Single crystal scintillator plates used for light weight material X-ray radiography

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Abstract. Very thin scintillator imaging plates have recently become of great interest. In high resolution X-ray projection imaging, very thin scintillators of about 5-20 micrometres are used to achieve high spatial resolution. Such thin screens are mainly used in micro-CT and nano-CT systems with either micro-focus X-ray tubes or with synchrotron sources. This work deals with a high resolution CCD camera in connection with an optical system and different single crystal scintillators in application for low energy X-ray micro-radiography. The thin screens used were prepared by mechanical polishing from \( Y_3Al_5O_{12} \) or \( Lu_3Al_5O_{12} \) single crystals. The screens can be used in equipment for the detection of different kinds of radiation and particles (UV, VUV, electrons or ions or their beams, X- or gamma-rays). A high resolution open type micro-focus X-ray tube was used to achieve the high resolution. The results show that the single crystal plates exhibit high spatial resolution and high sensitivity to low energy X-rays resulting in high image contrast. The use of the plates is highly suitable for light weight (low Z) material X-ray radiography. The resolution achieved is demonstrated using a test grid. Several light weight objects are imaged using the thin plates.

1. Introduction
X-ray micro-radiography is a non-destructive method that has been receiving much interest in recent years. In principle X-ray radiation passes through an inspected sample and a high resolution detector based on a scintillator and an optical device is used to detect the transmitted X-rays. It is a contrast imaging technology using the difference in absorption of X-rays in different materials. Recently, three-dimensional CT imaging has been experiencing growing interest.

Very thin single crystal scintillator imaging plates are radiation detectors that are used in low energy X-ray micro-radiography. In high resolution X-ray projection imaging, very thin single crystal scintillator plates of about 5-20 micrometres in thickness are used to achieve spatial resolution of about one micrometre. 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 an optical system to a high-resolution CCD chip. For a specific 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 due to optical effects caused within the scintillator-objective-CCD optical system. The resolution is limited mainly by the depth of focus and

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defect of focus of the optics, and by diffraction and spherical aberration arising from the scintillator thickness [1]. On the other hand an excessively thin scintillator does not provide enough absorption so that the integration time for an image is rather high.

1.1. Single Crystal Thin Plates

Single crystal thin plates are made from single crystal boles. The most used crystals are yttrium \( \text{Y}_3\text{Al}_5\text{O}_{12} \) (YAG) or lutetium \( \text{Lu}_3\text{Al}_5\text{O}_{12} \) (LuAG) garnet, both doped with cerium. High quality industrial YAG:Ce and LuAG:Ce single crystals are prepared by the Czochralski method [2] at Crytur.

These inorganic crystal scintillators are characterized by good mechanical and chemical stability, non-hygroscopicity, high scintillation efficiency and fast decay [3], [4]. The imaging scintillator screen made of this single crystal is optically transparent. The emission wavelength of YAG:Ce and LuAG:Ce is 550 nm and 535 nm, respectively. Imaging screens prepared from these crystals can be used in equipment for the detection of different kinds of radiation and particles (UV, VUV, electrons or ions or their beams, X- or gamma-rays).

1.2. X-Ray CCD Camera

The high-resolution X-ray camera consists of a highly sensitive digital CCD detector and a thin YAG:Ce or LuAG:Ce scintillator imaging screen and is used in low-energy X-ray radiation radiography [5]. The camera includes a CCD optical sensor with the dimensions of 24x36 mm\(^2\), and of about 11 Mpixel resolution. A Peltier thermoregulation system is used for cooling and temperature stabilization. The CCD pixel size is 9 micrometres and the optical system uses objectives with magnification of 1 x or 10 x. The CCD pixel size together with the optics magnification determines one of the limits for system spatial resolution. Also, the maximum system spatial resolution is limited by the screen thickness and numerical aperture of the objective.

2. Experiments

2.1. Testing Grid

In the experimental setup, the highly sensitive CCD camera and YAG:Ce or LuAG:Ce single crystal thin plates presented were used for X-ray micro-radiography. Different scintillator thicknesses were used to reach the highest possible resolution. The objective was focused into the plane inside the scintillator where the absorption image has the best contrast. The camera was in a sideway position to avoid direct impact of the X-rays on camera electronics.

The position of the object was very close to the scintillator plate, so almost no projection magnification was used. A Cu anode microfocus X-ray source was used with intensity maximum at about 8 keV. The X-ray CCD camera resolution was tested using a special grid, see figure 1. The 3 mm diameter grid was made of copper and the wires were about 8 micrometres in width.

**Figure 1.** X-ray radiographs of the grid using LuAG (left) and YAG (right) and the objective of 10x magnification.

**Figure 2.** X-ray radiograph of the grid using 1:1 magnification.
The absorption image of the grid (X-ray radiograph) is shown in figure 1. The image was taken using an objective with 10x magnification and a very thin single crystal screen with a thickness of 20 micrometres. The resolution of such imaging system is about 1 micrometre. The absorption image in figure 2 was taken using an objective with magnification of 1:1 and a single crystal screen with a thickness of 50 micrometres. The wires were imaged with good resolution and contrast. The resolution of this imaging system is about 10 micrometres.

2.2. Measurement of fine low contrast fibres
To illustrate the quality of the images obtained by the CCD camera with a YAG:Ce scintillation screen, a bundle of low contrast plastic fibres was measured (diameter of fibres is about 6-9 µm), see figure 3. The acquisition time for the image was 240 s (post-processed by background subtraction and flat field correction), on a micro focus X-ray tube set to 60 kV and 2 watts with a copper target on a beryllium window.

3. Discussion
The resolution of a scintillator based system depends on several factors, mainly on the X-ray absorption process, screen geometry (mainly thickness), and 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 which show that the great majority of scintillation photons is 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 a limiting factor at all. The resolution is limited practically only by geometry and optical system problems.

Moreover, there is a fundamental limit for the resolution of any optical system, this being the diffraction limit. Thus for the typical scintillator emission wavelength of 550 nm, the highest submicron resolution has probably already been reached in the synchrotron laboratory [6].

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 material transparency decreases with increasing imaging plate thickness. If the scintillator is thinner, the mean absorption depth is lower and the image created is sharper due to less blurring of the image, which in turn is due to less
lateral spread of the scintillation photons. Hence, the thinner the imaging plate is, the better the resolution achieved in the image. On the other hand, the detection efficiency decreases with scintillator thickness.

Light weight (low Z) materials are composed mostly of carbon, hydrogen, oxygen, and nitrogen, with atomic numbers smaller than 10, and up to 18. These low Z elements are characterized by the absence of an absorption edge (atomic shell energy) higher than 5 keV. Real X-ray tube spectrum has almost no energy below 5 keV, thus low Z elements have extremely low contrast due to, almost entirely, their density.

The efficiency of scintillation screens depends on the absorption of the X-ray energy spectrum in the material. The highest 2D-spatial resolution achieved in the images using the system presented was about 1 micron [5] utilizing a microfocus X-ray source.

4. Conclusions
In the experimental setup presented, a high resolution imaging system based on a CCD camera with lenses and precisely manufactured YAG:Ce and LuAG:Ce single crystal screens was used for X-ray micro-radiography.

The experiments proved that the YAG:Ce and LuAG:Ce screens are suitable for imaging with high spatial resolution. The highest resolution achieved by the presented imaging system is about one micrometer. The LuAG:Ce screen has higher conversion efficiency than the YAG:Ce screen, hence the signal to noise ratio of the image is better.

The sensitivity of the YAG:Ce and LuAG:Ce single crystals screens to low energies predestines them for applications in low weight material radiography. The YAG:Ce and LuAG:Ce single crystals are highly sensitive to low X-Ray energies (starting below 1 keV).

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