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High resolution low energy X-ray microradiography using a CCD camera

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ABSTRACT: A high resolution X-ray camera for micro-radiography is described and presented, consisting of a CCD detector and precise thin YAG:Ce or LuAG:Ce single crystal screens. Different applications and various results are described. The 2D-spatial resolution of an X-ray or other ionizing radiation imaging systems is one of the critical parameters in non-destructive microradiography and radiation beam inspection. The main goal of this work was to use the 2D-imaging system with different scintillation screens, and to compare the 2D-resolution in the micrometer range and sensitivity for low energy microradiography. These imaging systems can use various scintillation detectors. Specifically, thin YAG:Ce or LuAG:Ce single crystal screens are compared. Finally, the use of an X-ray CCD camera in imaging of small, light-weight biological objects is presented.

KEYWORDS: X-ray radiography and digital radiography (DR); Inspection with x-rays; Detection of defects
1 Introduction

X-ray microradiography is a non-destructive technique that has received much attention in recent years. In principle, low energy X-ray radiation passes through an inspected sample and a high position resolution detector, based on a scintillator and an optical device, is used to detect the transmitted X-rays. It is a contrast imaging technology which utilizes the difference in X-ray absorption by different materials. Recently, three-dimensional micro-CT imaging has been attracting growing interest.

1.1 Single crystal thin plates

Thin single crystal scintillator imaging plates are used as radiation detectors in X-ray microradiography. In high resolution X-ray projection imaging, thin single crystal scintillator plates of about 5-20 micrometer thickness are used to achieve spatial resolution of about one micrometer [1, 9]. Such thin plates are mainly used in micro-CT and nano-CT systems with either micro-focus X-ray tubes or with synchrotron sources. The light distribution on the plate is transferred by a lenses optical system to a high-resolution CCD chip. For any given set of parameters of the optical collection system, there exists an optimum thickness for the scintillator plate. A thicker plate absorbs high-energy photons more efficiently but the image on the CCD becomes blurred [1]. An excessively thin scintillator does not provide enough absorption so that the integration time for an image is rather high.
1.2 YAG:Ce and LuAG:Ce single crystals

YAG:Ce or LuAG:Ce inorganic crystal scintillators are characterized by good mechanical and chemical stability, non-hygroscopicity, high scintillation efficiency and fast decays [2, 3].

\( \text{Y}_3\text{Al}_5\text{O}_{12} \) (YAG) single crystals were among the first oxide materials grown by the Czochralski technique in the 1960s [4]. The potential of Ce\(^{3+}\)-doped YAG as a fast scintillator material was recognized sometime afterwards [5]. The first comprehensive description of YAG:Ce scintillator characteristics was reported by Moszynski et al. [6], who included this material among the high figure-of-merit oxide scintillators. Isostructural \( \text{Lu}_3\text{Al}_5\text{O}_{12} \) (LuAG) has a higher density and effective atomic number \( Z_{\text{eff}} \) (6.67 g/cm\(^3\), \( Z_{\text{eff}} = 62.9 \)) compared to YAG (4.56 g/cm\(^3\), \( Z_{\text{eff}} = 32.6 \)), which is an advantage in the case of hard X and gamma-ray detection. LuAG:Ce began to be systematically studied in about 2000 [7] and the latest improvements reported in literature confirm the great potential of this scintillator [8].

Screens prepared from these crystals can be employed in devices used for the detection of different kinds of radiation and particles (UV, VUV, electrons or ions or their beams, X- or gamma-rays).

1.3 High resolution X-ray camera

The high-resolution X-ray camera consists of a high sensitivity digital CCD detector and a thin YAG:Ce or LuAG:Ce scintillator imaging screen, and is used in low-energy X-ray radiation monitoring [9]. The CCD camera uses a sensor with the dimensions of 24x36 mm\(^2\), and 11 Mpixels (4008x2672). A Peltier thermoregulation system is used for cooling and temperature stabilization. The CCD pixel size is 9 micrometers thus, using the optical system magnification 1:1, the CCD limits the X-ray resolution to about 10 micrometers, and using the optical system with a 10-times magnification the system can reach 1 micrometer resolution in X-rays. The maximum resolution is limited by the screen thickness and numerical aperture of the objective. The objective is focused on the plane inside the scintillator where the absorption image has the best contrast. The scintillator has to be thin enough to avoid blurring of the image [1].

2 Experiment

In the first experiment YAG:Ce and LuAG:Ce single crystal thin plates are compared. The single crystal plates were 20 micrometers thick in order to achieve high resolution. A small wire test grid with wires 8 micrometers apart was imaged using a Cu-anode microfocus X-ray tube.

In the second experiment a YAG:Ce plate with 0.1 mm thickness was used for the microradiography of light-weight objects. Low Z (light-weight) materials are composed mostly of carbon, hydrogen, oxygen, nitrogen, with atomic numbers of up to 18 with absorption edge energies (atomic shell) below 5 keV. The YAG:Ce scintillator is highly sensitive to the low energies of several keV. The position of the object was very close to the scintillator plate, so almost no projection magnification was used. The Cu-anode X-ray tube was used with the 8 keV line.
Figure 1. The 8-micron wide wire grid taken using YAG:Ce (left) and LuAG:Ce (right).

Figure 2. X-ray radiography of a spider, 40 keV, 2 mA, Cu anode.

3 Results

Figure 1 presents images of the test grid imaged using YAG:Ce and LuAG:Ce single crystal thin plates. The LuAG:Ce plate emits about 30% more light than the YAG:Ce plate of the same thickness (using the same experimental conditions).

Figure 2 presents an X-ray microradiography image of a spider taken using the 1:1 magnification. The image has the size of 24x36mm$^2$ with 9 micrometer pixels and 16-bit grey depth. The use of an optically clear single crystal plate sensitive to low energies resulted in a high contrast image with high detail resolution.

Figure 3 presents another example of a low-weight, low X-ray absorption contrast sample. It is a mouse brain. In the image the bloodstream within the brain is resolved.
4 Discussion

The resolution of a scintillator based system depends on several factors, primarily on the X-ray absorption process, screen geometry (mainly thickness) and on the optical system.

An X-ray is absorbed and produces scintillation photons in a volume which is energy dependent. In [1] the authors report Monte Carlo simulations for YAG:Ce showing that the great majority of scintillation photons are generated in a volume with dimensions of less than 100 nm. This is less than the diffraction-limited resolution of any optical system, thus the scintillation material and X-ray absorption process itself are not limiting factors. The resolution is limited in practice only by geometry and optical system problems.

Moreover, there is a fundamental limit for the resolution of any optical system, namely the diffraction limit. Thus, with the typical scintillator emission wavelength of 550 nm, the highest submicron resolution has probably already been reached in the synchrotron laboratory [10].

The mean absorption depth of X-ray radiation in the scintillator depends on photon energy and material. The YAG:Ce and LuAG:Ce screens are optically transparent so the image of interaction points is easily transferred to the CCD. However, the advantage of material transparency decreases with the thickness of the imaging plate. If the scintillator is thinner, the mean absorption depth is lower and the image created is sharper due to less blurring caused by lateral spread of scintillation photons. Hence, the thinner the imaging plate is, the better the resolution achieved in the image. On the other hand, detection efficiency decreases with decreasing scintillator thickness.

5 Conclusions

The experiments showed that YAG:Ce and LuAG:Ce screens are suitable for the imaging of low density materials with high spatial resolution. The resolution of the imaging system presented is about one micrometer. The LuAG:Ce screen has a higher conversion efficiency than the YAG:Ce screen, hence in the former, the signal to noise ratio of the image is better.
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References


