High-resolution application of YAG:Ce and LuAG:Ce imaging detectors with a CCD X-ray camera

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Abstract

A high-resolution CCD X-ray camera based on YAG:Ce or LuAG:Ce thin scintillators is presented. High-resolution in low-energy X-ray radiation is proved with several objects. The spatial resolution achieved in the images is about 1 μm. The high-resolution imaging system is a combination of a high-sensitivity digital CCD camera and an optical system with a thin scintillator-imaging screen. The screen can consist of YAG:Ce or LuAG:Ce inorganic scintillator [J.A. Mares, Radiat. Meas. 38 (2004) 353]. These materials have the advantages of mechanical and chemical stability and non-hygroscopicity. The high-resolution imaging system can be used with different types of radiation (X-ray, electrons, UV, and VUV [M. Nikl, Meas. Sci. Technol. 17 (2006) R37]). The objects used for the imaging tests are grids and small animals with features of several microns in size. The resolution capabilities were tested using different types of CCD cameras and scintillation imaging screens.

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1. Introduction

The spatial resolution of an X-ray imaging system is one of the most important parameters in X-ray non-destructive micro-radiography. The general trend is to visualize smaller details of an inspected object. The imaging systems in X-ray micro-radiography are mostly based on two-dimensional position-sensitive detectors (PSDs). There are many different types of PSDs with each having its advantages and disadvantages [1–3]. X-ray micro-radiography is an X-ray imaging method well known from a number of medical and biological applications related to the imaging of very small objects. The sample is irradiated with X-rays with energies sufficient for penetrating the object and being detected with a fine resolution X-ray PSD. Different parts of the sample usually have different integral (different integral absorption lengths can be caused by different materials or different thicknesses) attenuation lengths for X-rays of given energy and therefore the intensity of detected X-rays depends on the properties of the sample materials.

In the presented article, an imaging system based on a CCD camera and a single-crystal imaging screen is used to obtain images of very high resolution. Two types of screens are compared: a YAG:Ce (Y3Al5O12) and a LuAG:Ce (Lu3Al5O12) single-crystal scintillator screen. The light emission efficiency (the number of visible photons per keV) and the spatial resolution of both types of screens are compared. A comparison of the YAG:Ce screen with a standard phosphor powder scintillator P43 (GOS-Gd2O2S:Tb) has already been carried out [4]. The thin YAG:Ce single-crystal screen was found to have better spatial resolution by an order of magnitude when compared to the P43 powder screen. To achieve the very high spatial resolution of 1 μm, which is about 10 times higher than standard X-ray imaging CCD cameras (standard X-ray imaging CCD cameras have pixel size...
from 10 to 24 μm, also due to charge capacity), the high-quality screens are used together with a high-sensitivity CCD camera.

2. High-resolution imaging system

A high-resolving and very sensitive X-ray CCD camera was successfully used for X-ray micro-radiography of several biological and other samples. It consists of three main parts: the CCD camera itself, the optics and a scintillator screen as the detector of X-rays.

For the experiments, two different CCD cameras have been developed by the companies Reflex s.r.o. and Crytur, Ltd. The cameras are based on different CCD sensors. The RX1 camera has a sensor size of 4.8 mm × 3.6 mm with pixel size of 7.4 μm², the RX2 camera has a sensor size 8.9 mm × 6.7 mm pixels with a pixel size 6.45 μm².

High-quality industrial YAG:Ce and LuAG:Ce single crystals were prepared by the Czochralski method [5] at Crytur. Some physical properties like the mechanical and chemical stability and the non-hygroscopicity of the aluminum garnets [2] allow the preparation of plates down to several micrometers in thickness. The imaging scintillator screen is optically transparent. The emission wavelength of YAG:Ce and LuAG:Ce is 550 and 535 nm, respectively. The spatial resolution of the screen depends on screen thickness, photon energy and the average depth of absorption of the photons. An optical system using a magnifying lens was used to transfer the scintillator screen image to the CCD image area surface.

3. Experiments

The scheme of the experimental setup is shown in Fig. 1. In the first experiment, the light emission intensity of the YAG:Ce and LuAG:Ce scintillators was compared. The scintillator was placed in the focused object plane of the optics. The scintillators have the shape of a round plate with diameter of 19 mm and thickness of 20 μm. The RX1 metrological-design camera was used for that experiment.

In the second experiment, several objects were placed in proximity to the imaging screen in order to keep the smearing effect caused by the X-ray focal spot size as low as possible. To achieve high resolution, a micro-focus (40 μm spot size on Cu anticathode) X-ray tube was used.

The temperature of the camera was stabilized by recirculating water-cooling chiller. To increase the signal-to-noise ratio, averaged raw images were calculated from several single raw images captured in sequence. The CCD image sensor was not cooled enough to take longer exposure times. In the case of signal levels, which are close to the saturation level of the CCD, only averaging can increase signal-to-noise ratio. The resulting images were processed via dark background subtraction and flat field correction.

4. Results and discussion

In the first experiment, the light detected by the CCD is averaged in a squared ROI of 200 × 200 pixels in the center of the CCD. The YAG:Ce gives a value 17,507 e⁻/pix/s (number of electrons in CCD pixel per second) and the LuAG:Ce gives the value 26,452 e⁻/pix/s, which is about 1.51 times the value of YAG:Ce.

The LuAG:Ce single crystal is more dense compared to YAG:Ce (density: 6.73–4.57 g/cm³) and the X-rays are absorbed stronger by LuAG (1.7 times more of X-ray radiation (photons) is absorbed in the range between 1 and 40 keV, as calculated using X-ray radiation attenuation coefficients).

In the second experiment, several test objects were used to prove the spatial resolution of the described imaging system in X-ray micro-radiography. Fig. 2 presents an image of a golden grid made of wires, which have a size of about 10 μm.

The image on the left-hand side was taken with the LuAG:Ce 20 μm screen and the picture on the right was taken using the YAG:Ce 20 μm screen. The effective pixel size of the CCD camera used was 0.74 μm. The X-ray micro-focus source was operated at 40 kV/2 mA. The image acquisition time was 5 s and the averaging was performed with samples of 25 images.

A zoom-in on a detail of the grid is shown in Fig. 3. It shows that the resolution of the imaging system is in the order of micrometers.

The line profile of one grid wire is shown in Fig. 4. The profile is compared with the geometric profile of the grid wire, which has trapezoidal shape with a base of 10.7 μm and top 6.8 μm wide (measured in an SEM image of the grid).

Several biological samples were studied in the next experiment. In this paper, only Drosophila is presented.
The image is shown in Fig. 5 with the gray scales indicating the transparency of the sample. The images were taken by the RX2 camera in the same setup as the images of the grid, using a YAG:Ce 20 μm screen and a magnifying lenses. The acquisition time was set to 20 s.

The zoom image showing selected details of the fly’s leg in Fig. 6 demonstrates that a resolution of about several μm is achievable by the used imaging system. The effective pixel size of the system is about 0.65 μm.

5. Conclusions

In the experimental setup presented, a high-resolution imaging system based on CCD camera with lenses and precisely manufactured YAG:Ce and LuAG:Ce single-crystal screens was used for X-ray micro-radiography. The mean absorption depth of X-ray radiation in the scintillator depends on photon energy and the 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 the material transparency decreases with the thickness of the imaging plate. If the scintillator is thinner, the mean absorption depth is lower and the created image is sharper due to less blurring of the image due to less lateral spread of the scintillation photons. Hence, the thinner the imaging plate is, the better is the resolution achieved in the image. On the other hand, the detection efficiency decreases with scintillator thickness.

The experiments proved that the YAG:Ce and LuAG:Ce screens are suitable for imaging with high spatial resolution. The submicrometer spatial resolution using synchrotron radiation has been already achieved [6]. The resolution of the presented imaging system is about 1 μm.

The LuAG:Ce screen has higher conversion efficiency than the YAG:Ce screen, so that the signal-to-noise ratio of the image is better for the use in the imaging system.

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References