the valence band to the conduction band by absorption of energy and leaving a gap in the valence band. Nevertheless, the emission of a photon is an inadequate process to return of an electron to the valence band. The addition of chemical additives e.g., thallium (Tl) into the crystal which are called activators, that can help to create the special sites in the lattice. The band gap structure and energy structure are adjusted to be narrowed. However, the perspective crystal of energy structure is unchanged, just the activator sites of the energy structure. The electron elevated to the conduction band is to migrate through the crystal until encounter an ionized activation site. The electron drops into the impurity site, creates a neutral impurity configuration with its own set of excited states. And then an excited state electron configuration will be transited to the ground state. De-excitation depends on a probability of photon emission. The photons are emitted in the visible range [5]. The cylindrical crystal scintillator was selected to use which has the diameter 2 centimeter and length 10 centimeter.

2.2. Optic scintillating fiber
Commercial plastic grade single-mode optic scintillating fiber is used to guide lights from the sensor probe to the light measuring device. The reason why we selected the single clad to use because the light transmission is better than multi-mode clad which low loss and long link distance wide bandwidth. The diameter of this fiber is 2 mm and length 0.5 meter with the cladding thickness is 0.5 mm. The optic scintillating fiber play the important role to transmit the light which has the ability to collect light from one place to another place. The property of optical is well known as refraction. The internal refraction of material can describe by the relationship between the index of refraction and the angle of the light which is defined by Snell’s law as shown in Equation (1);

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]  

(1)
where $n_1$ and $n_2$ are the refraction index of material 1 and 2 while $sin\theta_1$ and $sin\theta_2$ is the angel of light travels.

2.2.1. Scanning Electron Microscopy and Electron Dispersive Techniques

To study of the elemental compositions of optic scintillating material, the Scanning Electron Microscopy and Electron Dispersive (SEM: EDS) had been applied which was perform at Synchrotron Light Research Institute (Public Organization) or SLRI. Figure 1 and Figure 2 are showed the cross-sectional views of optic scintillating fiber from SEM technique. The spectra result of cladding found that carbon element 99.8% by weight whereas the chemical elements inside core consist of carbon, oxygen, fluorine, aluminium, and sulphur are 66.1, 30.1, 3.4, 0.3, and 0.1% by weight, respectively.

![Figure 1. Scanning Electron Microscopy image of optic scintillating fiber](image)

![Figure 2. Comparison between the inner (left) and outer (right) of optic scintillating fiber](image)

2.2.2. FT-IR Spectroscopy

Fourier transform infrared spectroscopy technique (FT-IR Technique) had been used to investigate the chemical bond of optic scintillating fiber material. FT-IR Technique had been done at SLRI.

![Figure 3. Spectra of optic scintillating fiber core](image)

![Figure 4. Spectra of optic scintillating fiber cladding](image)

The hit-quality index value was used to indicate how the sample matched with the library reference. The spectra indicated that the outer of optic scintillating fiber or cladding consists of polymethyl
(methacrylate) or PMMA (Hit quality index 1001) that is shown in Figure 3. Another one that is core, we found the fluorocarbon fiber (Hit quality index 537) inside which is illustrated in Figure 4.

2.3. Experimental Set up
The study was performed to study the CsI (Tl) photodiode detector with optic fiber wire for measure the X-rays and Gamma radiation. The crystal was coupled directly to Hamamatsu Si-photodiodes. Si-photodiode was used to study with the spectral response range 190 to 1,100 nm and active area of 100 cm². Optic scintillating fiber with diameter 2 mm and long 0.5 meter was applied. The crystal scintillator and optic scintillating fiber were combined with a Si-photodiode in the specific designed stainless-steel housing and were wrapped with the black tape. The experiments were set up to determine the performance of crystal CsI (Tl) photodiode detector with optic fiber wire is shown in Figure 5. In the case of radiation measurements, it had been performed at Radiation Calibration Laboratory at Thailand Institute and Nuclear of Technology. The experimental set up of X-ray measurement and Gamma measurement as illustrated in Figure 6 and Figure 7.

![Figure 5. Schematic diagram of Crystal scintillator with optic fiber wire and light sensor components.](image)

![Figure 6. X-ray measurement by using X-ray generator machine](image)

![Figure 7. Gamma measurement by using Gamma ray source](image)

3. Results
3.1. X-ray measurement
In this work the performance of X-ray measurement had been studied. An X-ray generator machine was used with the different photons generated from 40 to 300 kVp, and the tube current from 1 mA up to 20 mA as much as the maximum possible for this tube. The crystal CsI (Tl) photodiode with optic fiber wire was employed to measure the directional X-ray beam. The voltage outputs from these
measurements were compared with the reference dose rates of this machine in the unit of milli-sievert per hour (mSv/h) after the background values were removed. The results obtained that were shown in Figure 8 and Figure 9.

From Plank’s law the photon energy is varied by frequency and inversed by wavelength which is calculated using the relation.

$$E = \frac{hc}{\lambda}$$  \hspace{1cm} (2)

Where $E$ is the quantum energy, $h$ is plank’s constant, $c$ is the speed of light, and $\lambda$ is wavelength. The operating voltages between 40 to 300 kVp were converted to be the wavelength in the unit of nano-meter. These instruments can respond to the X-ray wavelength between 0.031 to 0.004 nano-meter or the energy range between 39.40 to 309.96 keV as shown in Table 1.

| No. | Operating voltage (kVp) | Wavelength (nano-meter) | Energy (keV) |
|-----|-------------------------|-------------------------|--------------|
| 1   | 40                      | 0.031                   | 39.40        |
| 2   | 60                      | 0.021                   | 59.04        |
| 3   | 80                      | 0.016                   | 77.49        |
| 4   | 100                     | 0.012                   | 103.32       |
| 5   | 120                     | 0.010                   | 123.98       |
| 6   | 150                     | 0.008                   | 154.98       |
| 7   | 200                     | 0.006                   | 206.64       |
| 8   | 250                     | 0.005                   | 247.96       |
| 9   | 300                     | 0.004                   | 309.96       |

3.2. Gamma measurement.
The radioactive source $^{137}$Cs was the standard source was used for the gamma ray measurement which has the activity 2.262 curie (Ci). When $^{137}$Cs source decays, the gamma radiation is emitted about energy 662 keV. The radioactive half-life (T$_{1/2}$) of specific $^{137}$Cs radioisotope is 30.15 years. To explore the relationship between the distance from the gamma radioactive source and the voltage including the reference dose rates, the gamma measurements had been done. The results of gamma detection response was shown in Figure 10 and Figure 11.
The results illustrated that the distance is an important factor when considering radiation detector application. The inverse square law shows an exponential decrease after the distance from source was increased.

4. Conclusions
It is a relatively new type of detector that involves coupling of a scintillator, an optical fiber, and a crystal scintillator-detector. The Crystal Photodiode Detector with Optic Fiber Wire achieved good accuracy measuring the radiation from X-rays source at 40 keV to 300 keV and Gamma ray source at 662 keV. The combination of the crystal scintillator and the optical fiber attractive merits such as linear response to dose rate and high voltage for X-rays and Gamma ray detection.

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