High Resolution Single Crystal Scintillator Plates Used for Light Weight Material X-Ray Radiography

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Abstract. Recently, very thin single crystal scintillator imaging plates became of great interest. 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 conjunction with a macro optical system and YAG:Ce single crystal scintillators for low energy X-ray micro-radiography applications. 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 plates are highly suitable for light-weight material X-ray radiography. The high resolution and contrast are demonstrated on single carbon fibers. Several other light-weight objects are also imaged.

1. Introduction

X-ray microradiography is a non-destructive technique that has received much attention in recent years. In principle, 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, 2]. 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 lens 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 Single Crystal

The YAG:Ce inorganic crystal scintillator is characterized by good mechanical and chemical stability, non-hygroscopicity, high scintillation efficiency and fast decays [3], [4]. \( \text{Y}_3\text{Al}_5\text{O}_{12} \) (YAG) single crystals were among the first oxide materials grown by the Czochralski technique in the 1960s [5]. The potential of Ce\(^{3+}\)-doped YAG as a fast scintillator material was recognized sometime afterwards [6]. The first comprehensive description of YAG:Ce scintillator characteristics was reported by Moszynski et al. [7], who included this material among the high figure-of-merit oxide scintillators. YAG has a density of 4.56 g/cm\(^3\) and effective atomic number \( Z_{\text{eff}} = 32.6 \). 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 CRYCAM 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 [2]. The CCD camera uses a sensor with the dimensions of 24\( \times \)36 mm\(^2\), and 11 Mpixels (4008x2672). A Peltier thermoregulation system is used for cooling and temperature stabilization. The camera gray depth is 16 bits. 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 with a 50 \( \mu \)m – 70 \( \mu \)m thick scintillator; and using the optical system with a 10-times magnification and 5 \( \mu \)m thick scintillator 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 experimental setup the presented high sensitive CCD camera and 50 \( \mu \)m thick YAG:Ce single crystal thin plate was used for micro-radiography of light-weight objects. A Cu-anode microfocus X-ray source was used with intensity maximum at about 8 keV.

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.

3. Results

The position of the objects was close to the scintillator plate, so only small projection magnification was used. Figure 1 presents a radiograph of a bundle of low contrast carbon fibres (fibre diameters are about 6-10 \( \mu \)m). The acquisition time for the image taken 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. The use of an optically clear single crystal plate sensitive to low energies resulted in a high contrast image with high detail resolution.
Figure 1. Radiograph of a Carbon Fibre Bunch (Fibre Diameters 6-10 µm)

Figure 2 presents another example of a low-weight, low X-ray absorption contrast sample. It is a porous plastic foam.

Figure 2. X-Ray Radiograph of a Plastic Foam

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. In practise, the resolution is limited 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 [8].
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. Spatial resolution of the CRYCAM at 0.05 MTF is 13.44 lp/mm [9].

5. Conclusions

The experiments showed that YAG:Ce screen are suitable for the imaging of low density materials with high spatial resolution. The resolution of the imaging system presented is about 10 micrometers.

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References