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## Effect of CWO and ZnSe(Te) Scintillation Detector on Image Quality of Non-intrusive Inspection System

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### Abstract

Due to its high detection efficiency and low after-glow, CWO ( $\text{CdWO}_4$ ) scintillation detector has been used in x-ray imaging systems for a long time in spite of its low light yield. Recently, much attention has been paid to ZnSe(Te) semiconductor after the finding of its good scintillation characteristics. Two types of scintillation detector array modules consisting of a photodiode and either  $\text{CdWO}_4$  (CWO) or ZnSe(Te) scintillator were fabricated for comparative investigation of CWO and ZnSe(Te) in one of x-ray imaging applications, non-intrusive inspection system. When irradiated by various x-ray beams and Cs-137, the current from CWO and ZnSe(Te) detectors was measured and compared with the calculated result. Also, their detective quantum efficiency (DQE) at zero frequency were calculated using Monte Carlo simulation. Finally, in order to demonstrate the results predicted by theoretical DQE, inspection test of a real-size container was performed using either CWO or ZnSe(Te) detector arrays.

This paper also suggests that ZnSe(Te) parallel to x-ray direction can achieve DQE comparable with CWO and can be used as a detector for detection of high energy.

Keywords : Scintillation Detector,  $\text{CdWO}_4$ , ZnSe(Te), DQE, x-ray imaging;

### 1. Introduction

In detecting radiation for  $\gamma$ -ray spectroscopic or digital imaging system, CWO ( $\text{CdWO}_4$ ) has been used due to its high detection efficiency and low after-glow. However, its low light yield has been one of most serious drawbacks in its application. Recently, interest in ZnSe(Te) semiconductor scintillator has been increased since Ryzihikov et al.[1] reported that the ZnSe(Te) has good scintillator characteristics such as large light yield, short after-glow and good optical matching to a Si photodiode. Previous studies have

been suggested that the ZnSe(Te) is preferable for low radiation detection in the 20 keV to 100 keV because of its low density and high optical absorption coefficient in bulk. To my knowledge, there are few studies on application of the ZnSe(Te) scintillator in detecting high energy radiation.

Non-intrusive inspection system for baggage, luggage or large container at airport or seaport has used various energy x-rays in the range of from a few hundred keV to a few MeV. The scintillator used for such non-intrusive inspection system is generally placed parallel to incident x-ray direction as shown in Fig. 1, since energetic radiation (x-ray or  $\gamma$ -ray) has long penetration ability. In this case, drawbacks of the ZnSe(Te) mentioned above isn't crucial because the scintillator parallel to x-ray can be made to have enough length to interact with energetic x-ray completely.

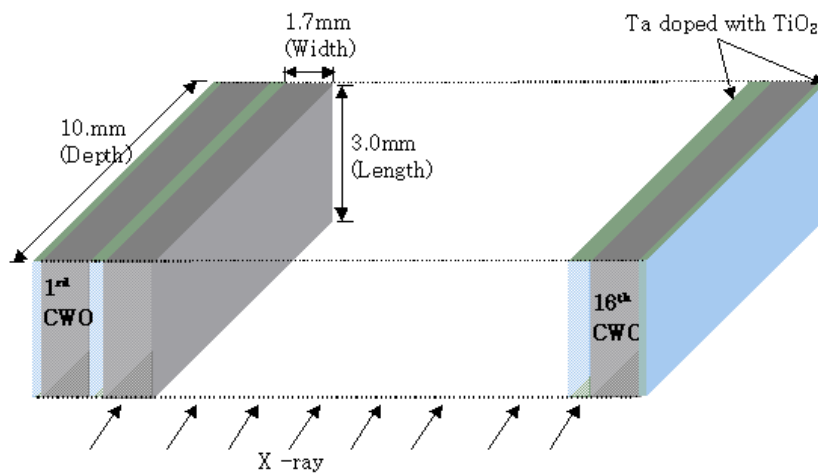


Fig.1 Placement of crystal element parallel to x-ray direction

The objective of this work is to examine the possibility of whether the ZnSe(Te) can be used for detection of high energy radiation instead of CWO. At first, we made CWO and ZnSe(Te) scintillator detectors of the same size. Under irradiation of eight kinds of x-ray beams (ISO 60, ISO 80, ISO100, ISO120, ISO150, ISO200, ISO250, ISO300)[2] and a mono-energy  $\gamma$ -ray(Cs-137), signal current from the two scintillator detectors were measured and calculated. Also, the effects of CWO and ZnSe(Te) on image quality were evaluated in terms of the zero frequency DQE(Detective Quantum Efficiency). Finally, the actual inspection test of an object in a real-size container was carried out using the CWO and ZnSe(Te) scintillation detector arrays.

## 2. Calculation

### 2.1 Photo-current

When irradiated by  $N_x$  x-ray quanta per unit of area, the photo current,  $I_{ph}$ , generated in a photodiode can be calculated using the following equation :

$$I_p = q \int_0^{E_{hn}} \int_0^{E_0} N_x(E) h_Q(E) E_a(E) Y(E) C(E_{hn}) S_{hn}(E_{hn}) R_{hn}(E_{hn}) E_{hn} dE dE_{hn} \quad (1)$$

Parameters used in this equation are defined in Table . To estimate the output signal current, Eq.(2) is approximated as follows:

$$I_p \approx q \cdot \overline{N_x} \cdot \overline{h_Q} \cdot \overline{E_a} \cdot \overline{Y} \cdot \overline{C_{hn}} \cdot \overline{R_{hn}} \cdot \overline{E_{hn}} \quad (2)$$

if we assume  $\overline{R_{hn}} = \int_0^{E_{hn}} S_{hn}(E) R_{hn}(E_{hn}) dE_{hn}$ . Finally, the photo current of a photodiode by x-ray quanta can be estimated by determining the values of parameters in Eq.(2).

Table  
Definition of parameters used in calculation

Definition	Parameter
Incident x-ray energy, MeV	E
Energy of light photon generated in scintillator, MeV	E <sub>h</sub>
Energy deposited by x-ray, MeV	E <sub>a</sub> (E)
X-ray fluence, #/cm <sup>2</sup>	N <sub>x</sub> (E)
X-ray quantum detection efficiency	η <sub>Q</sub> (E)
Light yield of a scintillator, lights/MeV	Y(E)
Light collection efficiency	C(E <sub>h</sub> )
Spectral response of a photodiode, A/W	R(E <sub>h</sub> )
Light emission spectrum of a scintillator	S <sub>h</sub> (E <sub>h</sub> )

In Eq. (2), the mean number of x-ray quanta ( $\overline{N_x}$ ) was calculated approximately from exposure rate of x-ray beams incident on scintillator. X-ray quantum detection efficiency ( $\overline{h_Q}$ ) and the amount of energy ( $\overline{E_a}$ ) deposited by x-ray were determined by Monte Carlo simulation codes, MCNP4B (Monte Carlo N-particle Transport version 4B)[3]. The light collection efficiency ( $\overline{C_{hn}}$ ) was also estimated using Monte Carlo code (DETECT97)[4] with some assumptions : (1) the optical gap between the crystal block and the top surface of a photodiode was about 40μm, which was measured with Form Talysurf Series 2 of Rank Taylor Hobson company; (2) the optical attenuation coefficients of CWO and ZnSe(Te) were about 0.05 and 0.2, respectively[1]. In eq. (2),  $\overline{R_{hn}}$  was determined from the measured spectral response of the photodiode[5] and known optical light emission spectrum of two scintillators. Fig. 1 shows the light emission spectra of CWO and ZnSe(Te) compared with spectral response of the photodiode used in this work.

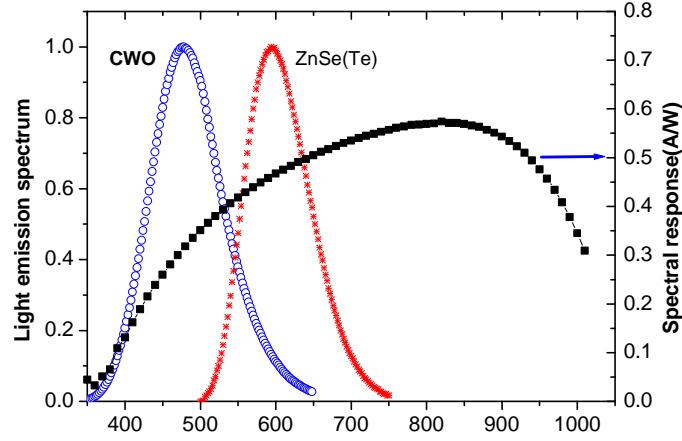


Fig. 2 Light emission spectra of scintillators(CWO and ZnSe(Te)) and spectral response(A/W) of a photodiode

## 2.2 DQE (Detective quantum efficiency)

DQE are one of the parameters describing the signal-to noise transfer properties of image detector[6]. DQE at zero frequency is defined by

$$DQE = \frac{SNR_o^2}{SNR_i^2} \quad (3)$$

$SNR_o$  is the output signal-to-noise ratio and  $SNR_i$  is the input signal-to-noise ratio. When assumed that

$\overline{N_x}$  and  $\overline{Y_a}$  follow Poisson statistics, while  $\overline{h_q}$  and  $\overline{C_{hn}}$  have binomial probability distributions,

finally, DQE can be re-written as follows [7] :

$$DQE = \frac{\overline{N_x} \cdot \overline{h_q} \cdot \overline{E_a} \cdot \overline{Y} \cdot \overline{C_{hn}}}{\overline{N_x} \cdot (\overline{E_a} \cdot \overline{Y} \cdot \overline{C_{hn}} + 1)} \quad (4)$$

## 3. Experimental Setup and Measurement

### 3.1 Fabrication of CWO and ZnSe(Te) scintillation Detector Array

The scintillation detector made in this work consisted of a photodiode and either  $CdWO_4$  (CWO) or ZnSe(Te) scintillator. The CWO and ZnSe(Te) were obtained from ISC(Institute for Single Crystals), Ukraine. Fig.1 shows 16-channel crystal array fabricated in this work. The size of one crystal element is 1.7mm(W) x 3.0mm (L) x 10.0mm (D). The spacing between crystal elements is 0.3mm and the detector pitch is 2.0 mm. To prevent scattered x-ray and light from entering a neighboring detector element, the spacer of Ta, doped with  $TiO_2$ , is inserted between the scintillator elements.

### 3.2 Measurement of photo-current

The photo-current generated in one channel was measured with a picoammeter during exposing one scintillator element of 16-channel detector array to eight different x-ray beams and Cs-137. The beams are standardized narrow-energy spectra (ISO 60, 80, 100, 120, 150, 200, 250, 300) as shown Fig. 2 ; Their corresponding average energies are 48, 65, 83,101, 118, 163, 208, and 250 keV. The iron collimator with 1.7mm wide slit and 50mm depth was used to irradiate x-ray quant to only one scintillator element (1.7mm x 3.0mm x 10.mm) in 16-channel scintillator array.

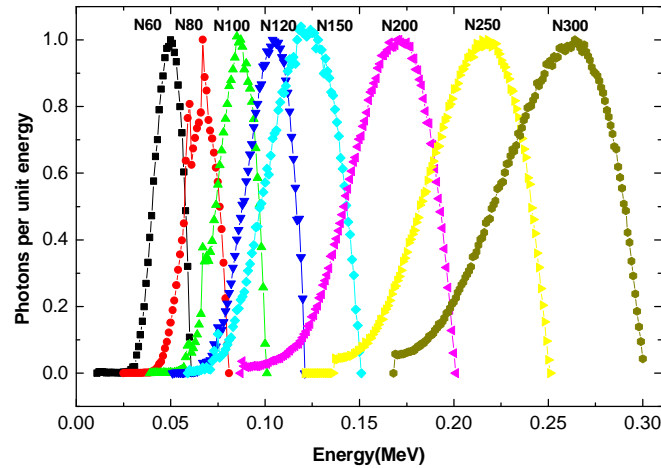


Fig. 3 Normalized spectra of eight x-ray beams

### 3.3 X-ray Inspection Test

To compare the image quality depending on the employed scintillator, inspection test of a real-size container was performed using two types of scintillator detector arrays. Full image of about 4 m high container was obtained with CWO arrays and partial image of the container was obtained with ZnSe(Te) array because we have had prepared only several ZnSe(Te) detector arrays (8x16=128channels) . The x-ray tube [10] used in the system produces a 120 Hz x-ray with maximum of 340 kVp. FWHM and an electric current of one pulse are 30  $\mu$ sec and 0.7 A, respectively. Container moved with 8.0cm/sec during test.

## 4. Results and Discussion

### 4.1 Photo-current

The photo-currents calculated using Eq. (3) and measured were plotted in Fig. 4. The measured value corresponded to the current from scintillator of size of 1.7mm(W) x 3.0mm(L) x 10.0mm(D). In contrast with the measured current, the calculated currents also included two different depth (10mm and 20mm) in addition to 10.0 mm depth in Fig. 1. Fig. 4 reveals that signal from ZnSe(Te) is wholly higher than that from CWO although ZnSe(Te) has low quantum detection efficiency in the high energy region. The

current increases with x-ray tube voltage and decreases beyond 120kVp x-ray. This is mainly due to two competing effects of the x-ray quantum detection efficiency and the amount of energy deposited by x-ray. That is, the x-ray quantum detection efficiency reduces with x-ray tube voltage, while the deposited energy increases with x-ray tube voltage.

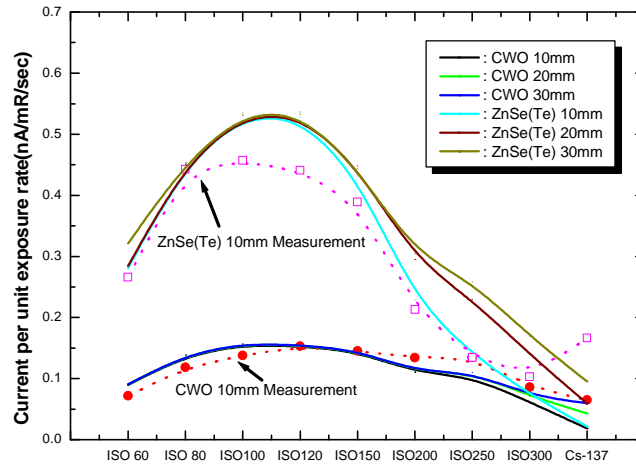


Fig. 4 Comparison of photo current(nA/mR/sec) of CWO and ZnSe(Te)

From Fig. 4, difference between the measured and calculated current was about within  $\pm 20\%$  except for at 662 keV. In case of both CWO and ZnSe(Te), large difference at 662 keV seems to arise from photons scattered by the collimator and experimental jig. The scattered photons in low energy have few effects on the current signal of a photodiode, while the scattered photo in high energy like 662 keV seemed not to be neglected.

#### 4.2 DQE

Fig.5 shows the results obtained using Eq. (4) for both CWO and ZnSe(Te) DQE at various x-ray energies. CWO in Fig. 5 was found to exhibit better DQE than ZnSe(Te). For 10 mm depth, two type of scintillators were found to have almost same DQE at low energy region but their difference in DQE becomes large with incident x-ray energy. On the other hand, as the depth of scintillator increases, it is appeared that difference of DQEs of CWO and ZnSe(Te) decreased even at high energy region. The average energy of ISO150 is about 118 keV, which is almost identical with that ( $340/3=113$  keV) of 340 kVp x-ray used in performing inspection test of a real container. Fig. 5 also exhibits that CWO and ZnSe(Te) have similar DQE of 0.85 under ISO150 x-ray irradiation. This means that there may be no difference in image quality obtained using two scintillation detector array.

#### 4.3 Comparison of digital radiographic image of CWO and ZnSe(Te)

To evaluate the effects of CWO and ZnSe(Te) on image performance, digital radiographic image of a motorcycle in a real container was obtained using CWO linear detector array(2048 channels) and

ZnSe(Te) linear array(128 channels). CWO linear detector arrays could cover full size of about 4.0m high container, but ZnSe(Te) could cover some portion of 4m container. Full image of CWO was compared with partial image of ZnSe(Te) in Fig. 6. From Fig.6, it was appeared that there was no difference in image quality of CWO and ZnSe(Te) obtained under 340 kVp x-ray. This agreed with the results estimated by DQE.

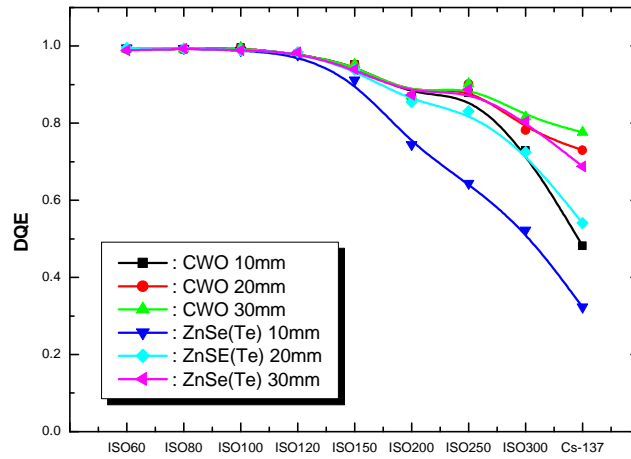


Fig.5 DQE of CWO and ZnSe(Te)

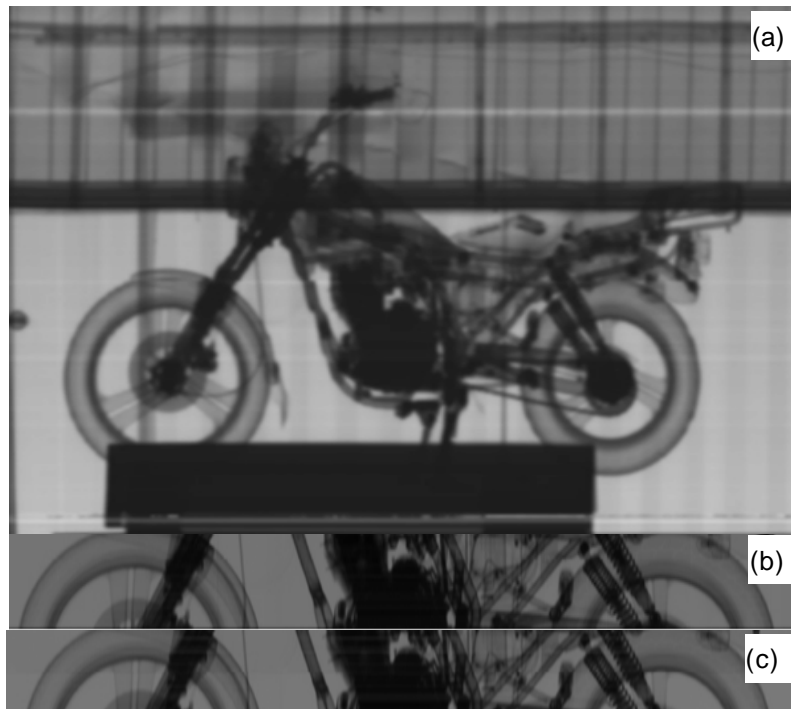


Fig. 6 (a) Full image of a motorcycle in container obtained by CWO linear arrays, (b) Partial image obtained by CWO detector, (c) Partial image obtained by ZnSe(Te) detector.

## 5. Conclusion

This work showed that there was visually no difference in quality of radiographic images obtained using CWO and ZnSe(Te) scintillator detector under 340 kVp x-ray. From the results of this paper, we can conclude that ZnSe(Te) can be used for detecting high energy radiation. However, in analyzing the effects of crystal's type on digital image, this paper hasn't dealt with electric circuit noise. Crystal length coupled to a photodiode is directly related to the detector capacitance, which gives rise to a detector noise. Thus, special attention should be paid to determining the crystal size of a scintillator detector.

## 6. References

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