Contrib. Astron. Obs. Skalnaté Pleso **53/4**, 198 – 205, (2023)
https://doi.org/10.31577/caosp.2023.53.4.198

Preliminary optical tests of lobster eye X-ray optics prototype for nano-satellite missions based on new technology

V. Tichý[1], **M. Míka**[2] **and R. Hudec**[1]

[1] *Czech Technical University in Prague, Faculty of Electrical Engineering, Technická 2, 166 27 Prague, Czech Republic (E-mail: vladimir-tichy@email.cz)*

[2] *University of Chemistry and Technology Prague Technická 5, 166 28 Prague, Czech Republic*

Received: July 4, 2023; Accepted: October 9, 2023

Abstract. This paper presents preliminary results of optical tests of Schmidt lobster eye module based on a new technology. The module was tested using visible light, which is possible because glass plates coated with gold are used as mirrors. The results show good accordance with simulations. It means that the technological concept offers precise assembly of optical mirrors, which is the key aspect to obtain sharp focal image.

Key words: lobster eye – multi-foil optics – reflective optics – grazing incidence optics – x-ray optics

1. Introduction

The Schmidt lobster eye (Schmidt, 1975) is composed of flat rectangular mirrors. These mirrors form an uniform pattern around a virtual cylinder with the centre **C** and radius r, see Fig. 1. This set of mirrors is called stack. In a real case, grazing angles are much smaller and mirrors are closer one to each. The point **F** represents the focus of the system. The lobster eye optics is intended mainly for X-rays. Its main advantage is wide field of view, therefore the lobster eye optics is suitable mainly for space X-ray monitors (Dániel et al., 2022; Hudec & Feldman, 2022; Hudec et al., 2018, 2017b,a,c,e,d)

Schmidt lobster eye geometry is defined by these parameters:

- r radius of the system
- a mirror spacing
- t mirrors thickness
- h mirrors depth

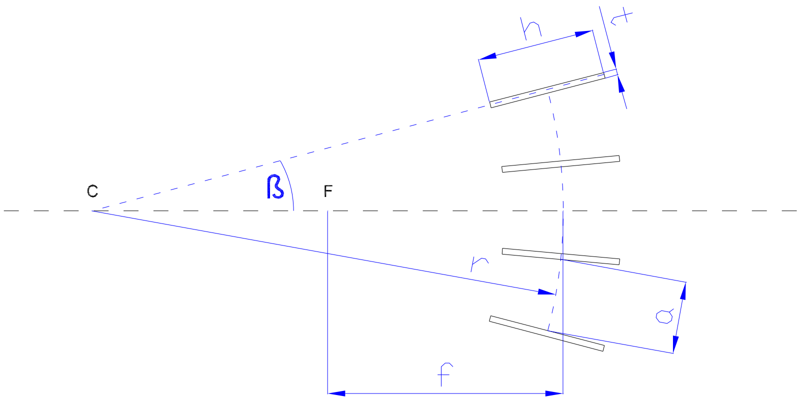


Figure 1. Arrangement of mirrors of one-dimensional Schmidt lobster eye

- N number of mirrors
- β represents angle position of a mirror

Operation of a single stack is similar to a cylindric lens.

Two orthogonally arranged stacks form a double-reflecting device, see Fig. 2. Note that there exists another concept of lobster eye based on square pores (Angel, 1979).

The main manufacturing problem of Schmidt lobster eye is to achieve exact positioning of each mirror. Therefore a new technological concept has been proposed and registered as utility model (Tichý, 2022b) and patent application (Tichý, 2022a).

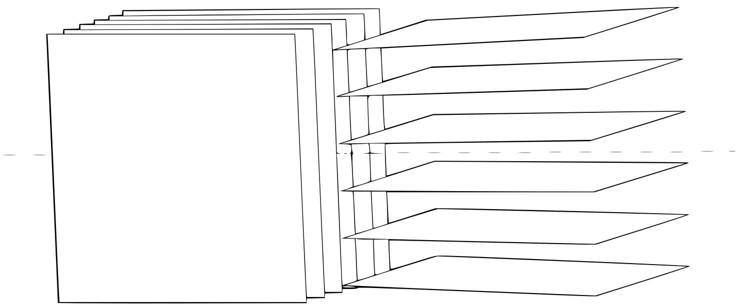


Figure 2. Arrangement of stacks of two-dimensional Schmidt lobster eye.

2. Prototype one-dimensional Schmidt lobster eye optics module LNA-215

To prove the technological concept, prototype one-dimensional Schmidt lobster module LNA-215 was manufactured, see Fig. 3.

The module LNA-215 has following parameters:

- Focal length $f = 215$mm
- Input aperture 84x84mm
- Composed of N=66 glass mirrors of depth h=24mm and thickness t=0.28mm coated with gold
- Mirror spacing $a = 1.05$mm
- Outer dimensions 95.8x95.8x26mm without external housing
- Intended for X-ray energy 1keV
- Calculated field of view 22°.

CubeSat satellites represent a common platform to test new space devices. Therefore, the focal length and the input aperture of the optics were chosen so that the optics together with a focussed detector would fit three units of a CubeSat satellite.

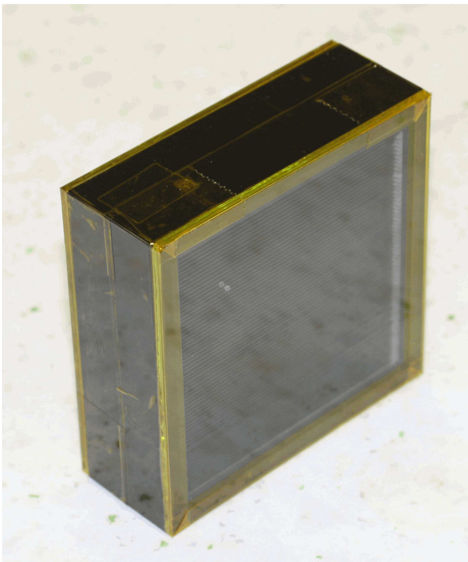


Figure 3. Prototype of one-dimensional Schmidt lobster eye optics module LNA-215.

3. Experimental setup

As the mirrors are made of glass coated with gold, they reflect visible light, too. It allows to use visible light to perform the preliminary experiment, which proves the technological concept. This experiment was performed in laboratories of the University of Chemistry and Technology in Prague.

The experimental setup is shown in Fig. 3. A white high-power light emitting diode was used as the light source. The source was equipped by aperture of diameter ca. 0.1mm made of aluminium foil. A plano-convex lens of focal length 130mm was used as collimator. Distance between the planar side of collimator and the center of the optics was 850mm. The image was taken by a camera Canon EOS 50D. This camera has a sensor of size 22.3 x 14.9mm and resolution of 4752 x 3168 pixels.

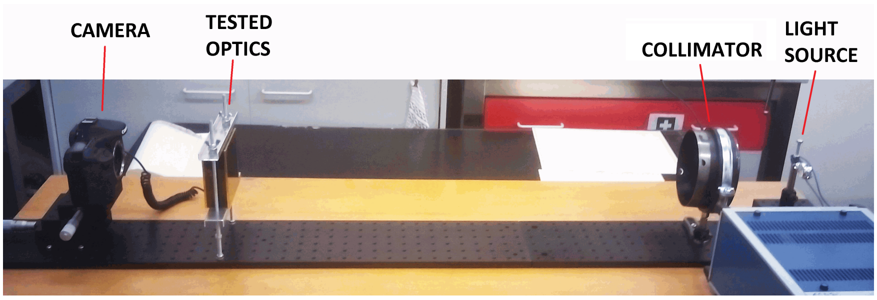


Figure 4. Experimental setup

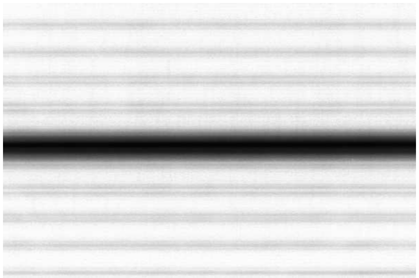
4. Results

The image acquired by camera is shown in Fig. 5(a). Red color channel was used. The image is in negative colors and with enhanced contrast. The focal line does not have an observable skew error contrary to results with previous prototype presented in (Tichý et al., 2018).

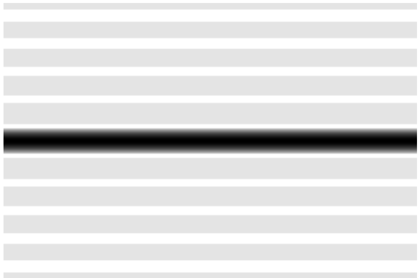
Simulations were done using LOPSIMUL software (Tichý, 2023) by the simplified ray-tracing algorithm (Tichý et al., 2016; Tichý, 2013; Tichý et al., 2011). Perfectly flat mirrors of 100% reflectivity were considered for the simulations. Resulting image of the simulation for aligned optics is seen in Fig. 5(b).

It is seen that the central focal line in images Fig. 5(a) and Fig. 5(b) has different position relative to positions of shadows of mirrors. This is because the entire lobster optics module was tilted a little relative to direction of incoming rays. However, the setup did not allow perfect alignment.

Therefore, the tilt angle was included in next simulations and the tilt value was manually found by comparison of the experimental image to the result of



(a) Experiment



(b) Simulation, aligned optics

(c) Simulation, optics tilted by 0.1°

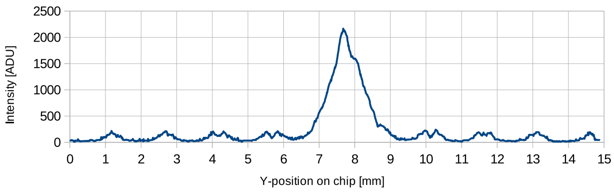
Figure 5. Focal images

the simulations. It was found that tilt value of 0.1° gives the good accordance between experimental image (Fig. 5(a)) and result of the simulation including the tilt angle (Fig. 5(c)). The experimental image with visible light is affected by diffraction effects.

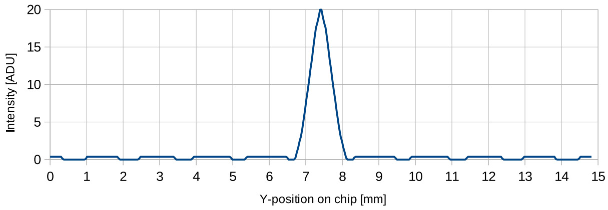
Graphs of intensity along vertical axis are shown in Fig. 6. FWHM of the peak of the experimental image (Fig. 6(a)) is 0.96mm while FWHM of the peaks of both simulated images (Fig. 6(b), Fig. 6(c)) reaches 0.71mm. The experimental value is slightly worse compared to the result of simulation due to diffraction effects and due the fact that the diameter of aperture was not small enough.

5. Conclusions

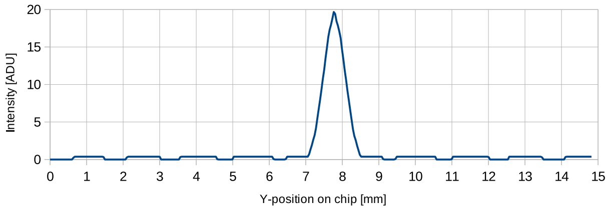
The experiment with visible light proves that the prototype optics is functioning and the technological concept is promising. FWHM of the experimental image is slightly worse than the result of the simulation, which is due to diffraction effects and due to the small divergence of rays. The focal line does not have the skew error.



(a) Experiment



(b) Simulation, aligned optics



(c) Simulation, optics tilted by 0.1°

Figure 6. Intensity along vertical axis. Vertical scales of experimental and simulated images are not comparable.

The authors expect that experiment in X-ray tunnel at designed energy around 1keV will give result that will be in perfect accordance with the simulation.

Acknowledgements. We would like to thank Mr. Pavel Maun for machining works. Thanks for funding from the European Union's Horizon 2020 Programme under the AHEAD2020 project (grant agreement n. 871158). We also acknowledge CVUT FEL grant No. SGS21/120/OHK3/2T/13.

References

Angel, J. R. P., Lobster eyes as X-ray telescopes. 1979, *Astrophysical Journal*, **233**, 364, DOI: 10.1086/157397

Dániel, V., Maršíková, V., Hudec, R., et al., Small Spacecraft Payload Study for X-ray Astrophysics including GRB Science. 2022, *Universe*, **8**, 144, DOI: 10.3390/universe8030144

Hudec, R. & Feldman, C., Lobster Eye X-ray Optics. 2022, in *Handbook of X-ray and Gamma-ray Astrophysics*, 45

Hudec, R., Inneman, A., Pina, L., et al., Innovative space x-ray telescopes. 2017a, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. **10568**, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 105681D

Hudec, R., Pína, L., & Inneman, A., Novel wide-field x-ray optics for space. 2017b, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. **10569**, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 105692F

Hudec, R., Pina, L., Marsikova, V., et al., Lobster Eye X-ray optics for astrophysics: Recent status. 2018, *Contributions of the Astronomical Observatory Skalnate Pleso*, **48**, 456

Hudec, R., Pína, L., Semencova, V., et al., Novel technologies for space x-ray optics. 2017c, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. **10567**, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 105673L

Hudec, R., Semencova, V., Inneman, A., et al., Space optics with silicon wafers and slumped glass. 2017d, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. **10566**, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 105660Q

Hudec, R., Sveda, L., Pína, L., et al., LOBSTER: new space x-ray telescopes. 2017e, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. **10567**, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 1056719

Schmidt, W. K. H., A proposed X-ray focusing device with wide field of view for use in X-ray astronomy. 1975, *Nuclear Instruments and Methods*, **127**, 285, DOI: 10.1016/0029-554X(75)90501-7

Tichý, V., Simple and fast algorithm for computer simulations of reflective optical systems. 2013, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. **8777**, *Damage to VUV, EUV, and X-ray Optics IV; and EUV and X-ray Optics: Synergy between Laboratory and Space III*, ed. L. Juha, R. Hudec, L. Pina, S. Bajt, & R. London, 877710

Tichý, V. 2022a, Patent, CZ PV 2022-511

Tichý, V. 2022b, Utility Model, CZ UV 36 961

Tichý, V. 2023, LOPSIMUL simulator, available for download at www.lopsimul.eu

Tichý, V., Barbera, M., Butcher, G. I., et al., Effects of manufacturing inaccuracies on spatial resolution of lobster eye optics. 2018, *Contributions of the Astronomical Observatory Skalnate Pleso*, **48**, 405

Tichý, V., Barbera, M., Collura, A., et al., Lobster eye optics for nano-satellite x-ray monitor. 2011, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. **8076**, *EUV and X-Ray Optics: Synergy between Laboratory and Space II*, ed. R. Hudec & L. Pina, 80760C

Tichý, V., Hudec, R., & Němcová, Š., Effective algorithm for ray-tracing simulations of lobster eye and similar reflective optical systems. 2016, *Experimental Astronomy*, **41**, 377, DOI: 10.1007/s10686-016-9493-2