Thin imaging screens based on Ce-doped lutetium–aluminum garnets

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ABSTRACT

Cerium-doped lutetium–aluminum garnets prepared in the form of thin films (grown by Liquid Phase Epitaxy) and thin plates (thin imaging screens prepared by mechanical polishing) are compared. Different methods were used for light yield measurements: pulse-height analysis, cathodoluminescence and X-rays. The homogeneity of light emission was examined in an X-ray imaging setup. The relative light yield and homogeneity of bulk crystal screens and LPE screens were compared.

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1. Introduction

Very thin scintillator imaging screens have recently become of great interest. In high resolution X-ray projection imaging, very thin scintillation screens (5–20 μm thick) are used to achieve spatial resolutions down to 1 μm . Such thin screens are mainly used in micro-CT and nano-CT systems with either microfocus X-ray tubes or with synchrotron sources. The light distribution on the screen is transferred by an optical system to a high resolution CCD chip. For the given parameters of an optical collection system, there exists an optimum thickness of the scintillator screen. A thicker screen absorbs high-energy photons more efficiently but the image on the CCD becomes blurred (Koch et al., 1998). An excessively thin scintillator does not provide enough absorption so that the integration time for an image can be rather long. The collection efficiency of emitted light from a thin scintillating screen is extremely small due to small numerical aperture of optics, e.g. it is about 1% for an objective $f/2.8$. However, all high resolution (submicrometer) systems are limited by this effect (Koch et al., 1998).

Thin $\text{Lu}_3\text{Al}_5\text{O}_{12}:\text{Ce}$ (LuAG:Ce) screens were prepared from bulk single crystals grown by the Czochralski technique from melt (plates), and by the Liquid Phase Epitaxy technique (LPE) – epitaxial growth from $\text{PbO}-\text{Ba}_2\text{O}_3$ flux on single crystal substrates (films) (Nikl, 2006). Other types of screens (e.g. deposited powder) do not reach the required spatial resolutions. Epitaxial preparation

methods could offer better homogeneity of thickness and better homogeneity of luminescence efficiency. Also, lower growth temperatures could increase scintillation efficiency because of lower concentration of the antisite defect in the garnet (Zorenko et al., 2007).

This work presents an evaluation of the parameters achieved in these thin scintillators and compares the homogeneity of bulk and epitaxy screens.

2. Samples and methodology

Seven LPE-grown single crystal films (SCF) (Zorenko et al., 2003) of LuAG:Ce on a LuAG substrate (quarter-arc of 37 mm diameter), and one LuAG:Ce plate of 20 μm thickness and 19 mm diameter, prepared from Czochralski grown bulk single crystals and glued on a BK7 glass substrate, were used in the experiments, see list of samples in Table 1 and Fig. 1.

A 2D imaging experiment consisted of a microfocus X-ray source, a sample holder and a digital CCD camera fitted with a high resolution optical system.

In the imaging experiments, a sample was placed on the sample holder with the active layer/plate oriented towards the X-ray source Fig. 2. During X-ray exposure (500 ms), the luminescence image from the scintillator was collected by the CCD camera. Exposures were made with no objects being imaged in order to compare the scintillation efficiency and film/plate homogeneity of the samples. The efficiency thus obtained is called the imaging system detection efficiency (ISDE).

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Table 1

Sample list, thickness and relative scintillation efficiencies measured by different methods. *RLY* is recorded at 0.5 μ s shaping time whereas other efficiencies have much longer integrating times.

Sample number	<i>d</i> (μ m)	<i>RLY</i> (%)	<i>CLE</i> (%)	<i>ISDE</i> (%)	<i>AE</i>	<i>RLY</i> * <i>AE</i> (%)
Reference (bulk)	20	100	100	100	0.702	100
1 (LPE)	22	113	109	76	0.733	118
2 (LPE)	43	94	78	62	0.904	121
3 (LPE)	35	85	80	70	0.863	104
4 (LPE)	17	70	68	52	0.647	65
5 (LPE)	29	63	60	50	0.816	73
6 (LPE)	15	62	48	42	0.605	53
7 (LPE)	27	67	47	42	0.796	76

In the present experiment, the standard method of estimating the relative luminescence yield (*RLY*) of thin screens was by pulse-height analysis using a ^{63}Ni emitter (beta spectrum with maximum energy of 67 keV). In the case of LuAG, the radiation is almost completely absorbed in a layer 2–3 μ m thick.

Another alternative for comparing luminescence efficiency is to record the cathodoluminescence signal/image in an SEM. In this manner another type of efficiency, the cathodoluminescence efficiency (*CLE*), can also be established. The present measurements were carried out with 5–15 keV accelerating voltage which means that the *CLE* results provide information about the top 100–1000 nm of the surface layer. A significant advantage of the *CLE* technique is the large dynamic range of measured efficiencies and detailed imaging of potential non-homogeneities.

The last two techniques (*RLY* and *CLE*) hence measure a kind of relative volume efficiency as the radiation is completely absorbed in the layer. On the contrary, X-rays are partially transmitted through the scintillator layer and the *ISDE* efficiency has to be corrected for the layer thickness (*d*).

3. Results and discussion

3.1. Optical quality

Fig. 3 shows optical microscope images of one of the LPE SCF samples and of the reference bulk sample. The SCF samples show occasional incrustations and surface flaws which scatter luminescence light out from the sample; these appear as bright spots. Plates prepared from Czochralski grown bulk crystals are very homogeneous and do not show any scattering effects.

3.2. 2D imaging

In case of X-ray excitation, a similar effect was observed using the CCD camera on the back face of the samples: surface flaws in the LPE-grown samples appear as bright spots while the

Fig. 1. LuAG:Ce thin samples: LPE SCF (left) and bulk crystal plate (right).

Fig. 2. 2D experimental set-up.

Fig. 3. Optical quality of screen surfaces, LPE SCF (left), bulk crystal plate (right) at the same magnification. Both images show boundaries of the screen or support.

Czochralski grown plate gives a homogeneous and spot-free image, Fig. 4.

The above mentioned flaws in the LPE SCF samples degrade image quality as compared with that obtained in Czochralski grown plates. Further, a better signal-to-background ratio from the CCD camera, by a factor of 1.5, was achieved in the Czochralski grown sample due to its higher scintillation efficiency.

From the images displayed in Fig. 4, the integrated emission intensity was evaluated from the samples as the average of 25 500 ms exposures and was used to evaluate the scintillation efficiency *ISDE* of the samples Table 1. The results are normalized with respect to the reference Czochralski grown sample. The best of the LPE SCF samples showed about 76% efficiency with respect to the reference sample.

A Cu anode microfocus X-ray source operating at 40 kV and 2 mA was used in these X-ray experiments.

3.3. X-ray absorption efficiency

The efficiency of a scintillation screen depends on the absorption of a particular X-ray spectrum in the material. A realistic emission spectrum (I_{RTG}) of a copper target under 40 kV, passing through a 0.2 mm Be window and 40 cm of air (see Fig. 5), was simulated. In order to calculate the absorption efficiency (*AE*) of such a spectrum, the following relationship was used:

Fig. 4. The samples under the 2D X-ray imaging, LPE SCF on the left, bulk crystal plate on the right.

Fig. 5. Absorption spectrum of a LuAG:Ce scintillator and emission spectrum of a copper target X-ray tube operating at 40 kV.

$$AE(d) = 1 - \frac{\int I_{RTG}(E) \exp(-\alpha(E)d)}{\int I_{RTG}(E)}$$

The absorption efficiency for the relevant thicknesses is plotted in Fig. 6. For a 20 μm thick LuAG layer, AE is 70%.

3.4. Luminescence efficiency

Table 1 summarizes the values of the three luminescence efficiencies *RLY*, *CLE* and *ISDE*. As expected, there is a good correlation between *RLY* and *CLE* (corr. coeff. R^2 of 0.87).

When attempting to compare *RLY* and *ISDE*, several problems arise. Firstly, the influence of layer thickness on *ISDE* via the $AE(d)$ factor must be taken into account. Secondly, *RLY* depends on the shaping/integrating time used. Since luminescence decay is dependent on defect nature, in the present case the bulk material shows luminescence decaying slower as compared to the LPE scintillator. As a consequence, for the case of the bulk material, the *RLY* measured with 0.5 μs shaping time is about 25% less than the *RLY* measured with 10 μs shaping time. The third problem is related to varying sample geometries leading to different collection of light for different light-collection systems. This is why the most relevant light yield measurement technique is direct testing in the target application, in the present case X-ray imaging, and its *ISDE* value.

In summary, it can be seen from Table 1 that the *ISDE* of the best LPE layer (number 1, 22 μm thick) is only 76% of the efficiency of the reference plate screen (20 μm thick) prepared by polishing from a single crystal.

Fig. 6. Energy-absorption efficiency of LuAG:Ce for a copper target X-ray tube operating at 40 kV.

4. Conclusions

Imaging methods based on thin LuAG:Ce LPE films or bulk plates (thickness of about 20 μm) can achieve sufficient contrast, high X-ray absorption and can reach spatial resolutions of about 1 μm (Zorenko et al., 2003; Tous et al., 2008).

Three different methods of light yield evaluation of thin imaging screens were compared. An X-ray imaging setup was used to measure the homogeneity of projection images which was found to be good for the bulk screen. The LPE layers show crucial flaws that scatter scintillation light. These spots appear much brighter than the background. We also conclude that the integrated scintillation efficiency of the best LPE LuAG:Ce film is up to now inferior to that of the screen prepared from bulk material at the same thickness.

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