

X-ray Luminescence Efficiency of GAGG:Ce Single Crystal Scintillators for use in Tomographic Medical Imaging Systems

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Abstract. The purpose of the present study was to evaluate different scintillator crystal samples, with a cross section of $3 \times 3 \text{ mm}^2$ and various thicknesses ranging from 4mm up to 20mm, of the new mixed $\text{Gd}_3\text{Al}_2\text{Ga}_3\text{O}_{12}:\text{Ce}$ (GAGG:Ce) scintillator material under X-ray irradiation, for potential applications in Tomographic Medical Imaging systems. Evaluation was performed by determining the X-ray luminescence efficiency (XLE) (emitted light energy flux over incident X-ray energy flux) in energies employed in general X-ray imaging. For the luminescence efficiency measurements, the scintillator samples were exposed to X-rays using a BMI General Medical Merate tube, with rotating Tungsten anode and inherent filtration equivalent to 2 mm Al. X-ray tube voltages between 50 to 130 kV were selected. An additional 20 mm filtration was introduced to the beam to simulate beam quality alternation equivalent to a human body. The emitted light energy flux measurements were performed using an experimental set up comprising a light integration sphere coupled to an EMI 9798B photomultiplier tube which was connected to a Cary 401 vibrating reed electrometer. The GAGG:Ce sample with dimensions $3 \times 3 \times 10 \text{ mm}^3$ exhibited higher XLE values, in the whole X-ray energy range examined. XLE value equal to 0.013 was recorded for this crystal at 130 kVp - a setting frequently used in Computed Tomography applications.

1. Introduction

Scintillators are used as radiation converting media in various applications, from medical imaging to high energy physics experiments [1-4]. Particularly, in medicine, scintillators have been applied from low energy examinations, such as mammography and general radiography to nuclear medicine and radiotherapy, in powder or crystal form [5]. Among the various crystal detectors, Cerium (Ce) doped scintillators are the dominant due to their internal properties, such as, fast emission and high light yield [2,5]. Ce doped Gadolinium Aluminum Gallium Garnet ($\text{Gd}_3\text{Al}_2\text{Ga}_3\text{O}_{12}:\text{Ce}$ or GAGG:Ce) is a recently developed mixed scintillator crystal with high density (6.69 g cm^{-3}), fast scintillation response ($\sim 90 \text{ ns}$) and high light yield ($\sim 46000 \text{ ph/MeV}$) [6]. Compared to many current efficient scintillators, GAGG:Ce is non hygroscopic (like $\text{LaBr}_3:\text{Ce}$, $\text{LaCl}_3:\text{Ce}$, CsI and NaI:Tl crystals) and it does not have natural radioactivity (like Lutetium based materials) [6-8]. GAGG:Ce emits optical photons at 520nm and has an effective atomic number equal to 54.4. As it has been previously reported [7], the production of GAGG:Ce is based on the Czochralski method. Several studies of energy resolution and timing performance of GAGG crystals readout, using a variety of photon detection technologies



(APD, SIPM, PMT, MPPC, PIN diode), have shown that the crystal is promising for medical imaging and gamma-ray spectroscopy applications [9-10]. Moreover, the development of a sub millimeter GAGG block detector, using 0.4 mm GAGG pixels, was reported for PET and SPECT applications [11]. Very recently, the evaluation of the GAGG:Ce scintillator array (with $2 \times 2 \times 5 \text{ mm}^3$ pixel elements) under low energy isotopes (^{57}Co and $^{99\text{m}}\text{Tc}$) for SPECT applications, as well as, with ^{137}Cs and ^{22}Na isotopes for PET imagers based on 4×4 discrete SIPM optical detector were published [12-13].

Although several studies reported on the performance of the GAGG:Ce scintillator material under gamma ray excitation, only a few have been published for X-ray excitation [14], e.g. for potential use in tomographic X-ray imaging or integrated PET/CT and SPECT/CT detector systems.

The purpose of the present study was to evaluate seven different scintillator crystal samples with a cross section of $3 \times 3 \text{ mm}^2$ and various thicknesses, ranging from 4mm up to 20mm of the new mixed GAGG:Ce scintillator material under X-ray excitation for applications in tomographic medical imaging detectors, i.e. CT or integrated SPECT/CT or PET/CT detectors. Experimental measurements such as the X-ray luminescence efficiency (light energy flux over exposure rate) under X-ray excitation in the radiographic energy range from 50 to 130 kVp were performed.

2. Materials and Methods

GAGG:Ce single crystals are produced in the Materials Research Laboratory, Furukawa Co. Ltd. in Japan. The seven scintillators were cut from the same bolus with 4, 5, 6, 8, 10, 15 and 20 mm thicknesses and a cross section of $3 \times 3 \text{ mm}^2$. All the crystal samples surfaces have been polished. The dimension of the GAGG:Ce crystal's output face was selected to be $3 \times 3 \text{ mm}^2$, in order to have compatibility between scintillator and photodetector's pixel size, since most new optical detectors, that are currently used in medical imaging systems have similar pixel sizes [15-16].

The crystals were exposed to X-rays from a BMI General Medical Merate tube with rotating Tungsten anode and inherent filtration equivalent to 2 mm Al, with energies ranging from 50 to 130 kVp. An additional 20 mm filtration was introduced in the beam to simulate beam quality alternation similar to a human body [17]. The light flux measurements were performed using a light integration sphere (Oriel 70451), coupled to a photomultiplier (EMI 9798B), connected to a Cary 401 vibrating reed electrometer [18]. The X-ray exposure rate was measured at the crystal's position using a Radcal 2026C dosimeter.

2.1. X-ray luminescence efficiency (XLE)

The X-ray luminescence efficiency (XLE) describes the efficiency of a scintillator to transfer the signal from the input to the output. XLE can be determined by the ratio of the emitted light energy flux (Ψ_{Λ}) over the incident X-ray energy flux (Ψ_0): ($XLE = \Psi_{\Lambda} / \Psi_0$). XLE was determined by measuring the X-ray exposure rate and emitted light energy flux [18]. The X-ray energy flux (Ψ_0) was determined by converting X-ray exposure rate (X) [18], as follows: $\Psi_0 = X \hat{\Psi}$ where $\hat{\Psi}$ is defined as the X-ray energy flux per exposure rate, estimated according to (1):

$$\hat{\Psi} = \int \Psi_0(E) dE / (\int \Psi_0(E) [X / \Psi_0(E)] dE) \quad (1)$$

where

$$X / \Psi_0(E) = (\tau_{en}(E) / \dots)_{air} \cdot (W_A / e)^{-1} \quad (2)$$

is the factor converting energy flux into exposure rate, $(\sim en / \dots)_{air}$ is the X-ray mass energy absorption coefficient of air, at energy E, and W_A / e is the average energy per unit of charge required to produce an electron-ion pair in air. W_A / e and $(\sim en / \dots)_{air}$ were obtained from tabulated data [19].

2.2. Detector quantum optical gain (DQG)

Detector quantum optical gain (DQG) is the ratio of the light photon flux Φ_Λ over the X-ray photon flux (Φ_X). Using this quantity, the emitted light photon flux can be expressed in terms of experimentally measurements (absolute efficiency, exposure rate, mean light wavelength), by using (3):

$$\Phi_\Lambda = \Psi_\Lambda / hc \bar{\lambda}^{-1} \tag{3}$$

Where the denominator is the mean energy of the emitted light photons, λ being the mean light wavelength determined from emission spectra measurements. Φ_X was determined by using (1) and (2), replacing Ψ_0 by Φ_0 and dividing (2) by the X-ray energy [18]. More details about the quantity of DQG can be found in [20].

3. Results and Discussion

Figure 1 shows the XLE for the seven GAGG:Ce crystals, for various tube voltages. In every case, XLE values show a tendency to decrease with increasing tube voltage, due to the energy absorption properties and light transmission through the crystals. The higher XLE values are shown for the $3 \times 3 \times 10$ mm³ GAGG:Ce crystal. Crystals with higher thickness presents slightly lower XLE values due to increase of the scintillation light absorption by the crystal mass.

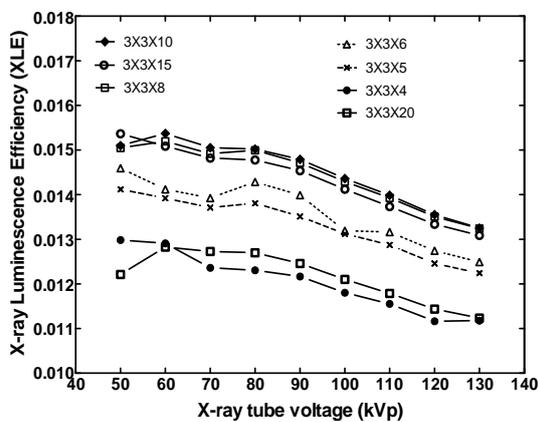


Figure 1. Variation of the X-ray luminescence efficiency (XLE) of the GAGG:Ce crystals with X-ray tube voltage.

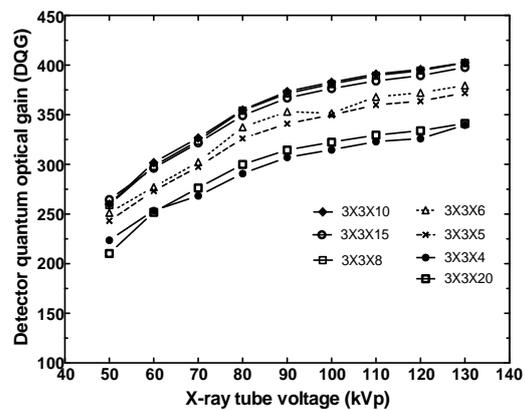


Figure 2. Variation of the detector quantum gain (DQG) of the GAGG:Ce crystals with X-ray tube voltage.

Figure 2 show DQG values for the GAGG:Ce crystals, in the energy range under investigation. DQG can be a measure of light yield and increases as the photon energy increase, showing that GAGG:Ce crystals could produce efficiently optical photons up to the X-ray computed tomography (CT) energy range (i.e. 130kVp). DQG reflects more accurately the detector intrinsic properties, since it is not affected by the air-ionization chamber properties used to determine AE. The latter depends on the X-ray energy flux to exposure conversion factor, which exhibits a highly non-linear variation with X-ray energy. The behaviour of DQG curves can be explained by considering the following: The number of optical photons created per absorbed X-ray increases due to the light created per photon is

larger in higher X-ray energies and therefore DQG increase. We note that the X-ray photons are totally absorbed by the GAGG:Ce scintillators mass, due to high density of the material.

4. Conclusions

In the present study, seven different GAGG:Ce scintillator crystals with a cross section of $3\times 3\text{mm}^2$ and various thicknesses were examined under X-ray irradiation for potential applications in tomographic medical imaging detectors. The GAGG:Ce sample with dimensions equal to $3\times 3\times 10\text{mm}^3$ provided higher XLE and DQG values, almost in the whole X-ray energy range examined. XLE value equal to 0.013 and DQG up to 400 was recorded for this crystal at an X-ray tube voltage of 130 kVp used in Computed Tomography applications.

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References

- [1] Blasse G G and Grabmaier B C, 1994, *Luminescent Materials* (Springer-Verlag, Berlin, Heidelberg)
- [2] Van Eijk C W E 2002 *Phys. Med. Biol.* **47** 85
- [3] Kandarakis I S 2014 *J. Lumin.* in press: <http://dx.doi.org/10.1016/j.jlumin.2014.11.009>
- [4] Guerra A 2004 *Ionizing Radiation Detectors for Medical Imaging*, (World Scientific Publishing Company, Singapore) p 53
- [5] Nikl M 2006 *Meas. Sci. Technol.* **17** 37
- [6] Iwanowska J *et al.*, 2013 *Nucl. Instr. and Meth. Phys. Res. A.* **712** 34
- [7] Kamada K, Yanagida T, Endo T, Tsutumi K, Usuki Y, Nikl M, Fujimoto Y, Fukabori A and Yoshikawa A 2012 *J. Cryst. Growth* **352** 88
- [8] Kobayashi M, Tamagawa Y, Tomita S, Yamamoto A, Ogawa I and Usuki Y, 2012, *Nucl. Instr. and Meth. Phys. Res. A.* **694** 91
- [9] Yeom J Y, Yamamoto S, Derenzo S E, Spanoudaki V C, Kamada K, Endo T and Levin C S 2013 *IEEE Trans. Nucl. Sci.* **60** 988
- [10] Kato T *et al.*, 2013 *Nucl. Instr. and Meth. Phys. Res. A.* **699** 235
- [11] Kataoka J *et al.*, 2013, *Nucl. Instr. and Meth. Phys. Res. A.* **732** 403
- [12] Georgiou M, David S, Fysikopoulos E and Loudos G 2013 *IEEE Nucl. Sci. Symp. & Med. Imag conf.* M21-48 DOI: [10.1109/NSSMIC.2013.6829327](https://doi.org/10.1109/NSSMIC.2013.6829327)
- [13] David S, Georgiou M, Fysikopoulos E and Loudos G 2015 *EJMP* DOI: <http://dx.doi.org/10.1016/j.ejmp.2015.03.008> in press
- [14] Seferis I E, Michail C M, David S L, Bakas A, Kalivas N I, Fountos G P, Panayiotakis G S, Kourkoutas K, Kandarakis I S and Valais I G 2014 *IFMBE proc.* **41** 455
- [15] <http://sensl.com/products/silicon-photomultipliers/>
- [16] <http://www.hamamatsu.com/us/en/product/category/3100/4004/4113/index.html#>
- [17] Michail C, Kalyvas N, Valais I, David S, Seferis I, Toutountzis A, Karabotsos A, Liaparinos P, Fountos G and Kandarakis I 2013 *J. Lumin.* **144** 45
- [18] Michail C, Valais I, Seferis I, Kalyvas N, David S, Fountos G and Kandarakis I 2014 *Radiat. Meas.* **70** 59
- [19] Hubbell J H, Seltzer S M, 1995, Tables of X-ray mass attenuation coefficients and mass energy absorption coefficients 1 to 20MeV for elements Z=1 to 92 and 48 additional substances of dosimetric interest. US Department of commerce, NISTIR 5632
- [20] Kalyvas N, Valais I, David S, Michail C, Fountos G, Liaparinos P and Kandarakis I 2014 *Optics and Spectroscopy* **116** 743