A systematic study of the performance of the CsI:Tl single-crystal scintillator under X-ray excitation

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Abstract

The light emission performance of the X-ray excited CsI:Tl single-crystal scintillator was investigated as a function of X-ray tube voltage and crystal thickness. Four CsI:Tl single-crystal layers (CRYOS Ltd., Ukraine) with thickness from 1 to 7 mm were irradiated employing two X-ray tube voltage ranges: (i) the 22–45 kV (molybdenum anode–molybdenum filter (Mo/Mo)) range, employed in mammographic imaging and (ii) the 40–140 kV (tungsten anode–aluminum filter) tube voltage range, used in general X-ray projection and tomographic imaging. The X-ray luminescence efficiency (light emission spectrum over incident X-ray fluence) of the crystals was determined by performing light emission spectrum and X-ray exposure measurements. In addition, the intrinsic conversion efficiency (fraction of the absorbed X-ray converted into light) and the spectral compatibility to various optical detectors were estimated from these measurements. The luminescence efficiency was found to be a nonlinear function of crystal thickness and of X-ray tube voltage. Peak efficiency (29.5 mW/m\textsuperscript{2}/mR) was observed for the 5 mm thick crystal at 140 kV. A secondary efficiency peak was observed at 42 kV (Mo anode) probably due to the effect of the K-photoelectric absorption edge (at 33 and 35 keV for Cs and I, respectively). For the thicker (7 mm) crystal, the efficiency was found to decrease due to light attenuation effects within the scintillator mass.

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1. Introduction

Scintillator detectors using Cesium Iodide crystal(s) doped with Thallium, CsI(Tl), show high γ-ray detection efficiency per unit volume. The most important features of CsI(Tl) is its high-light yield ($\geq 10^4$ photons/MeV) and its emission spectrum having the maximum at about 550 nm, well compatible to amorphous and crystalline silicon photodiodes. Due to the above characteristics, CsI(Tl) has been widely used in many medical imaging applications [1].

In this study, the light emission efficiency of the CsI:Tl single-crystal scintillator was investigated as a function of crystal thickness and X-ray tube voltage in the energy range used in X-ray mammography and in general X-ray
imaging. A similar approach has been carried out by Onyshchenko et al. [2], however using γ-rays.

2. Methods and materials

Four CsI:Tl single crystals with thicknesses ranging from 1 to 7 mm were studied by determining the following parameters:

1. The absolute luminescence efficiency, which was experimentally determined in a wide range of X-ray energies employed in X-ray imaging (40–140 kV) and in mammographic imaging (22–49 kV). The absolute efficiency (\( \eta_A \)) has been previously defined as the ratio of the light energy flux (\( \Psi \)) emitted by an excited scintillation crystal over the incident X-ray exposure rate (\( \bar{X} \)) [3,4]:

\[
\eta_A = \frac{\Psi}{\bar{X}}. \tag{1}
\]

\( \eta_A \) is given in units of (\( \mu \text{W s/mR m}^2 \)) or efficiency units (EU) [5].

2. The light emission spectrum, which was measured under X-ray excitation.

3. The intrinsic X-ray to light conversion efficiency (\( \eta_C \)), which expresses the fraction of the absorbed X-ray energy that is converted into light within the crystal, given as [6]

\[
\eta_C = \frac{\langle h\nu / \bar{\lambda} \rangle}{\beta E_g} \tag{2}
\]

where \( h\nu / \bar{\lambda} \) is the average energy of the emitted light photons, \( \beta E_g \) is the average energy required to create an electron–hole pair in the scintillator material.

4. The spectral compatibility of the emitted light with the spectral sensitivity of various optical photon detectors. This can be estimated by the spectral matching factor (SMF)

\[
\text{SMF} = \int \frac{S_P(\lambda)S_D(\lambda)}{S_P(\lambda)} \, d\lambda \tag{3}
\]

where \( S_P \) is the spectrum of the emitted light, \( S_D \) is the spectral sensitivity of the optical photon detector and \( \lambda \) denotes the wavelength of the light [5].

The four CsI:Tl crystals were supplied by CRYOS-BETA Ltd., Ukraine, with thicknesses 1, 3, 5 and 7 mm. The crystals were irradiated by X-rays using: (i) A Philips Optimus X-ray unit with a tungsten anode target and 2 mm Al filter and (ii) a General Electric Senographe DMR X-ray mammography unit equipped with a molybdenum anode target and molybdenum filter, using an experimental set-up previously described [7,8].

The absolute luminescence efficiency was determined according to Eq. (1), by performing X-ray exposure and light flux measurements [7].

The spectral matching factor was determined using Eq. (3) and data for five optical photon detectors currently used in a large variety of X-ray digital imaging detectors (digital radiography, computed tomography, nuclear medicine) (Table 1).

3. Results and discussion

Figs. 1 and 2 show the variation of the absolute luminescence efficiency of the four CsI:Tl crystals with X-ray tube voltage in the mammographic and in the general radiography ranges, respectively. These ranges include X-ray voltages used in X-ray computed tomography, digital radiography, fluoroscopy and other X-ray medical imaging applications.

<table>
<thead>
<tr>
<th>Optical detectors</th>
<th>CsI:Tl matching factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-20 EMI</td>
<td>0.763</td>
</tr>
<tr>
<td>Si/Si133 Hamamatsu</td>
<td>0.838</td>
</tr>
<tr>
<td>a-Si:H/108H</td>
<td>0.851</td>
</tr>
<tr>
<td>CCD S100AB SITE®</td>
<td>0.926</td>
</tr>
<tr>
<td>GaAs</td>
<td>0.941</td>
</tr>
</tbody>
</table>

Fig. 1. Variation of absolute luminescence efficiency (AE) of CsI:Tl crystals for mammography (22–49 kVp) X-ray tube voltages. AE units: \( \mu \text{W s/mR m}^2 \). Points: measured data, line: fitted curve.

Fig. 2. Variation of absolute luminescence efficiency (AE) of CsI:Tl crystals for radiographic (40–140 kVp) X-ray tube voltages. AE units: \( \mu \text{W s/mR m}^2 \). Points: measured data, line: fitted curve.
The AE of the 1 mm CsI:Tl crystal found to increase continuously with X-ray tube voltage up to 100 kV, whereas for higher tube voltages no significant increase was observed. This can be explained if one considers that X-rays of energy higher than 100 kV penetrate the crystal with lower absorption. Hence, light creation shows a tendency to saturate. The 5 mm thick CsI:Tl crystal had higher AE at all X-ray tube voltages (Fig. 3).

The emission efficiency of the single-crystal CsI:Tl was higher than other scintillators, previously measured under similar experimental conditions[7,8]. These data on CsI:Tl crystal could be useful in designing detectors for X-ray computed tomography as well as for the recently proposed breast X-ray computed tomography systems[9].

The intrinsic conversion efficiency $\eta_c$ value, shown in Table 2, was found adequately high and explains the high-luminescence efficiency, experimentally assessed in our study.

The emission spectra peak of CsI:Tl crystal was found at $545 \pm 5$ nm. This peak was found to be well situated within the spectral sensitivities curves of most optical detectors considered in this study (Table 1) giving high-effective efficiency values (Fig. 4).

4. Conclusions

In conclusion, our measurements showed that the absolute efficiency of CsI:Tl scintillator crystal increased with X-ray tube voltage under X-ray mammographic and general X-ray conditions. All scintillators examined exhibit absolute luminescence efficiency higher than 20 EU. The performance of 5 mm thick CsI scintillator was found higher than the thicker ones. In addition, the CsI:Tl emission spectrum, is well situated within the spectral sensitivities of optical detectors (photodiodes, photocathodes and charge coupled devices) often employed in radiation detectors. CsI:Tl may also be considered for use in mammographic applications mainly because of its high absorption and conversion efficiency at low energies. Although for high-speed digital radiography, microcolumnar CsI:Tl screens maybe used [11].

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References