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NANOSATELLITE X-RAY LOBSTER EYE OPTICS – MEASUREMENT OF OPTICAL PERFORMANCE

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Abstract. This paper presents the results of tests of a one-dimensional Schmidt lobster-eye prototype module. The optics benefits from the new technology used for the mechanical part which ensures accurate positioning of individual mirrors, resulting in a sharp image in the focal plane. The prototype is designed for X-ray energy of around 1 keV, but it was tested in the visible part of the spectrum. FWHM is determined. The experimental results agree well with the simulations.

Keywords: Lobster eye, multi-foil optics, reflective optics, grazing incidence optics, X-ray optics.

1. Introduction

The lobster eye concept of grazing incidence optics offers a wide filed of view that makes this optics convenient for space X-ray sky monitors [1–8]. The Schmidt lobster eye [9] is assembled from planar rectangular mirrors, mutually tilted. There exists another design called the Angel lobster eye [10], which is formed by rectangular channels. The lobster eye optics is commonly used for X-rays. Its main advantage is the wide field of view that makes it suited mainly for space X-ray monitors.

The mirrors of a one-dimensional lobster eye are arranged around a virtual cylinder, see Figure 1. This set of mirrors will be further referred to as the stack. The optical behaviour of a single stack is similar to a cylindric lens. The focus of the system is marked **F**. The point **C** denotes the centre of the cylinder. β is the angular mirror position

Schmidt lobster eye geometry is defined by these parameters:

- r radius of the cylinder,
- a mirror spacing,
- t mirror thickness,
- h mirror depth,
- N number of mirrors.

It is possible to use two orthogonally arranged stacks to make a double-reflecting device mimicking the function of a spherical lens, see Figure 2.

The technical challenge of the realisation of the Schmidt lobster eye is to ensure the accurate positioning of individual mirrors. That is why a new technological concept has been proposed and covered by patent [11] and utility models [12, 13].

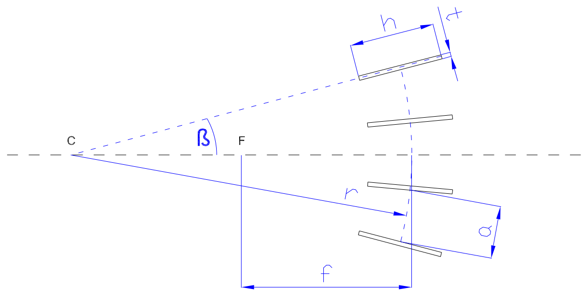

Figure 1. Layout of one-dimensional Schmidt lobster eye. The figure is not scaled to real dimensions.

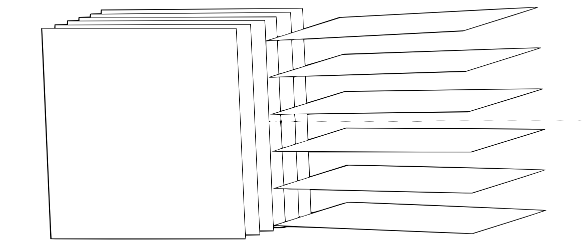

Figure 2. Optical layout of stacks of two-dimensional Schmidt lobster eye.

The results of optical measurements of the prototype module assembled by this technology are presented in this paper.

2. Description of LNA-215 prototype module

The photo of the prototype one-dimensional lobster eye LNA-215 is shown in Figure 3. The module has been designed to be tested on a CubeSat platform. Therefore, the focal length and the input aperture of

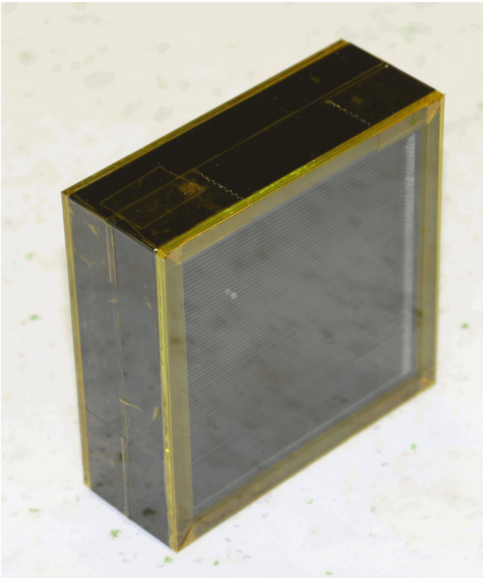

Figure 3. Photo of prototype module LNA-215.

the optics were chosen so that the optics together with a focussed detector would fit three units of a CubeSat satellite. The mirror spacing has been set to maximise the effective collection length.

Prototype lobster eye LNA-215 has the following design parameters:

- Focal length $F = 215$ mm.
- Entrance aperture 87×84 mm.
- Stack consists of $N = 66$ gold-coated glass mirrors with a depth of $h = 24$ mm and thickness of $t = 0.28$ mm.
- Mirror pitch $A = 1.33$ mm.
- Footprint $95.8 \times 95.8 \times 26$ mm without external housing. This allows it to be used on a 3U or larger CubeSat.
- Designed for energies of around 1 keV but tests are possible in a wider spectral range.

The following performance was calculated by simulations:

- Field of view 10.4°.
- Effective collecting length 1.6 cm at 1 keV.
- Corresponding effective collecting area 2.4 cm^2 for 2-D system.

Preliminary tests with a simple aparatus using polychromatic light were presented in [14]. In this paper, the results of measurements on an optical bench in a laboratory are presented.

3. Experimental setup

The lobster-eye prototype was tested in the optical laboratory of the Faculty of Mechanical Engineering of Czech Technical University in Prague. The setup consists of a light source, collimator, tested optics and a camera, see Figure 4. The mirrors are made of gold-coated glass, which also reflect visible light. This allows the test to be performed in the visible part of the spectrum. A green high-power LED was used as the light source. The focal length of the collimator was 1 600 mm. A Canon EOS 50D camera was used to take the image. Its resolution is $4\,752 \times 3\,168$ pixels and the sensor area is 22.3×14.9 mm.

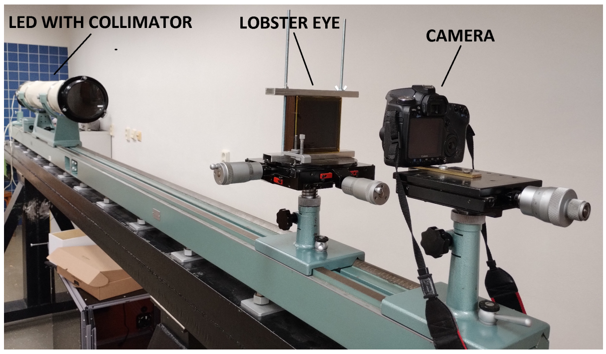

Figure 4. Experimental setup.

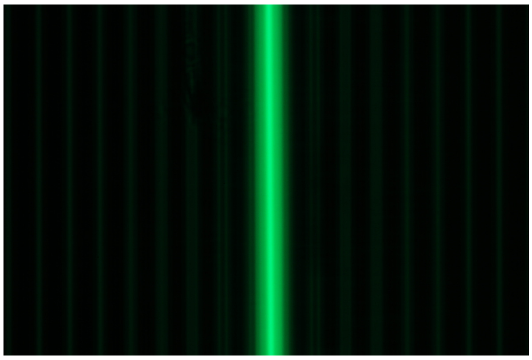

Figure 5. Acquired focal image.

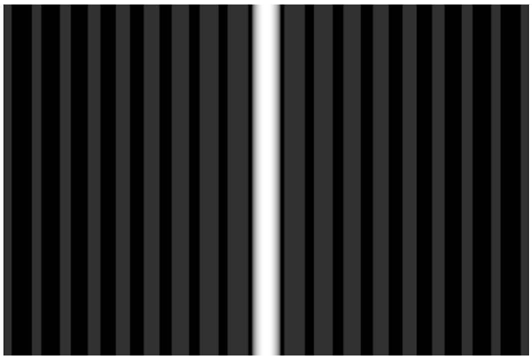

Figure 6. Focal image – simulation.

4. Results

The acquired focal image is shown in Figure 5. The tests with the previous prototype showed a significant skew error [15]. No error of this type is observable on the focal line in Figure 5.

LOPSIMUL software [16, 17] was used for the simulations. The simulations are based on the simplified ray-tracing algorithm [18–20]. Ideal mirrors were considered for the simulations. The result of the simulations of the focal image is presented in Figure 6.

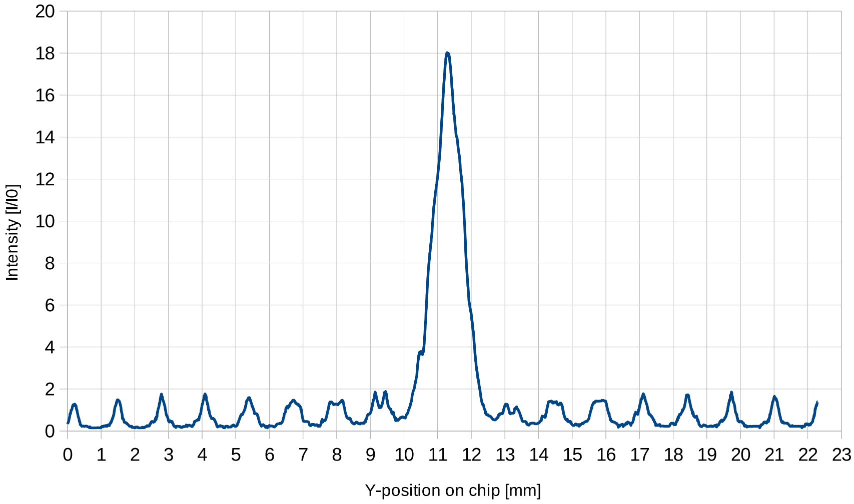

Figure 7. Profile of intensity – experiment.

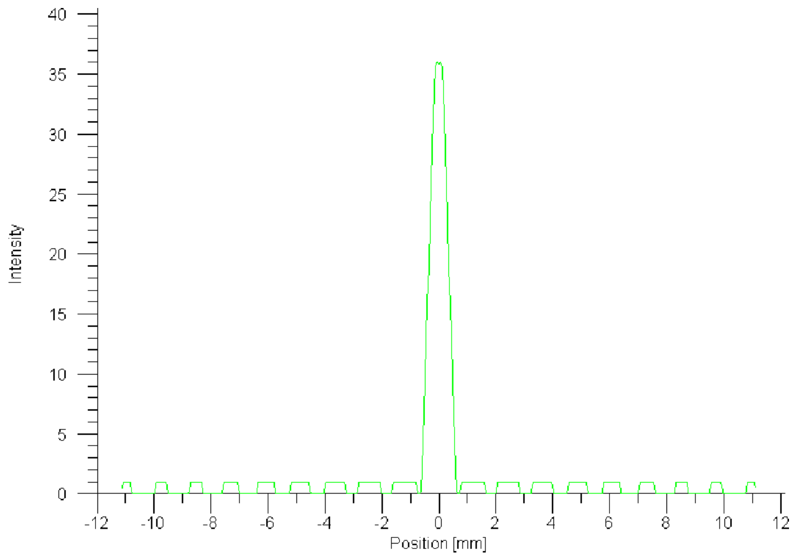

Figure 8. Profile of intensity – simulation.

The profile of intensity along the horizontal axis of the experimental image is shown in Figure 7 while Figure 8 presents the result of the simulation.

Note that the simulation is performed for mirrors with 100 % reflectivity (for tests in X-rays, it is planned to include relevant reflectivity model into the simulations). Therefore, the vertical scales of images Figure 7 and Figure 8 are not comparable.

The FWHM of the experimental profile reaches 1.02 mm while the simulated image shows a better FWHM of 0.71 mm.

The graph in Figure 8 shows one main peak that is formed mainly by reflected rays. Some rays come through the optical system directly through spaces between mirrors. These rays form secondary maxima of uniform intensity.

However, the measured profile in Figure 7 shows that the secondary maxima are not uniform in intensity. This is caused by the diffraction of light. The diffraction also causes the measured FWHM of the main peak to be wider than the result of the simulation. The diffraction will not appear in X-rays because X-rays have a much shorter wavelength.

Another problem that makes the main peak wider is that the light beam has some small divergency as the LED chip has a non-zero size. However, the LED chip size is not known and therefore, it cannot be included into simulations.

For these reasons, the authors expect that results of tests in X-ray will be in much better agreement with the simulations.

5. Conclusion

The experiment showed that the lobster-eye prototype is functional. The experimentally obtained focal image is very similar to the calculated one. The FWHM of the focal line on the image acquired in the experiment is slightly inferior to the calculated one. It is caused by the small divergence of rays and the diffraction effects. The focal line does not show an observable skew error.

This proves that the technology used is promising. An experiment in an X-ray tunnel is necessary to measure the performance of the lobster-eye prototype more precisely. The authors plan to test the module in an X-ray tunnel at the design energy of about 1 keV. We expect that the results of this test will show good accordance with the simulation as it will not be affected by diffraction effects because the X-ray wavelength is much shorter.

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