Axicon for imaging spectrometer

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Abstract. The operation of the imaging spectrometer based on the axicon is modelled in the Matlab. The imaging spectrometer consists of an annular scanning slit, lenses and axicon. Simulation conducted for two schemes: non-imaging and imaging. We simulated and showed that it is possible to obtain a spectral resolution of 10 nm and a point spread function of 30-50 μm. We obtained the spectral distribution from a model object with parts in which the wavelength of monochromatic radiation took one of three values: 0.46 μm (blue), 0.54 μm (green), 0.70 μm (red).

1. Introduction

Recently, more and more attention is paid to weight and size of hyperspectrometers. The main constructions of hyperspectrometers which are used for remote sensing, are generally not suitable for mass use, because of the design complexity, the cost of such spectrometers is also too high. And hyperspectrometers that are used in spacecraft have rather complex structures. For example, constructions based on the Offner scheme [1-3]. Consequently, an extremely simple solution is needed for using imaging spectrometers with mobile devices [4-9], thus the price of such a hyperspectrometer have to be comparable with the price of the mobile device itself. Often such simplification of the design leads to a loss of spectral resolution. However, 40–60 spectral lines are enough for the hyperspectral analysis tasks in everyday life, so this approach is justified. Thus, in paper [8], an optical scheme of a hyperspectrometer was implemented based on the use of typical lenses as part of a telescopic system with a dispersion element in the focal plane. Usage of such an optical scheme really leads to a strong decrease in the resolution of the hyperspectrometer in the spectrum as well as in the spatial coordinates. Paper [10] publishes the results of numerical experiments which investigated hyperspectrometer design based on telescopic system and axicon in the focal plane with an annular diaphragm. The main idea of this work was that the point spread function (PSF) of the system will be unchanged across the slit diaphragm, because the system contains only radially symmetric elements. This has been confirmed, but the size of the PSF was quite large. Obviously, the usage of ordinary spherical lenses with strong aberrations as elements of the telescopic system [10], becomes a reason of PSF increased size. In this paper, we consider two four-element lenses that form an image with a low level of aberrations in a telescopic system.

The imaging properties with the axicon were investigated originally by McLeod in 1954 [11]. Axicons can be manufactured in refractive, diffractive, or reflective versions. A diffractive axicon is a
grating consisting of concentric circles. Axicons have been used in imaging systems sometimes [12, 13]. The paper [14] describes the imaging properties of axicon in the imaging system. The zero-order diffraction axicon is considered as a dispersion element [11].

2. Imaging spectrometer based on axicon

Paper [8] describes a simple scheme in which the prisms and the diffraction grating are located in the frequency plane. The scheme is assembled in the form of a pencil-like imaging spectrometer, which weighs only 140 g. The spectral resolution is 17 nm in the visible range from 400 to 675 nm. We will consider a similar scheme, but we will use the diffraction axicon as the dispersion element.

The mathematical model of the spectrometer is modeled in the Matlab. Fig. 1 shows the optical scheme with ray tracing, where 1 – the annular slit, 2 and 4 – lenses, 3 – axicon, 5 – recording plane.

Figure 1 shows that a parallel beam of light hits a circular slit diaphragm. If we put the lens in front of the slit diaphragm, then we get an annular intensity distribution (Figure 2). The annular diaphragm is illuminated evenly on the exit plane. We get a non-imaging system with PSF in the form of a ring, if the source is located on the optical axis.

![Figure 1. Optical scheme of spectrometer based on axicon.](image)

Figure 2. The PSF for wavelengths: a) 0.54 μm and b) 0.7 μm.

Figure 3 shows the PSF for a scheme in which a point source is located in the area of a slit diaphragm. We get a distorted ring.

The lens is absent in front of the annular diaphragm in the imaging mode. A parallel beam enters the input of the hyperspectrometer (Figure 4). In this scheme, two lenses with a focal length of 50 mm with an aperture diameter of 20 mm, and a diffraction axicon with a period of 32 μm are considered. A model image in the form of a set of square areas (Figure 5a) was applied to the input, in each of which the wavelength of monochromatic radiation takes one of three values: 0.46 μm (blue), 0.54 μm (green), 0.70 μm (red). The slit diaphragm (10 μm wide) cut a narrow annular region from this model image, which, after passing through the hyperspectrometer, was decomposed by an axicon into an annular spectrum.

Spectra of individual points can be observed in the recorded region. The lighting table was selected as a model image. Figure 5a shows the original image, and Figure 5b shows the recorded image.
Figure 3. The spectral distribution at the output plane of the hyperspectrometer for wavelengths: a) 0.38 μm, b) 0.46 μm, c) 0.54 μm.

Figure 4. Optical scheme modeled in Matlab.

Figure 5. Original image (a), recorded image (b), section of intensity distribution (c).
As can be seen from figure 5b, the recording plane contains a set of three rings clearly modulated for each wavelength. The PSF can be estimated from this intensity distribution in two directions: radial and axial.

The approximate width of the PSF along the radius is about 30 μm, along the ring 30-50 μm depending on the wavelength as measured by radial and axial sections. Thus, the spectral resolution of such a hyperspectrometer is about 10 nm in this configuration. About 30 spectral channels are obtained in the visible part of the spectrum. If we consider the entire range of sensitivity of modern CCDs from 400 nm to 1000 nm, then in this range about 60 spectral channels are obtained. This is a good result for a compact hyperspectrometer.

3. Conclusion
The operation of the axicon based spectrometer as a dispersion element is modeled in the commercial Matlab package. It is shown that the proposed axicon optical system forms decomposition into a spectrum with a spectral resolution of about 10 nm, with a resolution along the spatial coordinate in the plane of the photosensitive matrix of 30-50 μm.

4. References
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Acknowledgments
This work was supported by the Russian Foundation for Basic Research (RFBR) (grants Nos. 16-29-11744 ofi_m and 16-29-09528 ofi_m) and by Russian Federation Ministry of Education and Science grant number 3.3025.2017/4.6 and by leading scientific school NSh-6307.2018.8.