A high resolution soft X-ray scintillation detector based on the Young-Weierstrass points of a lens shaped YAG crystal

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Abstract. Shaping a YAG scintillator crystal into a truncated-ball lens enables to image with a high numerical aperture its front surface, where the image converted from X-rays to visible light is localized. Hence, both resolution and luminosity gains can be expected. Moreover if the plane surface is set at the Young-Weierstrass point of the spherical refractive surface, stigmatic imaging is achieved. On this principle, we have constructed an imaging detector from a 10 mm diameter YAG:Ce sphere and a long working distance plane-apochromatic microscope objective which does not limit the numerical aperture. The effective numerical aperture of the built system is 1.08, giving a Rayleigh resolution limit of 0.3 µm. Images of test objects (diatoms) have been recorded, in contact mode, with 103 eV. Periodic features of 0.4 µm pitch are visible on these images. The field of view is close to 200 µm. The device is intended as an aid for X-ray optics fine-tuning and characterization.

1. Introduction

YAG doped crystals are scattering free materials which, in principle, allow imaging at resolutions only limited by the penetration depth of the X-ray radiation. In the soft X-ray range, sub-micrometer resolution should be achievable. YAG crystals are usually manufactured into thin plane parallel plates. The image formed in the vicinity of the exposed surface is collected through the plate by a microscope lens and projected with magnification on an imaging detector. However, because of the high index of refraction of YAG (n=1.8361 for YAG:Ce at 550 nm, mean emission wavelength) [1] the plane parallel geometry severely limits the collection aperture inside the crystal, namely to NA₀/n, where NA₀ is the numerical aperture of the imaging lens (figure 1 a). A large amount of light is reflected at the interfaces and is lost, and, moreover, the resolution is spoiled by the spherical aberration of the plane refracting surface.

Higher collection apertures, and hence gain on resolution and flux, can be achieved by giving a spherical shape to the exit face. Gluing the scintillator to a high index glass hemisphere has been used to improve the flux collection [2], but do not solve the stigmatism problem. However, by shaping the YAG itself into a truncated-ball, with a flat surface at the nearest Young-Weierstrass point of the spherical refracting surface (figure 1 b), a factor n² can be gained on the collection aperture and imaging is stigmatic at the center of the field of view. This is the usual design of the first lens of a microscope immersion objective.

An imaging detector, was build according to this principle from a 10 mm diameter YAG:Ce sphere and a long working distance X 20 Mitutoyo plan-apochromat microscope objective. This paper...
describes its main optical and mechanical design features, then reports the first experimental results obtained in soft x-rays on the SEXTANTS beamline of SOLEIL.

Figure 1. Aperture inside and outside the YAG scintillator according to the shape of the exit surface.

a) the crystal is a plane and parallel plate: the internal aperture is lower than the external one.

b) the crystal is a truncated sphere: the internal aperture is larger than the external one.

2. Optical and mechanical design

A refractive spherical surface (Σ) separating a medium of index n inside from a medium of index 1 outside, is rigorously stigmatic for the couple of points A A’ which is harmonically divided by the diameter SS’ with the ratio n. A and A’ are the Young or Weierstrass points (figure 1b). They verify:

\[ n \frac{AP}{A'P} = 1 \quad \forall P \in \Sigma \]

and hence fulfill the Abbe condition with \( \frac{\sin \alpha}{\sin \alpha'} = n \quad \forall \alpha \). In our device, the YAG:Ce scintillator from Crytur[3] has been ground and polished into a sphere of 10.198 mm diameter then cut to a thickness of 7.879 mm, only 3 µm thicker than the nominal position of the Weierstrass point. The image point is located at the other Weierstrass point 6.6 mm outside (figure 2). The Mitutoyo X 20 objective has a working distance of ~20 mm and its first surface is distant of approximately 5.5 mm from sphere apex. The YAG plane face is pressed against the mounting flange and seals, with a small O ring, the Ø 2mm aperture drilled into it to let the X-rays through. The maintaining mechanics frees a 55° area of the sphere allowing maximum apertures \( \sin \alpha = 0.59 \) and \( \sin \alpha' = 0.322 \). Hence, the numerical aperture of the imaging system is 1.08, and the 0.42 NA of the microscope objective is not limiting. The theoretical resolution of the imaging system at 550 nm wavelength is 0.3 µm, according to the Rayleigh criterion or equivalently, the cutoff spatial frequency is nearly 4 µm⁻¹.

Figure 2. Schematic diagram showing the geometry of the YAG ball lens for imaging at the stigmatic Young -Weierstrass points, and the position of the first lens of the microscope objective.

The magnification given by the lens ball is (from Lagrange invariant) \( M = \frac{y'}{y} = \frac{n \sin \alpha}{\sin \alpha'} = n^2 = 3.37 \).

The infinity corrected objective, is used in its focal plane and, with a 200 mm relay lens, adds its nominal X 20 magnification, giving an overall magnification of 67.4 from the scintillation image to
the CCD detector. A 10 nm wide filter centered at 550 nm is placed between these two lenses to avoid chromatic effects. For the first experiment the detector was a Basler Scout CCD camera with 660 x 490 pixel. The pixel size is 7.4 µm and corresponds to 0.11 µm on the object plane. The system has been designed for a 1392 x 1040 pixel camera and a pixel size of 6.45 µm (0.1 µm/px on the object). The corresponding field of view of 132 x 100 µm, remains well inside the 200 µm diameter full resolution field of view of the ball lens set by its field curvature.

3. Experimental results

The detector has been tested in soft X-rays on SEXTANTS beamline of SOLEIL on the KB focused branch, where beam size and flux can be easily adjusted by means of the KB benders and the size of the intermediate slits. Images of figures 3 to 5 were recorded during this beamtime.

Figure 3 is the image of a 1500 mesh/inch gold grid which was placed as close as possible to the YAG surface. Unfortunately, the grid fragment stayed a few mm away from the YAG. Partial coherence of the beam gives rise to an interference pattern which is difficult to interpret because the exact distance is not known. However, the minimum period must be equal to the grating pitch i.e. ~16.9 µm. The shown profile gives a period of 144.5 pixels, hence a magnification of 63.2, which, in respect of grid orientation uncertainty, is close enough to the theoretical value.

Figure 4 is an image of the KB focus, with the intermediate slits closed to their minimum width of a few µm.

None of these images can be used to evaluate the resolution and it was difficult to find an object giving enough contrast with submicron features. We finally went for diatoms dispersed in a drop of water which was deposited on the YAG surface. Though the thin silica walls of diatom frustules create only a weak contrast, we could isolate a region of 300 x 100 pixels of the field containing a diatom and some diatom fragments showing distinctive structures. Figure 5a is an image of this field of view with 103 eV x-rays [4].

The well known shape and size stability of diatoms silica frustules allows us to compare the x-ray images to the SEM image, showed on figure 5b, of a sample prepared from the same suspension where the same entire boat-shaped diatom and a fragment of a diatom girdle-band can be clearly identified. The boat-shaped diatom is measured with a length of 12 µm by the SEM and 107 pixels in x-rays, giving a 66X magnification which is almost the theoretical one. The series of holes of the girdle-band
Figure 5. a) Image of a 300 x 100 px part of the field of view containing one entire diatom and some other diatom fragments. The photon energy is 103 eV; b) Reference SEM image showing the shape and size of similar diatoms; c) magnified view of the girdle-band diatom fragment, framed area on view a.; d) intensity profile along the marked white line showing a faint 0.4 µm period modulation.

diatom fragment with a 0.4 µm period is just resolved, while the ribs of the boat-shaped diatom, which SEM sees with a 0.3 µm period, are faintly visible on original images.

4. Conclusion
We have build a fluorescence detector based on a YAG:Ce crystal shaped into a ball lens designed to work at the Young-Weierstrass points. The setup has a large object NA of 1.08 which gives a diffraction limited resolution of about 300 nm, and allows a high collection efficiency. The optics limited field of view is close to 200µm. The overall magnification of the device is 67.4 and is confirmed by the image of a calibrated grid. Images of test objects (diatoms) have been recorded, in contact mode, with 103 eV x-rays. Periodic features of 0.4 µm pitch are visible on these images. Further characterization should be done to assess the exact resolution and flux gain.

The device is intended as an aid for fine-tuning and characterization of high resolution soft X-ray optics. Further improvement could be done, namely by replacing the commercial objective by a specially calculated one in order to correct field curvature and chromatism. A plan-achromatic design of the whole optics would not only increase the field of view but also the collection efficiency by eliminating the need of a wavelength selection filter.

References
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[2] Yamamoto K, Tanji T, Hibino M, Schauer P and Autrata R 2000 Microsc. Res. Tech. 49 596 -604
[3] www.crytur.cz
[4] The diatoms of unidentified species were collected and prepared by one of us. All organic matter was removed in sulfochromic mixture so that only the silica skeletons (frustules) remain.