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Effect of the phosphor screen optics on the Swank noise performance in indirect-conversion x-ray imaging detectors

C.H. Lim, S. Kam, J.C. Han, S. Yun, H. Youn, M.-K. Moon, H. Jeon and H.K. Kim

Neutron Science Division, Korea Atomic Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 305-353, Korea
School of Mechanical Engineering, Pusan National University, Busandaehak-ro 63, Geumjeong-gu, Busan 609-735, Korea
Department of Radiation Oncology, Pusan National University Yangsan Hospital, Mulgeum-eup, Yangsan-si, Gyeongnam 626-770, Korea
Center for Advanced Medical Engineering Research, Pusan National University, Busandaehak-ro 63, Geumjeong-gu, Busan 609-735, Korea

E-mail: hokyung@pusan.ac.kr

1Corresponding author.
ABSTRACT: The optics between the scintillators and photodiode arrays of indirect-conversion x-ray imaging systems requires careful design because it can be a cause of secondary quantum sink, which reduces the detective quantum efficiency at high spatial frequencies. The aim of this study was the investigation of the effect of the optical properties of granular phosphor screens — including optical coupling materials and passivation layers in photodiode arrays — on the imaging performance of indirect-conversion x-ray imaging detectors using the Monte Carlo technique. In the Monte Carlo simulations, various design parameters were considered, such as the refractive index of the optical coupler and the passivation layer, the reflection coefficient at the screen backing, and the thickness of the optical coupler. We developed a model that describes the optical pulse-height distributions based on the depth-dependent collection efficiency obtained from the simulations. We used the model to calculate the optical Swank noise. A loss in the number of collected optical photons was inevitable owing to the introduction of intermediate optics and mismatches in the optical design parameters. However, the collection efficiency marginally affected the optical Swank factor performance. The results and methodology of this study will facilitate better designs and optimization of indirect-conversion x-ray detectors.

KEYWORDS: Detector design and construction technologies and materials; Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc); X-ray detectors; X-ray radiography and digital radiography (DR)
1 Introduction

Whereas the direct-conversion method uses photoconductors for converting x-rays into electric signals, the indirect-conversion method uses scintillators for converting the x-rays into optical photons. The optical photons are subsequently converted into electric signals using photo-sensors, which are generally photodiode pixel arrays [1, 2]. Compared to direct-conversion technology, indirect conversion affords greater flexibility in the design of the x-ray imaging detectors because the scintillator can be optimized independently of the photodiode array, and vice versa [3]. The intensifying screen based on Gd$_2$O$_2$S:Tb phosphors is still widely used as a scintillator owing to its well-known technology and ease of handling in size, thickness and flexibility, and low cost [4].

However, the indirect-conversion detector is usually vulnerable to secondary quantum sink, which limits the pixel signal-to-noise ratio to less than the square root of the number of quanta per pixel [5, 6]. This reduces the detective quantum efficiency (DQE). The main cause of secondary quantum sink is the loss of optical photons, which are generated within the scintillator, due to their incomplete escape from the scintillator, as well as mismatch between the optical photon spectra and the spectral quantum efficiency of the photodiode array [2, 7]. This phenomenon can be described by the quantity “optical-photon collection efficiency”.

The coupling of a sheet of scintillator and a photodiode array can be achieved by various approaches, namely simple mechanical compression, gluing with optical grease or fluid, the use of fiber optics, or direct coating of scintillation layers on the photodiode arrays. The efficiency of the coupling optics between the scintillator and the photodiode array is evidently too important to be neglected [8, 9]. Nevertheless, the effect of optical coupling has frequently been ignored in empirical and theoretical investigations of the imaging performances of indirect-conversion detectors [10–13]. Moreover, attention has not sufficiently been paid to the evaluation of the performance degradation of an indirect-conversion detector due to the coupling optics.

In a previous study [9], we reported that the use of an optical coupler having mismatched refractive indices with the scintillator and photodiode array can cause significant loss in the detector signal, which may reduce the DQE performance. Statistical variations in the number of optical...
photons collected from the photodiode array can further degrade the DQE performance, and this
effect can be quantified by the optical Swank factor [14, 15]. In this study, we used Monte Carlo
techniques to investigate the degradation of the statistical noise performance caused by the intro-
duction of optics to indirect-conversion detector configurations. Neglecting the absorption noise
due to x-ray interactions in the scintillators [16], we estimated the Swank noise produced by the
transportation of the optical photons for various design parameters of the coupling optics. These
include the refractive index and thickness of the optical coupler and the reflection coefficient at the
phosphor screen backing.

2 Theoretical background

For an x-ray photon with energy $E$ impinging on the phosphor screen, the probability that it would
survive to a depth $z$ without any interaction and subsequently interact through an additional depth
$dz$, where its energy is converted to $g$ optical photons, can be described by $e^{-\mu_{tot}(E)z} \times \mu_{pe}(E) \times g(E) \times dz$ [17]. Here $\mu_{tot}$ and $\mu_{pe}$ denote the total linear attenuation coefficient and photoelectric
attenuation coefficient, respectively. We assume that only photoelectric interactions result in energy
absorption events and the entire x-ray photon energy is deposited. In addition, we assume that the
energy of the generated optical photons is monochromatic; hence, $g(E) = E/w$, where $w$ is the
energy required to liberate one optical photon in the phosphor screen. If the depth-dependent
collection efficiency $\eta(z)$ at the photodiode for the optical photons produced at a depth $z$ in the
phosphor screen is known, the mean number of optical photons collected in the photodiode can be
calculated such that

$$N(z;E)dz = s(E)e^{-\mu_{tot}(E)z} \mu_{pe}(E)g(E)\eta(z)dz,$$  \hspace{1cm} (2.1)

where $s(E)$ denotes the number of x-ray photons per keV. We note that $\eta(z)$ describes the survival
probability of the optical photons through the phosphor screen and the underlying optics.

Equation (2.1) implies that there will be variations in the number of collected optical photons
even for the interaction (i.e., absorption) of the same energy in the phosphor. This is because of the
dependency of $\eta$ on the interaction depth and the transport properties of the optical photons.
Because all the processes are stochastic, including the generation and transportation of the optical
photon, further variations in the distributions of the collected optical photons are expected. To take
into consideration the stochastic nature of secondary quanta generation and collection, we simply
assumed that the gain of the system is Poisson distributed about $N(z;E)dz$ [18]. Hence, we
obtained a composite optical pulse-height distribution (OPD) by combining each Poisson distribution
with $N(z;E)dz$ at a discrete $z$ with a step of $dz$ over the screen thickness of $t_{scn}$. Therefore,
the zeroth moment of OPD, $M_0(E)$, should represent $N(E)dz = \int_{0}^{t_{scn}} N(z;E)dz$. We calculated
eq (2.1) with respect to $z$ as well as its numerical integration over $t_{scn}$, and compared the results
with the zeroth moments of OPDs. We found that the differences were negligible. Therefore, we
calculated the optical Swank factor using

$$I_{opt}(E) = \frac{M_1^2(E)}{M_0(E)M_2(E)},$$ \hspace{1cm} (2.2)

where $M_1(E)$ and $M_2(E)$ describes the first and second moments of OPD, respectively.
3 Methods

In order to estimate $\eta(z)$ for various design parameters of the detector optics, we performed the optical photon transport simulations by using the DETECT2000 (Laval University, Quebec, Canada) Monte Carlo code [19]. We then numerically calculated eq. (2.1) with increments of $dE = 1$ keV and $dz = 0.005$ mm.

For the optical Monte Carlo simulations, we modeled the indirect-conversion detector configuration as a layered structure, which mimics the phosphor screen, the optical coupler, and the photodiode layer, with infinite lateral dimensions. Figure 1 depicts the detector model for the Monte Carlo simulation. The assumptions and rationales behind the detector model, as well as the optical parameters which determine the behavior of optical photon transports, can be found in reference [9]. Briefly, the phosphor screen was regarded as a weak absorbing medium in which scattering is due to refraction at the boundaries between the phosphor grains and polyurethane polymer binders. The average refractive index $n_{\text{scn}}$ for two compositions was taken for the optical photon transport simulations. Variable reflection coefficients $R_{\text{back}}$ were introduced at the top surface to account for the backplane reflector in typical phosphor screen designs. The optical coupler was defined as a thin layer with a wide range of refractive index $n_{\text{opt}}$ and thickness $t_{\text{opt}}$. Similarly, the photodiode for collecting the optical photons which escape from the phosphor screen was modeled as a thin oxide passivation layer with a wide range of refractive index $n_{\text{ox}}$. Because the actual photo-sensing silicon layer is a strong absorber of optical photons, we defined the bottom surface of the passivation layer as the detection plane.

Table 1 summarizes the physical and optical parameters used in this study for the optical Monte Carlo simulations.

It should be noted that the collection of optical photons at the bottom surface of the phosphor screen overestimates the optical-photon collection efficiency as some optical photons that hit the bottom surface never escape through the surface. Instead they return back by refraction or reflection. It is true that the consideration of further optical layers, even an air gap for example, between the phosphor screen and the photodiode array can provide a reasonable collection efficiency. Ac-
Table 1. Physical and optical parameters used for the optical Monte Carlo simulations. Without any indication, the values in parentheses were used for the simulations as reference values. The term “mfp” designates the mean free path.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Phosphor</th>
<th>Optical coupler</th>
<th>Passivation layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption mfp $\mu_{\text{abs}}$ (mm)</td>
<td>10</td>
<td>—</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Scattering mfp $\mu_{\text{scat}}$ (mm)</td>
<td>$2 \times 10^{-2}$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Refractive index</td>
<td>2.4</td>
<td>1.0–3.0 (1.5)</td>
<td>1.2–3.0 (1.46)</td>
</tr>
<tr>
<td>Reflection at backing</td>
<td>0.0–1.0</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Thickness ($\mu$m)</td>
<td>85</td>
<td>1–50 (10)</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 2. Estimated collection efficiencies for various optical design parameters: (a) $\eta(z = 0.0425 \text{ mm})$ as a function of $n_{\text{opt}}$, (b) $\eta(z)$ with respect to various $t_{\text{opt}}$, (c) $\eta(z)$ with respect to various $n_{\text{ox}}$, and (d) $\eta(z)$ with respect to various $R_{\text{back}}$.

According to a previous study [9], the introduction of an air gap reduced the collection efficiency by about 40% compared to the collection at the bottom surface of the phosphor screen, whereas the coupling reduced the efficiency by about 20%.
Figure 3. Calculated optical Swank noise factors for various optical design parameters: (a) \( I_{\text{opt}}(E) \) with respect to various \( n_{\text{opt}} \), (b) \( I_{\text{opt}}(E) \) with respect to various \( t_{\text{opt}} \), (c) \( I_{\text{opt}}(E) \) with respect to various \( n_{\text{ox}} \), and (d) \( I_{\text{opt}}(E) \) with respect to various \( R_{\text{back}} \).

4 Results

Figure 2 summarizes the depth-dependent collection efficiency for various optical design parameters. Figure 2(a) shows \( \eta \) as a function of \( n_{\text{opt}} \) when the optical photons are generated in the middle of the phosphor screen (i.e., \( z = 0.0425 \) mm). We note that \( \eta \) shows a maximum value of 0.58 when \( n_{\text{opt}} = n_{\text{scn}} \) or \( n_{\text{ox}} \). This value was also achieved when the phosphor screen was directly coupled onto the photodiode layer (i.e., the oxide layer) without the optical coupler. It is noted that \( \eta \) was 0.76 without any optical layers. The effect of \( t_{\text{opt}} \) on \( \eta \) is negligible as shown in figure 2(b). The effect of \( n_{\text{ox}} \) on \( \eta \) shows a similar tendency with \( n_{\text{opt}} \) as shown in figure 2(c). In other words, the maximum \( \eta \) is achieved when \( n_{\text{ox}} = n_{\text{opt}} \). \( \eta \) is enhanced with increasing \( R_{\text{back}} \) as shown in figure 2(d). We note that, however, the increase in \( t_{\text{opt}} \) and \( R_{\text{back}} \) enlarges the optical photon spreading in space; hence degrading the spatial resolution property [9].

The tendency of the effects of various optical design parameters on the depth-dependent collection efficiency, as shown in figure 2, is well reflected in the statistical noise performance. As shown in figures 3(a) and (b), the mismatch of \( n_{\text{opt}} \) with \( n_{\text{scn}} \) or \( n_{\text{ox}} \) degrades the Swank factor \( I_{\text{opt}} \), whereas \( t_{\text{opt}} \) does not. The effect of the mismatch of \( n_{\text{ox}} \) with \( n_{\text{opt}} \) on \( I_{\text{opt}} \) is shown figure 3(c) and shows similar trend to figure 3(a). For a given x-ray photon energy, \( I_{\text{opt}} \) is gradually degraded as the mismatch in refractive indices between optical layers increases. This observation holds for nearly the entire energy range investigated in this study (1–100 keV). The effect of \( R_{\text{back}} \) on \( I_{\text{opt}} \) is
shown in figure 3(d), and is clearly the most significant parameter. Regardless of any mismatches in optical properties, $I_{\text{opt}}$ generally decreased with increasing x-ray photon energy, and showed a minimum value of $\sim 0.35$ around 10 keV. It then rapidly increased to greater than 0.93, and maintained this value for the energy range of 30–100 keV (Note that this observation is not shown in figure 3 as the y-axis scale was selected to range from 0.96 to 1. This produces clearer views of the small variations in $I_{\text{opt}}$ due to the design parameters). At an x-ray photon energy of $\sim 50$ keV, which corresponds to the $K$-edge energy of Gd, $I_{\text{opt}}$ shows lower values. It should be noted that $I_{\text{opt}}$ is greater than 0.93 for the energies relevant to diagnostic radiology (i.e., 30–100 keV) and the degradation due to any mismatches in optical design parameters is negligible.

5 Discussion and conclusion

We observed that a change in the thickness of the optical coupler did not affect the collection efficiency. The reason can be explained by that we tallied (or scored) the optical photons, which escape from the phosphor screen, at the virtual detection plane which covers the whole area of the phosphor screen. Therefore, the optical Swank factor estimated in this study, implies the value obtained for an “infinitely-sized” pixel element or at the zero-spatial frequency in the Fourier domain. This analysis is true only for a system that has a shift-invariant response to an input signal and has a stationary response in noise. Strictly speaking, most x-ray imaging detectors consisting of discrete pixel arrays violate these assumptions; however we assume that our system follows these assumptions [20, 21].

Thallium-doped cesium iodide (CsI:Tl) scintillators have received much attention because of their advantages compared to the Gd$_2$O$_2$S:Tb phosphor investigated in this study [2]. CsI:Tl can be directly evaporated onto a readout photodiode array. This direct deposition avoids the use of the optical coupler, so that further losses or optical photon spreading which occur through the optical coupler are eliminated. The CsI:Tl scintillator is typically formed in columnar or needle-like structures, which restrict the sideways diffusion of optical photons; hence allowing high spatial resolution. In addition, the CsI:Tl scintillator gives the highest light output of any known scintillator. The imaging performance of the CsI:Tl scintillator has been investigated empirically [10] and theoretically [12, 22, 23]. However, these investigations neglected the effects of the intermediate optics. We will refine the imaging performance of the CsI:Tl scintillator by accounting for the effects of intermediate optics and compare the results with those obtained in this study in further reports.

Although the collection efficiency determined the optical Swank noise performance, its impact was negligible. This observation agrees with a previous study by Zhao et al. [10], except that they assumed the optical Swank factor was energy-independent. The overall Swank noise can be given by the Swank noise due to x-ray interactions, times that due to optical interactions [14, 16, 24], and we may conclude that the x-ray Swank factor dominates the overall Swank factor for the diagnostic x-ray photon energies, except for the energies around the $K$-edges.

The reduction in optical photons collected at the photodiode is inevitable when additional intermediate layers of optics are introduced between the phosphor screen and the readout photodiode array. This loss can be minimized by proper selection of the refractive index, which should be the same as that of the phosphor, or that of the top passivation layer of the photodiode, of the intermediate optics. Although the collection efficiency determines the Swank noise performance, its
impact is negligible. Rather, the reduction of detector sensitivity due to the use of intermediate optics is important. We believe that this study can provide the guidelines and insights necessary for an improved design or optimization of indirect-conversion x-ray detectors employing intermediate optics.

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