Nuclear Instruments and Methods in Physics Research A 833 (2016) 68–76

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Broadband X-ray edge-enhancement imaging of a boron fibre on lithium fluoride thin film detector

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ARTICLE INFO

Article history:
Received 21 April 2016
Received in revised form
22 June 2016
Accepted 4 July 2016
Available online 6 July 2016

Keywords:
Radiation detectors
X-rays
X-ray edge-enhancement imaging
Lithium fluoride
Colour centres
Photoluminescence

ABSTRACT

The white beam (~6–80 keV) available at the TopoTomo X-ray beamline of the ANKA synchrotron facility (KIT, Karlsruhe, Germany) was used to perform edge-enhancement imaging tests on lithium fluoride radiation detectors. The diffracted X-ray image of a microscopic boron fibre, consisting of tungsten wire wrapped by boron cladding, was projected onto lithium fluoride thin films placed at several distances, from contact to 1 m. X-ray photons cause the local formation of primary and aggregate colour centres in lithium fluoride; these latter, once illuminated under blue light, luminesce forming visible-light patterns —acquired by a confocal laser scanning microscope—that reproduce the intensity of the X-ray diffracted images. The tests demonstrated the excellent performances of lithium fluoride films as radiation detectors at the investigated photon energies. The experimental results are here discussed and compared with those calculated with a model that takes into account all the processes that concern image formation, storing and readout.

1. Introduction

Dielectric materials containing point defects [1] are successfully utilised in several fields, including radiation detection [2]. For instance, colour centres (CC's) [3] in lithium fluoride (LiF) are well known for their application in tuneable solid-state lasers [4], dosimeters [5], and miniaturised light-emitting devices [6]. Certain types of CC's in LiF are optically active, stable at room temperature, and possess broad absorption and emission bands in the visible [7]. Among them, F_2 and F_3^+ aggregate centres, consisting of two electrons bound to two and three closely spaced fluorine vacancies, respectively, emit in the red (F_2) and green (F_3^+) portions of the spectrum and have almost overlapping absorption bands peaked at the wavelength of ~450 nm (M band) [7]. For this reason, F_2 and F_3^+ centres can be simultaneously excited with a single-wavelength optical pump in the blue.

Because of their high-penetration properties, X-rays are widely used to analyse the internal structure of objects, including biological samples. Absorption contrast is perhaps the most elementary and intuitive technique utilised to record radiographies; this is possible when samples present details whose absorption properties are clearly distinguishable (contrasted) at the operating X-ray wavelengths. On the other hand, for high-energy X-rays, the absorption coefficient of most materials is relatively small so that they behave as almost pure phase objects. The lack of absorption contrast can be compensated by adding phase information to the recorded image [8]. A possible approach to that is edge-enhancement imaging, also known as in-line phase-contrast imaging [8,9].

Edge-enhancement imaging is a technique—utilised with spatially coherent X-rays—based on wave free propagation that allows enhancing visibility of sharp spatial details of samples by detection of the transmitted electromagnetic wavefront after it has freely propagated in the near field [10–16]. When an X-ray beam is transmitted through a sample that consists of parts with different refractive indices and absorption coefficients, its wavefront locally experiences distinct amplitude and phase changes. While, in case of a sample consisting of solely absorbing materials at the probing wavelengths, the borders among the sample parts can be visualised even on a detector, sensible to electromagnetic intensity,

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http://dx.doi.org/10.1016/j.nima.2016.07.005
0168-9002/

placed at zero distance (absorption contrast), differences in phase are not directly visible in a setup where sample and detector are in contact because they induce no direct intensity change. Fresnel diffraction [17] comes in helpful in this case, because it is a known fact that at increasing distances from the sample more and more spaced Fresnel fringes appear along lines separating wavefront areas that bring distinct phase information, thus making them clearly visible provided that the wavefront intensity is recorded by a suitable high-resolution detector. As a matter of fact, interference fringes in Fresnel diffraction are proportional to the second spatial derivative (Laplacian) of the phase of the wavefront [11,16], so that they appear where abrupt phase changes take place, like those due to borders among materials with different refractive indices. Applicability of edge-enhancement imaging is strongly related not only to the characteristic of the utilised X-ray source, especially as far as its transverse coherence properties are concerned, but also to those of the detector, which should be able to spatially resolve the Fresnel fringes.

High-resolution X-ray imaging can be accomplished with a variety of methods [18]; however, all of them are limited by the resolution and/or the dynamic range of the most common radiation detectors. Solid-state LiF detectors, based on radiation sensitivity of the material and optical readout of photoluminescence (PL) from F_2 and F_3^+ CC's, can overcome the above-mentioned limitations so that they become potentially suitable for the characterisation of micro and nanostructures as well as biological samples. High spatial resolution across a large field of view, wide dynamic range, and versatility make them very convenient as recording plates for both X-ray absorption-contrast [19–23] and phase-contrast [24,25] imaging. LiF imaging radiation detectors were successfully used by using several X-ray sources, such as synchrotrons [25–27], laser plasma sources [20,21,28,29], capillary discharge lasers [30], table X-ray tubes [22,31].

Suitableness of LiF, either in bulk or thin film form, as edge-enhancement imaging detector for white beam synchrotron X-rays was recently tested at the ANKA light source of the KIT synchrotron facility in Karlsruhe, Germany [25]. The test consisted of transmitting the white beam spectrum through an Xradia test pattern, and exposing LiF-based detectors, placed at a distance of 17.5 cm, to the transmitted beam. Optically-active CC's were created, in this way, in LiF, with a transversal distribution reproducing the diffracted shadow of the test pattern. With no further treatment or special handling, the stored CC distributions were detected and acquired as bi-dimensional maps of visible PL in a fluorescence microscope, by illuminating the exposed LiF samples with blue light in order to optically pump F_2 and F_3^+ CC's [25].

In the present paper, the results of a systematic experiment are reported and discussed. With a selected specimen, consisting of a boron fibre (BF) [32], LiF thin-film radiation detectors were tested in an X-ray edge-enhancement imaging setup in the same beamline of [25], that is by using a white X-ray beam whose energy spectrum ranges approximately from 6 to 80 keV. In the literature other papers are available where BF's are dealt with as far as imaging with coherent X-rays is concerned [33–38]; the main novelty here is the use of luminescent LiF film detectors instead of more traditional ones, such as scintillators and CCD arrays or cameras. Furthermore, with respect to a recent paper reporting a similar test at the same beamline [25], in the present study a good portion of the sample—the B cladding—is an essentially pure phase object with refractive index gradient along one axis, while in [25] the sample was mostly an amplitude object. Another difference is that here the LiF detectors are placed at various distances from the specimen, ranging from complete contact to 1 m, to test their suitableness to both absorption-contrast (concerning the W wire) and phase-contrast imaging. As in [25], the CC distributions generated in LiF are later observed as bidimensional PL maps under the blue light of a confocal laser scanning microscope (CLSM); one-dimensional cross-sections of the detected maps are here compared with those calculated with a theoretical model. The results confirm the good performances of LiF films as imaging detectors for broadband X-ray beams, even when used with samples having important phase-only components.

The paper is organised as follows. The experimental part is reported in Section 2, while the theoretical model is explained in Section 3. In Section 4 a comparison between experimental and simulated PL maps is reported and discussed. Section 5 closes the paper with conclusions.

2. Experimental

The irradiations were performed at the TopoTomo beamline of the ANKA light source (Institute for Synchrotron Radiation, Karlsruhe Institute of Technology KIT, Germany). The ANKA synchrotron facility is operated with an electron energy of 2.5 GeV. The TopoTomo beamline can work either in 'white beam' (polyenergetic) or in monochromatic mode; the available white-beam energy spectrum ranges approximately from 6 to 80 keV. Other specifications are available elsewhere [25] and online at the ANKA website [39].

For the X-ray imaging experiment here reported, the TopoTomo beamline was operated in white-beam mode. After an in-vacuum propagation of 27.7 m, a 250 μm thin vacuum-sealing beryllium (Be) window allowed the passage of the beam into air, where a 2 mm thick silicon (Si) plate was placed before the sample in order to cut the beam low-energies and thus minimise the absorbed dose. The distance of the BF from the X-ray source was 29 m. After interacting with the BF, the beam wavefront freely propagated to the LiF film detector, that was placed at various distances—five sampled distances from contact to 1 m—from the BF itself.

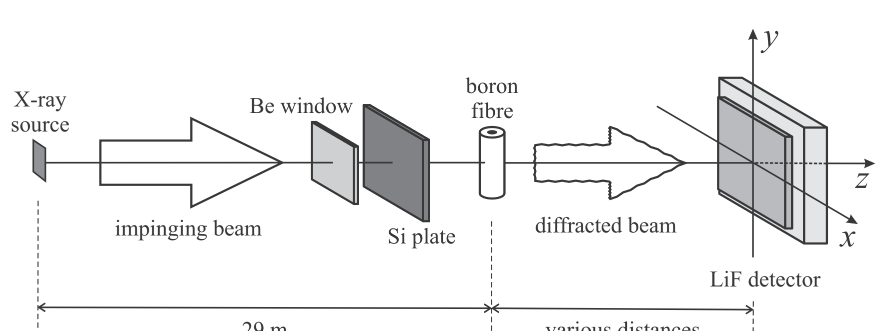

Fig. 1. Simplified scheme of the irradiation setup in the X-ray edge-enhancement imaging experiment on LiF film detector at the TopoTomo beamline of the ANKA light source (Institute for Synchrotron Radiation, Karlsruhe Institute of Technology KIT, Germany).