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Optical analysis of a $CdWO_4$-photodiode linear array for x-ray container inspection systems

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1. Introduction

To screen precisely and rapidly the abnormalities in ocean-going cargo containers has been an important issue for homeland security and contraband control. Radiographic imaging with an x-ray beam produced by a linear accelerator operated at up to 9 megavoltage is a well-known technique. The commercial detector systems employ the scintillator-coupled photodiode array configuration, however, their dimensions are different to one another even for the same energy of x-ray beam. Moreover, the detailed design philosophy of detector systems is rarely found in literature.

In a previous study [1], we studied the dimension of a $CdWO_4$ (CWO) scintillator, which is typically employed for cargo-container inspection systems, by investigating x-ray interaction-induced signal-to-noise performance.

In this study, we investigate the optical efficiency of the CWO-coupled photodiodes in a linear array form for various optical design parameters using an Monte Carlo (MC) simulation model, so called DETECT2000 [2]. Mismatch of optical parameters, such as refractive index, between the scintillator and the photodiode can cause loss of optical signal or its spatial spreading (or "cross-talk"). The main purpose of this study is to investigate the effects of optical glue, which is used to couple the scintillator and photodiode layers, and the reflector surrounding the scintillator on the signal and cross-talk.

2. Methods

The MC geometry describing the CWO-coupled photodiode linear array is shown in Fig. 1. The information of MC simulation, refractive index, reflection coefficient (RC) and size are summarized in table. 1. The x-ray photons are incident along the *z* direction while a photodiode is faced at the *y-z* plane. All the surfaces are regarded as "ground" optical surfaces, which adopt the Fresnel reflection and the Snell's law of refraction of which angle follows a Lambertian distribution. Except the detection plane, five boundary surfaces surrounding the MC geometry are considered as the complete absorption surfaces, which imply the optical photons meet those surfaces never return back. Unless otherwise stated each simulation includes 10^7 histories (N_{gen}) at the center of the zeroth channel CWO

Layer		Refractive index	RC	Size (mm)	
Scintillator ($CdWO_4$)		2.3	-	$a_x = 4$ $a_y = 4$ $a_z = 30$	
Reflector	Al	2.5	0.78	$t_{Al} = 0.1$	
	TiO_2	2.5	0.96	$t_{Ti} = 0.1$	
	Teflon	1.4	0.99	$t_{tef} = 0.1$	
Optical glue		1.5 (1.0-4.5)	-	$t_{opt} = 0.1$ (0.01-1)	p_y = 4.6 p_z = 30.6
Passivation layer (Si_3N_4)		2.0 (1.0-4.5)	-	$t_{pass} = 10^{-4}$ (10^{-5}-10^{-3})	
Silicon layer		4.4	-	$t_{Si} = 10^{-3}$	

Table 1. The information of MC simulation.

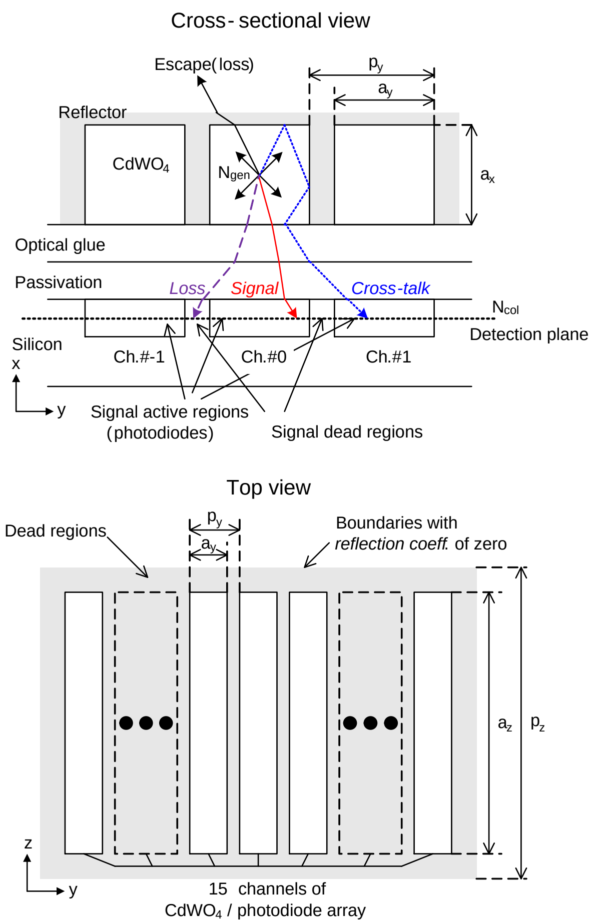

Figure 1. Detector geometry designed for Monte Carlo simulations. The $CdWO_4$/photodiode linear array consists of 15 channels. At boundaries of the detector system the complete absorption conditions are assigned so that optical photons at the boundaries never return back. The pitch along the y direction is p_y while the active aperture size is ay. Since some of optical photons arriving at the interface between the passivation and silicon layers can be reflected backward, the virtual detection plane is placed below the interface. Three cases of N_{col} quanta, such as signal, cross-talk, and loss, at the detection plane are illustrated.

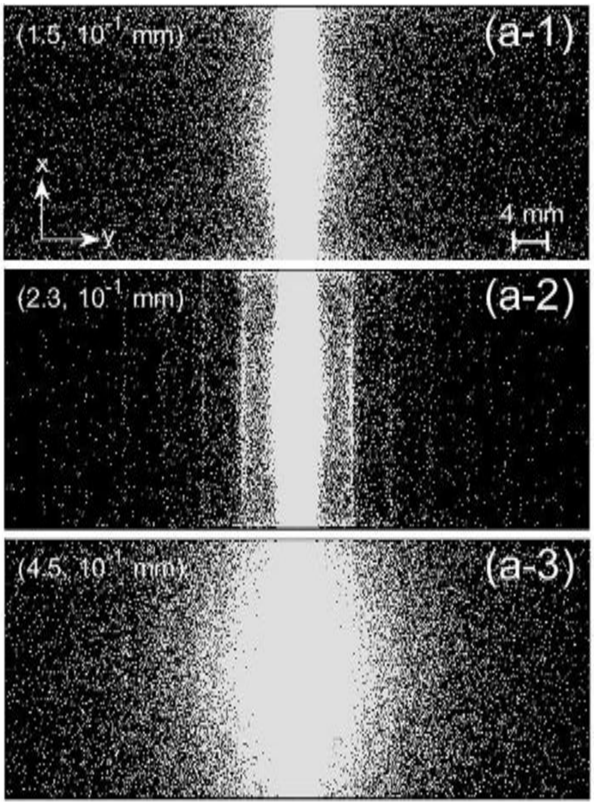

Figure 2. Quantum image with the varying refractive index of optical glue layer at Al reflector

scintillator and they are randomly sampled through isotropic directions.

For N_{gen} histories, each MC simulation outputs a list of random coordinates vector, $\mathbf{r}_i = (y, z)_i^T$, at the detection plane, and each vector implies a single optical quantum survived from the optical-transport simulation for given detector geometries and optical properties of components. The total sum of vectors implies the number of optical quanta collected, N_{col}, which is also a random variable per each MC simulation. Then, a spatial distribution of N_{col} quanta can be described as

$$q(y, z) = q(\mathbf{r}) = \sum_{i=1}^{N_{\text{col}}} \delta(\mathbf{r} - \mathbf{r}_i) \qquad (1)$$

with the constraint of

$$\int_z \int_y q(y, z)\, \mathrm{d}z\mathrm{d}y = N_{\text{col}}, \qquad (2)$$

The $q(y, z)$ is referred to as a "quantum image".

The "light collection efficiency (LCE)" is defined as the ratio between the number of optical quanta collected at the virtual detection plane and the number of optical quanta generated within a scintillator [3]:

$$\kappa = \frac{N_{\text{col}}}{N_{\text{gen}}}. \qquad (3)$$

3. Preliminary result

Figure 2 shows the quantum image with the Al foil as a reflector. Each quantum image was obtained at varying refractive indices (1.5, 2.3, 4.5) of optical glue layer while the thickness of the optical glue layer was constant (10^{-1} mm). The refractive indices, 1.5, 2.3 and 4.5 are the value of optical glue, CWO and silicon, respectively. As shown in Fig 2, the quantum image is the sharpest at n_{opt}=2.3 and the most blurred at n_{opt}=4.5. The smaller the difference between the refractive indices of two adjacent layers, CWO and optical glue layer, is, the less the optical spreading is. Fig 3 shows the LCE according to the type of reflector material and various thicknesses of the optical glue layer. The LCE is the best when the teflon is used as a reflector and when the thickness of optical glue is small. The LCE curves show the peaks at n_{opt}=2.0 and 2.3.

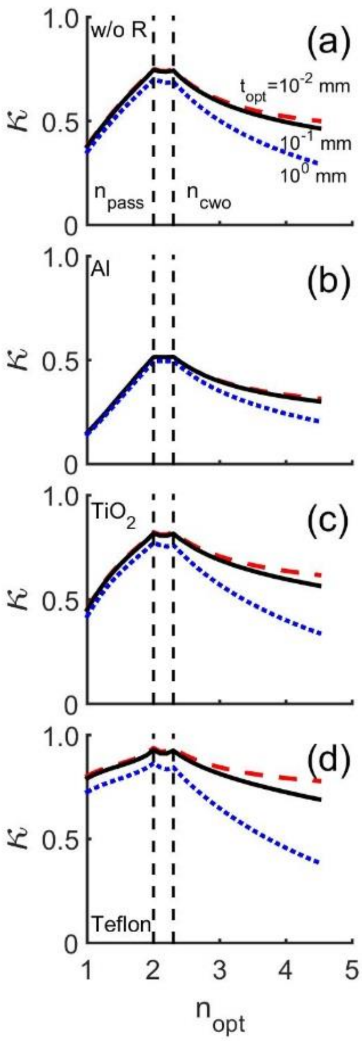

Figure 3. LCE results with the varying thickness and refractive index of optical glue layer at three reflector material, Al, TiO_2 and teflon

Similar to quantum images, the optical performance becomes better as the refractive index difference between the optical glue and adjacent layer is small.

4. Further study

We will calculate the LCE for various thicknesses and refractive indexes of passivation layer. In addition, crosstalk and loss of optical photons that affect the optical performance will be investigated. Finally we will suggest the optimal parameter of CWO-photodiode detector using the figure of merit concept.

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