Modeling of the Performance of Scintillator Based X-ray Detectors

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Abstract

Over the last years several prototypes of detectors for digital radiography have been developed. One of the several approaches is based on scintillating crystals. Generally, these prototypes have been developed in a purely experimental basis, with a lack of mathematical and physical support. In the present work we have performed a systematic study of the various interactions and processes essential to the construction of x-ray sensors based in scintillator crystals. These results are an important help in the simulation of the performance of the whole sensor before its construction, which allows a better selection of the materials, the dimensions, shape and fabrication process.

Keywords

X-ray detector, scintillator, modeling.

INTRODUCTION

Several x-ray detectors for digital radiography are based on the utilization of scintillating crystals that convert the x-rays into visible light, which is then read by photodetectors[1, 2, 3]. Despite great improvements in the technological aspects and performance of these kind of detectors have been achieved, most of the approaches have been rather empirical, lacking a mathematical and physical support. In the present work we have separated the whole process into its main constitutive steps. For each of these steps a mathematical model has been developed that deals with the main parameters that are essential for the detection process, can be simulated and are eligible in the fabrication process. This will allow the improvement of the fabrication of this types of detectors.

MODEL

X-ray detectors based in scintillating crystals first convert the x-rays into visible light which in turn is converted into an electrical signal by a photodetector. Figure 1 shows a cross-section of a scintillator based x-ray detector with three channels or pixels. The scintillating crystal (CsI:Tl in figure 1) must be coated by a reflective layer (Aluminum in figure 1) allowing the pass of the x-rays to the crystal and not allowing the escape of the generated visible light to the outside, driving it to the photodetector (n^+/p-substrate junction in figure 1). The most critical steps of this process, that can affect the efficiency of the detector are:

- Transmission of the x-rays through the reflective layer.

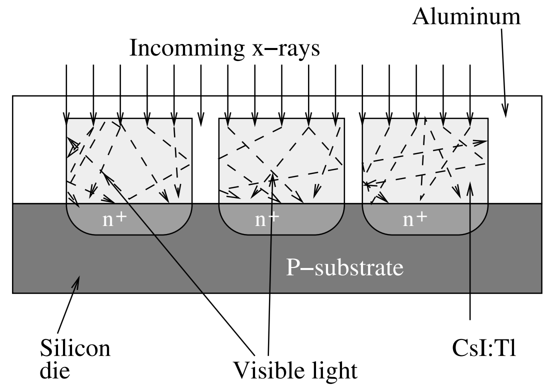

Figure 1. Typical structure of a x-ray detector based on scintillating crystals.

- Absorption of the x-rays by the scintillating crystal and their conversion into visible light.
- Reflection of the visible light by the reflective layer.
- Transmission of the visible light to the photodetector.

In the following sections, each of these steps will be addressed independently.

Transmission of the x-rays through the reflective layer

Similar to the visible light, when a beam of x-ray photons penetrates into the matter it is absorbed according to the Lambert-Beer law:

$$I = I_o e^{(-\mu/\rho)\rho x}, \quad (1)$$

where I_o is the intensity of the incident beam, I is its intensity at the distance x from the surface and ρ is the density of the material. The quantity μ/ρ of equation 1 is the mass absorption coefficient (coefficient of linear absorption for unit of density). The mass absorption coefficient μ/ρ is related to the cross-sections of the x-ray interaction processes with matter in accordance to:

$$\mu/\rho = \frac{N_{AV}}{A} \sum_i \sigma_i, \quad (2)$$

where σ_i is the atomic cross-section of the interaction process i (photoelectric, Compton, etc), A is the relative atomic mass of the atom with which the interaction occurs and N_{AV} is the number of Avogadro. The mass absorption coefficient (μ/ρ) depends on the energy of the incident x-ray photons. For energies from $1\ keV$ to $100\ keV$, the most important

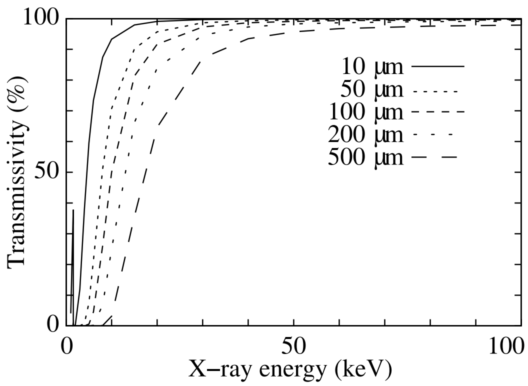

Figure 2. Transmission of x-rays by aluminum sheets of different thicknesses.

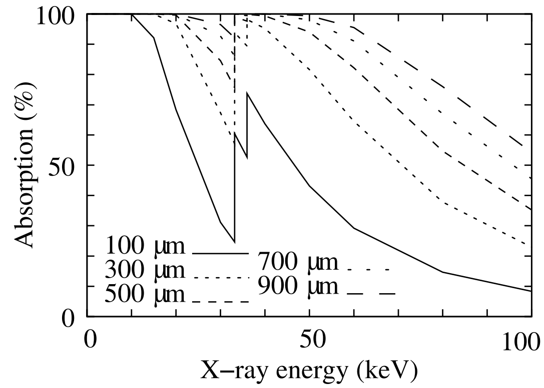

Figure 3. Absorption of x-rays by CsI:Tl crystals of different thicknesses.

interaction processes are the photoelectric absorption and the Compton scattering [7]. The values of σ_i can either be calculated [4] or can be found in tables like the one published by Hubbell [5].

The transmission of the x-rays (I in equation 1) through an aluminum reflective layer was simulated for thicknesses from 10 μm to 500 μm. The result is presented in figure 2. As can be observed a general decrease of the transmissivity occurs with increasing aluminum thickness.

In the case of a composite reflective layer (eg. Al_2O_3), the method described in the next section should be applied.

Absorption of x-rays by the scintillating crystal and their conversion into visible light

The absorption of x-rays by a scintillating crystal depends on the same laws described in the previous subsection. Usually, the scintillating crystals are composites or mixtures of elements. The mass attenuation coefficient of a composite or mixture can be calculated from the individual coefficients of each of its elements:

$$\left(\frac{\mu}{\rho}\right)_c = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i, \tag{3}$$

where the factors w_i represent the fraction of mass of the element i present in the composite or mixture. For example, in the CsI:Tl scintillator, the iodine with atomic number 53 and relative atomic mass of 126.9 contributes with a fraction of mass of 48.8%, while the cesium, with atomic number 55 and relative atomic mass of 132.9, contributes with a fraction of mass of 51.2%. The concentration of thallium in the CsI:Tl scintillator is about 0.02% to 0.03% [6] and its contribute for the x-rays absorption is negligible.

Figure 3 shows the results from simulations of the x-rays absorbed by a CsI:Tl crystal with thicknesses from 100 μm to 900 μm. A general increase of the absorption with increasing scintillator thickness is obtained.

A scintillator converts the absorbed energy into visible light. In the case of the CsI:Tl, it produces about 65900 visible photons for each 1 keV of absorbed energy, at room temperature [8]. So, the total amount of produced light is obtained by the product of four factors: the absorption percentage (shown in figure 3), the number of incident x-ray photons, 65900 photons$/keV$ and the energy of each x-ray photon. With this result, the first step of the x-ray detector working principle (conversion of x-rays into visible light) is completely characterized.

Reflection of the visible light by the reflective layer

The light that reaches the reflector can show two independent polarizations. The light incident in the reflector surface, forming an angle θ with its normal, can have either the electric field vector or the magnetic field vector parallel to the plane of incidence. In the first case, the polarization is called p and in the second, the polarization is called s. In a general way, the electric field vector forms an angle with the plane of incidence. In this in case, it can be decomposed in two components, one of polarization p and other of polarization s

The normal refractive index n is equal to H/E, where H and E are the amplitudes of the magnetic and electric fields, respectively. In a similar way, a generalized refractive index u can be defined for each of the polarizations, such that:

$$\begin{aligned} u_p &= H/(E\cos\theta) = n/\cos\theta \\ u_s &= (H\cos\theta)/E = n\cos\theta. \end{aligned} \tag{4}$$

Notice that the directions of the electromagnetic fields of the light produced by a scintillator is random and can be decomposed in the two polarizations with equal probability. The reflectivity of the interface between the scintillator and the reflector is calculated as:

$$R = \left|\frac{u_{sc} - u_r}{u_{sc} + u_r}\right|^2, \tag{5}$$

where u_{sc} and u_r are the generalized refractive indexes of the scintillator and reflector respectively. Notice that in the case of materials absorbing light, the normal refractive index (n of equation 4) must be replaced by $n - jk$, where k is the extinction coefficient of the material and j is the complex operator ($\sqrt{-1}$).

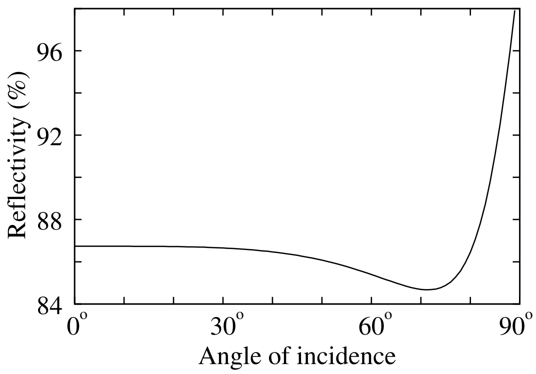

Figure 4. Dependence of the reflectivity of the visible light with the angle of incidence by the reflector (aluminum) - scintillator (CsI:Tl) interface.

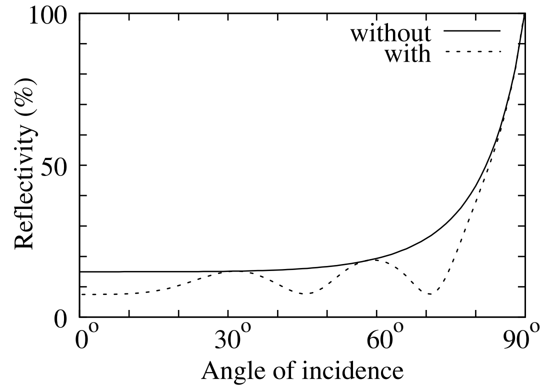

Figure 5. Dependence of the reflectivity of the visible light with the angle of incidence in the silicon-scintillator (CsI:Tl) interface, without and with a silicon nitride film between them.

In the case of the CsI:Tl scintillator, the output light has a wavelength of $560\ nm$ [8]. The dependence of the reflection on the angle of incidence of the light in the reflector is shown in figure 4. The reflectivity is almost constant up to an angle of incidence of sensibly 80^o. For higher angles the reflectivity heavily increases.

Transmission of the visible light to the photodetector

Due to the difference in the refractive indexes of the scintillator and the photodetector, some of the produced light is reflected at the photodetector surface, instead of being absorbed. To minimize this phenomenon an anti-reflective filter becomes necessary. The simplest way of obtaining an anti-reflective coating consists in the application of a thin-film on the surface of the photodetector. The parameters of the film are obtained from the equations 6:

$$\begin{aligned} E_{sc}^{+} &= \frac{1}{2u_{sc}u_{tf}}\left[(u_{sc}u_{tf}+u_{tf}u_{ph})\cos g_{tf}+\right. \\ &+ \left. j(u_{sc}u_{ph}+u_{tf}^2)\sin g_{tf}\right]E_{ph}^{+} \\ E_{sc}^{-} &= \frac{1}{2u_{sc}u_{tf}}\left[(u_{sc}u_{tf}-u_{tf}u_{ph})\cos g_{tf}+\right. \\ &+ \left. j(u_{sc}u_{ph}-u_{tf}^2)\sin g_{tf}\right]E_{ph}^{+}, \end{aligned} \quad (6)$$

where E_{sc}^{+} is the value of the electric field vector of the incident light, E_{sc}^{-} is the value of the electric field vector of the reflected light and E_{ph}^{+} is the value of the electric field vector of the light that is absorbed by the photodetector. The quantities u_{sc}, u_{tf} and u_{ph} are the generalized refractive indexes of the scintillator, thin-film and photodetector respectively, and g_{tf} is the phase thickness of the thin-film:

$$g_{tf} = \frac{2\pi u_{tf} d\cos\theta_{tf}}{\lambda}, \quad (7)$$

where d is the thickness of the film and θ_{tf} is the angle of incidence of the light given by the Snell's law:

$$u_{sc}\sin\theta_{sc} = u_{tf}\sin\theta_{tf} = u_{ph}\sin\theta_{ph}. \quad (8)$$

The reflectivity is given by $(E_{sc}^{-}/E_{sc}^{+})^2$:

$$\begin{aligned} R &= \left|\left[(u_{sc}u_{tf}-u_{tf}u_{ph})\cos g_{tf}+\right.\right. \\ &+ \left.(u_{sc}u_{ph}-u_{tf}^2)j\sin g_{tf}\right] / \\ &/ \left[(u_{sc}u_{tf}+u_{tf}u_{ph})\cos g_{tf}\ +\right. \\ &+ \left.\left.(u_{sc}u_{ph}+u_{tf}^2)j\sin g_{tf}\right]\right|^2. \end{aligned} \quad (9)$$

In order to make the reflectivity null, the numerator of the equation 9 must be zero. To do this it is enough to make $\cos g_{tf} = 0$ and $u_{sc}u_{ph} - u_{tf}^2 = 0$, i. e., $g_{tf} = (\pi/2 \pm k\pi)$ $(k = 1, 2, 3\ldots)$ and $u_{tf} = \sqrt{u_{sc}u_{ph}}$. A way of verifying both the conditions is producing a coating with a film whose refractive index is equal to $\sqrt{u_{sc}u_{ph}}$ and whose optical path (refractive index times thickness) is equal to

$$d \times n = \frac{(2k+1)\lambda}{4} \qquad k = 0, 1, 2, \ldots, \quad (10)$$

i. e., a quarter wave film. It is not always possible to obtain a material that satisfies the requirement of the refractive index to be equal to $\sqrt{u_{sc}u_{ph}}$. A good candidate is a silicon nitride film with $621\ nm$ of thickness. The result is shown in figure 5 with and without the silicon nitride film.

FINAL RESULT OF THE MODELING

The light produced by the scintillator, after multiple reflections at the reflector surface, reaches the photodetector. But each reflection introduce losses, which depend mainly on the geometry of the optical arrangement.

Consider a scintillator of parallelepipedic form with a photodetector in one of its faces and the other five coated by a reflector, as it is represented in figure 6. The relationship between the area of scintillator seen by the photodetector, a, and the total area of its surface, A is defined by:

$$R_A = \frac{a}{A}, \quad (11)$$

where $a = lc$, and $A = 2lc + 2hc + 2lh$, in figure 6. Considering that the scintillator is transparent and emits light

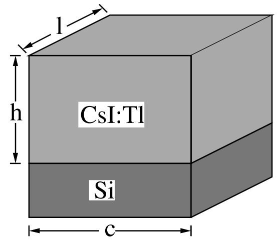

Figure 6. Scintillator on the top of a silicon photodetector.

uniformly in all directions, the amount of light that reaches directly the photodetector, without reflections is given by:

$$L^*_{pd} = L_R R_A, \tag{12}$$

where L_R is the total light produced by the scintillator. The light that is absorbed by the photodetector is:

$$L^{**}_{pd} = L^*_{pd}(1 - R_{ph}) = L_R R_A(1 - R_{ph}), \tag{13}$$

where R_{ph} is the reflectivity of the photodetector, given by equation 9. In a similar way, the light that reaches the reflector is given by:

$$L_{cm} = L_R - L^{**}_{pd} = L_R \left[1 - R_A(1 - R_{ph})\right]. \tag{14}$$

At the reflector interface, a percentage of light is lost, being the remaining light reflected back to the scintillator. The percentage of light lost is given by:

$$R_{loss} = 1 - R, \tag{15}$$

where R is the light that is reflected, being obtained from equation 5. After a high number of reflections, the light that arrives to the photodetector is given by:

$$L_{pd} = \sum_{i=0}^{\infty} L_R R_A(1{-}R_{ph}) \left[(1 - R_A(1 - R_{ph}))(1 - R_{loss})\right]^i . \tag{16}$$

The equation 16 represents a geometric series whose reason $(1 - R_a(1 - R_{ph})(1 - R_{loss})$ is lower than 1, so it is convergent and the percentage of light produced by the scintillator that reaches the photodetector is given by:

$$\frac{L_{pd}}{L_R} = \frac{R_A(1 - R_{ph})}{1 - (1 - R_A(1 - R_{ph}))(1 - R_{loss})}. \tag{17}$$

Figure 7 shows the efficiency of the optical setup given by equation 17 for $c = l =$ pixel size, $h = 700\ \mu m$ and without thin film. This efficiency depends heavily on the pixel size and decrease to values lower than 40% for pixel sizes low than 300 μm. For reference purposes, a 15 inches laptop screen with a resolution of 1024×768 has a pixel size of 300 μm.

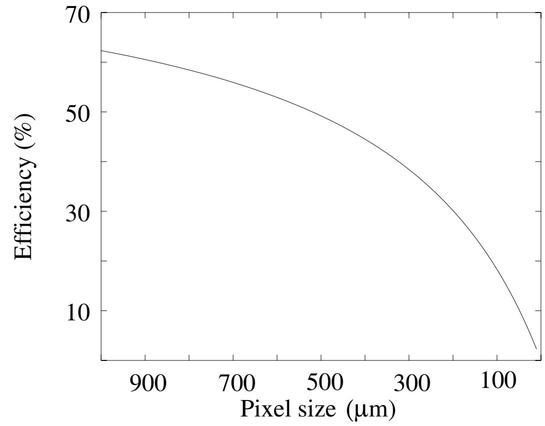

Figure 7. Efficiency of the optical setup versus pixel size. The parameters of figure 6 are: $c = l =$ pixel size, $h = 700\ \mu m$ and without thin film.

CONCLUSION

In the present work we have studied the main processes involved on scintillator based x-ray detectors. The mathematical modeling of the different steps: Transmission of the x-rays through the reflective layer, absorption of the x-rays by the scintillating crystal and their conversion into visible light, reflection of the visible light by the reflective layer and transmission of the visible light to the photodetector, as well as the calculation of the dependence of the efficiency with the pixel size will allow the improvement of the fabrication steps by choosing the right methods and materials optimizing the overall response of the detector previously to fabrication.

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