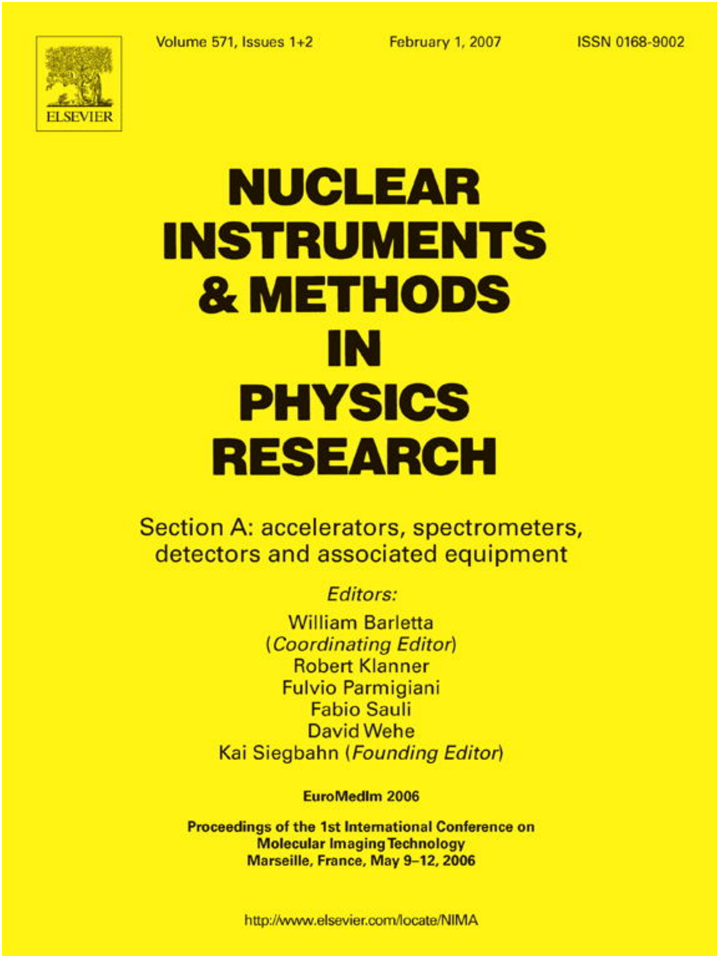
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Efficiency of Lu_2SiO_5:Ce (LSO) powder phosphor as X-ray to light converter under mammographic imaging conditions

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Abstract

The aim of the present study was to examine the light emission efficiency of Lu_2SiO_5:Ce (LSO) powder scintillator under X-ray mammographic imaging conditions. Powder LSO scintillator has never been used in X-ray imaging. For the purposes of the present study, a 25 mg/cm^2 thick scintillating screen was prepared in our laboratory, by sedimentation of Lu_2SiO_5:Ce powder. Absolute luminescence efficiency measurements were performed within the range of X-ray tube voltages (22–49 kVp) used in mammographic applications. Parameters related to X-ray detection, i.e. the energy absorption efficiency (EAE) and the quantum detection efficiency (QDE) were calculated. A theoretical model, describing radiation and light transfer, was employed to fit experimental data and to estimate values of the intrinsic conversion efficiency and the light attenuation coefficients of the screen. The spectral compatibility of the LSO powder scintillator to mammographic X-ray films and to various electronic optical detectors was determined by performing light emission spectrum measurements and by taking into account the spectral sensitivity of the optical detectors. Results in the voltage range used in mammography showed that Lu_2SiO_5:Ce powder scintillator has approximately 10% higher values of QDE and 4.5% higher values of EAE than Gd_2O_2S:Tb.

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Keywords: Inorganic scintillators; Radiation detectors; Luminescence efficiency; LSO:Ce

1. Introduction

Cerium (Ce^{3+})-doped scintillators or phosphors are of particular interest for medical imaging, because of their very fast response. The latter is dominated by the very efficient 5d→4f electronic transitions of the Ce^{3+} ion [1–3]. Since its discovery by Melcher and Schweitzer in 1992 [5], lutetium oxyorthosilicate (LSO) has attracted a great deal of attention and has been recognized as one of the best scintillating materials [4,5]. In effect, this material is very good compromise among fast scintillators (e.g., BaF_2), high light output scintillators (e.g., Gd_2O_2S:Tb) and dense scintillators (e.g., $Bi_4Ge_3O_{12}$) [5]. The great interest of LSO:Ce is due to many important advantages, such as high luminescence efficiency, high density of 7.4 g/cm^3, fast decay time of 40 ns, suitable emission wavelength (420 nm) and very good chemical stability compared to other scintillators.

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It is known that the scintillator LSO:Ce in crystal form has applications in positron emission tomography, nuclear physics, high-energy physics and environmental monitoring [6,7]. The purpose of this study was to evaluate powder LSO:Ce for use in X-ray mammography. To our knowledge, this material has not yet been studied under mammographic exposure conditions.

2. Materials and methods

2.1. Theory

Scintillators or phosphors are used as radiation to light converters in radiation detectors. The light energy flux Ψ_λ emitted by a phosphor material when irradiated by an X-ray energy flux Ψ_X, may be given as follows:

$$\bar{\Psi}_\lambda = \int_0^{E_0} \bar{\Psi}_X(E)\bar{n}_\varepsilon(E)n_c \int_0^{W_0} \bar{\Psi}_Q(E,w)\bar{g}_\lambda(\sigma,w)\mathrm{d}w\,\mathrm{d}E, \tag{1}$$

where E_0 is the maximum energy of the spectrum of X-rays, W_0 the coating thickness of the phosphor, E the X-ray photon energy, η_ε the energy absorption efficiency (EAE), η_c is the intrinsic X-ray to light conversion efficiency (ICE), expressing the fraction of absorbed X-rays converted into light within the phosphor. Ψ_Q is the probability of an absorbed X-ray photon to be absorbed at a depth $W < W_0$. g_λ is the fraction of light photons, created at depth W, that escape the phosphor and σ is an optical attenuation coefficient [8–10]. The second integral in (1) is defined as the light transmission efficiency (LTE) of the phosphor [9,11,12]. The first integral is used to integrate over the energies of X-ray spectrum. X-ray imaging scintillators are often evaluated by the absolute luminescence efficiency (η_A):

$$\eta_A = \bar{\Psi}_\lambda / X, \tag{2}$$

where X is the exposure rate incident on the phosphor, emitted by an X-ray tube with high voltage equal to E_0. To express the compatibility of emitted light with spectral sensitivity of the photodetector, the spectral matching factor α_S was calculated by the relation:

$$\alpha_S = \frac{\int S_P(\lambda)S_D(\lambda)\,\mathrm{d}\lambda}{\int S_P(\lambda)\,\mathrm{d}\lambda}, \tag{3}$$

where $S_P(\lambda)$ is the spectrum of the light emitted by the phosphor and $S_D(\lambda)$ is the spectral sensitivity of the optical detector coupled to the phosphor [13,14].

2.2. Experiments

LSO:Ce was purchased in powder form (Phosphor Technology Ltd., England, code: ZBK58/N-S1) with mean grain size of approximately 8 μm. The phosphor was used in the form of thin layer (test screen) to simulate the intensifying screens employed in X-ray mammography. A 25 mg/cm^2 thick screen was prepared by sedimentation of Lu_2SiO_5:Ce powder on fused silica substrate (spectrosil B). Sodium orthosilicate (Na_2SiO_3) was used as binding material between the powder grains [12]. The phosphor screen was exposed to X-rays on a General Electric Senographe DMR Plus mammographic unit, employing X-ray tube voltages ranging from 22 to 49 kVp with molybdenum anode target and molybdenum filter. The X-ray beam was filtered by a 35 mm thick block of Perspex to simulate beam hardening by human breast [9]. The absolute luminescence efficiency was determined, according to Eq. (2), by performing X-ray exposure and light flux measurements [15]. The experimental setup was previously described by Valais et al. [16]. To determine the spectral matching factor, the emitted light of the LSO:Ce powder phosphor was measured, while the spectral sensitivities of the optical detectors were obtained from manufacturers' data.

2.3. Calculations

Using relations (1) and (2), the absolute luminescence efficiency may be calculated as a function of the intrinsic physical parameters of the phosphor material. Calculation of the physical quantities employed in relation (1) were performed as described in detail in previous studies for other materials [13,17]. These quantities were used in order to fit relation (1) to the experimental absolute luminescence efficiency measurements [18]. A fit was obtained, for specific values of the parameters η_C and σ. These values, together with β and ρ_n [13], were then adopted as the intrinsic optical properties of the phosphor. The EAE, η_ε, expressing the fraction of X-ray energy locally absorbed as well as the quantum detection efficiency (QDE), expressing the fraction of X-ray quanta interacting with the phosphor, were calculated by considering exponential X-ray absorption [1,19].

3. Results and discussion

Fig. 1 shows the variation of absolute luminescence efficiency of the LSO:Ce screen with X-ray tube voltage. Points represent experimental data. A better fit to the data was obtained for η_c values varying from $\eta_c = 0.09$ to 0.11 and σ varying from $\sigma = 71$ to 75 cm^2 g^{-1}. The value of the intrinsic conversion efficiency (η_c), as estimated by the fitting, is lower than the corresponding value of Gd_2O_2S:Tb ($\eta_c = 0.2$) phosphor [1,9], which is used in conventional and digital radiographic detectors. It is approximately equal to the η_c values of CsI:Na, CsI:Tl and NaI:Tl phosphors ($\eta_c = 0.10$), used in a large variety of radiation detectors [20]. The optical attenuation coefficient σ was found higher than Gd_2O_2S:Tb phosphors ($\sigma = 30$ cm^2 g^{-1}). This may be explained by considering that the lower mean wavelength light of LSO:Ce (420 nm) exhibits higher attenuation than the light emitted by Gd_2O_2S:Tb (545 nm). An important observation from Fig. 1 is that absolute luminescence efficiency maintains

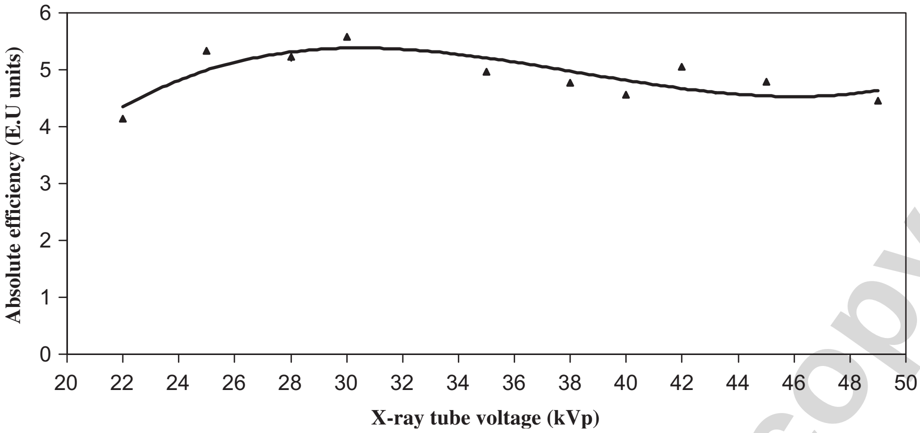

Fig. 1. Variation of the absolute luminescence efficiency of the LSO:Ce powder phosphor with X-ray tube voltage. Points correspond to experimental values. Efficiency units: $\mu W \times m^{-2}/(mR \times s^{-1})$.

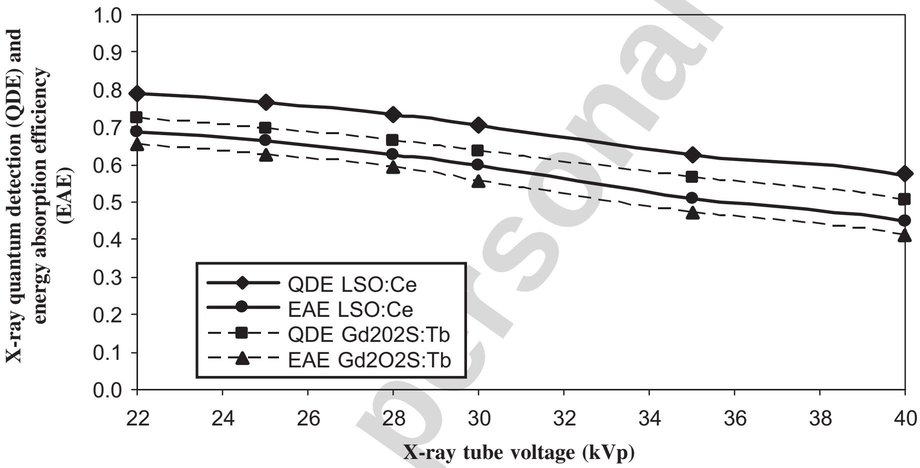

Fig. 2. Variation of calculated (QDE) and (EAE) of LSO:Ce and Gd_2O_2S:Tb with X-ray tube voltage for 25 mg/cm^2 powder screens.

high values within a range of X-ray tube voltages from 25 to 36 kVp. This property is of interest for mammographic imaging.

Fig. 2 illustrates the variation of calculated QDE and EAE with X-ray tube voltage for the 25 mg/cm^2 LSO:Ce screen. For comparison purposes, similar calculations were performed for a Gd_2O_2S:Tb screen. The first point to note is that EAE differs significantly from QDE. As it may be seen, at 28 kVp, EAE (0.62) is approximately 15% lower than QDE (0.73). Calculations also showed that the LSO:Ce powder scintillator has approximately 10% higher values of QDE and 4.5% higher values of EAE than Gd_2O_2S:Tb.

Fig. 3 shows the measured light emission spectrum of the LSO:Ce phosphor. The peak value of the light spectrum found at 420 nm.

Table 1 shows the values of the spectral matching factors of the LSO:Ce calculated according to relation (3). LSO:Ce exhibits excellent compatibility with the AgfaGS and KodakGR radiographic films. In addition, it was found adequately compatible with the amorphous silicon (AmorSi) photodiode.

4. Conclusions

In the present study, a LSO:Ce powder scintillator screen of 25 mg/cm^2 coating thickness was prepared and examined under X-ray mammographic conditions. The X-ray QDE and the X-ray EAE were found higher than currently employed materials (e.g., Gd_2O_2S:Tb) for detection of X-rays used in mammographic applications. The absolute luminescence efficiency maintains high values, within the mammographic energy range, while the intrinsic conversion efficiency was found close to that of CsI:Tl but lower than that of Gd_2O_2S:Tb. The emission spectrum of LSO:Ce screen showed excellent spectral compatibility with currently used detectors and taking also into account its very fast response it could be considered for applications in X-ray mammographic imaging systems.

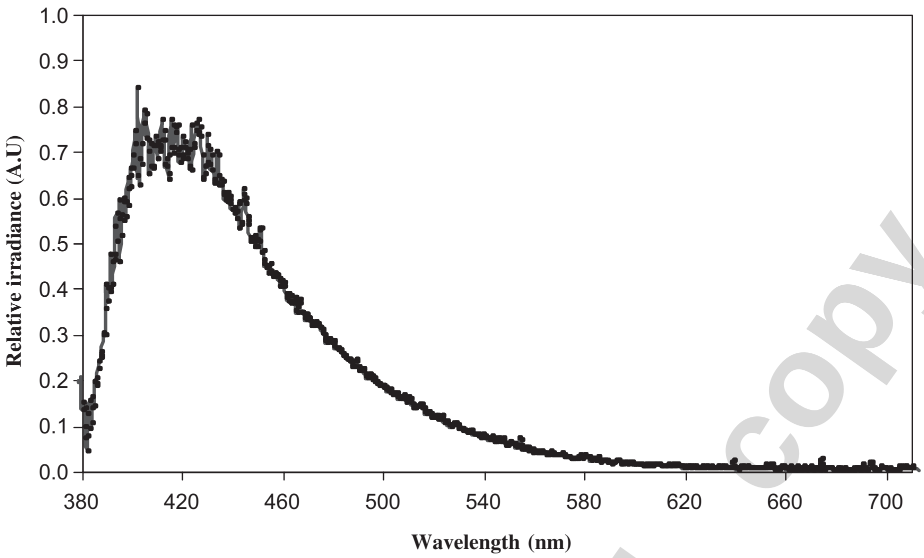

Fig. 3. Optical emission spectra of LSO:Ce phosphor measured at 30 kVp for 25 mg/cm^2 scintillator coating thickness.

Table 1
Spectral matching factors

Optical detectors	Lu_2SiO_5:Ce
GaAs	0.916
Si	0.320
AmorSi	0.580
MAMORAY	0.873
E/S 20	0.965
AgfaGS	0.960
KodakGR	0.965
FujiUM	0.896

Acknowledgments

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