Hyperspectrometer based on a harmonic lens with diffraction grating

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Abstract. We have produced a harmonic lens with a diffraction grating on one surface of the quartz substrate. We have made on the basis of such a harmonic lens a compact imaging spectrometer. We conducted experimental studies of the hyperspectrometer. We have confirmed the functionality of the hyperspectrometer as a result of research. We have defined modulation transfer functions.

1. Introduction

The optical spectrometer has become one of the most important and most commonly used instruments in modern science and engineering [1]. There are many spectrometer designs that can be used in conjunction with mobile devices [1-5]. Anyone can use them for a number of tests, which are usually carried out in a special laboratory. Indeed, the optical scheme of the spectrometer is relatively simple, and its implementation is not very difficult. A number of analyses cannot be performed using a simple spectrometer. Such analyses should be done using an imaging spectrometer (hyperspectrometer). Hyperspectrometers have been widely used in a variety of scientific fields last few years. Such hyperspectrometers are used on satellites or airplanes most often, but recently, developers are showing increased interest to compact spectrometers for the creation of portable devices [1]. Unfortunately, the optical scheme of the imaging spectrometer is more complicated than the optical scheme of a conventional spectrometer. Since it is necessary to minimize aberration distortions in the spectral block. Often, such spectrometers are composed of technologically complex dispersion elements [6]. This is the main obstacle to the creation of a hyperspectrometer which can be used in imaging mode alongside a smartphone. The spectrometer based on a standard diffraction grating and a standard Fresnel lens has been described [1]. This is a very technological approach, but the level of aberrations in such structures does not allow us to use it in the imaging mode. The diffraction lens itself is a spectral device [3], that forms a set of spatially-separated spectral images. However, these images are superposed on each other and subsequent digital processing for their separation is difficult to perform. The algorithms for processing the information obtained are very complex and do not allow to obtain sufficient spectral resolution. In this paper we consider a diffraction optical element, which consists of a harmonic lens with a microlief height of 6 µm and a diffraction grating with a microlief height of...
1 µm. This DOE has dual functionality, works simultaneously as a imaging lens and as a diffraction grating. Thickness of the harmonic lens is the thickness of the plate on which the relief is applied, this element allows to reduce the weight of the hyperspectrometer[1, 2] The higher the height of the microrelief of the harmonic lens, the closer the properties of the harmonic lens to the refractive lens [7-12].

2. Imaging spectrometer based on harmonic lens with diffracting grating

In paper [13] we considered a spectrometer based on an element that combines the properties of a diffraction lens and a grating – lens-grating. The lens-grating was made with a focal length of 12 mm for a wavelength of 550 nm. Diameter of the lens is 15 mm. The plane recorded the spectrum from 400 nm to 700 nm.

Based on the experiments, it was proved that such a scheme is workable. This scheme is difficult because of the precise selection of the tilt angle. The mistake leads to a bad result. In this regard, it was proposed to fabricate an element that would combine the relief of a harmonic lens and a diffraction grating, because in this case, we also get a compact size of the spectrometer, but the recording plane can be set in the usual way - perpendicular to the optical axis. A harmonic lens is a diffraction lens in which there are several wavelengths (harmonics) that are precisely focused in the calculated focal plane [12].

The element was fabricated with a microrelief in a resist on a quartz substrate at a laser recording station. The microrelief combines the relief of a harmonic lens and a diffraction grating, the focal length of the lens is 120 mm, the grating period is 10 µm. Height of relief is 6 µm. Fig. 1 shows the cross section of the microrelief of this element, that was obtained by measuring on the profilometer.

![Figure 1. Section relief of the edge of the harmonic lens with the diffraction grating.](image)

Fig. 2 shows the the microrelief of this element, that was obtained by measuring on the white light interferometer Zygo.

![Figure 2. The microrelief of harmonic lens with diffraction grating: small magnification (a), high magnification (b).](image)

![Figure 3. The appearance of a harmonic lens with a diffraction grating.](image)
The appearance of the element recorded at the laser recording station is shown in Fig. 3.

We made some calculations on the fabricated harmonic lens. The optical path-length step $m\lambda_0$ created has resonant (or harmonic) wavelengths at $m\lambda_0/k$, i.e., at each of the wavelengths the phase change between adjacent steps of the lens is a multiple of $2\pi$. For example, if $\lambda_0 550$ nm and $m=6$, then the resonances in the visible are at 412, 472, 550 and 660 nm for $k=8$, 7, 6, and 5 respectively.

**Table 1.** Wavelengths precisely focused by a harmonic lens.

| $\lambda$, nm | $k$  |
|---------------|------|
| 412           | 8    |
| 472           | 7    |
| 550           | 6    |
| 660           | 5    |

where $k$ is the diffraction order.

For example, the power of such a lens in air is

$$P \equiv \frac{1}{f} = \frac{k\lambda}{\eta^2} \text{ или } \frac{\Delta P}{P} = \frac{\Delta \lambda}{\lambda} = \frac{\Delta f}{f},$$

where first he focal length in millimeters, $\lambda$ is wavelength, $r_1$ – is the radius of the first Fresnel zone.

We calculated the value $\Delta f$ using formula (1). The value is 20,5mm.

The diffraction efficiency $\eta$ of the lens at any wavelength is

$$\eta = \sin \left( \frac{m\lambda_0}{\lambda} - k \right)$$

(2)

The diffraction efficiency is 100% for all wavelengths in which the diffracted order is an integer. We calculated the diffraction efficiency for wavelengths of 511 nm and 605nm. It is 93% and 90% respectively.

We assembled an imaging spectrometer based on a harmonic lens with a diffraction grating. The optical scheme of this spectrometer is shown in Fig. 4. The spotlamp with LEDs was used as a light source – 1, 2 – a harmonic lens with a diffraction grating, 3 – an objective lens that is located at a distance $f_1+f_2$ and 4 – CCD matrix.

![Figure 4. Optical scheme of the imaging spectrometer based on a harmonic lens with a diffraction grating.](image)

We obtained the spectral distributions of a set of point sources during the experiment. These distributions are shown in Fig. 5. The Fig.5 shows the visible spectrum for the point source even without the use of a slit diaphragm.

![Figure 5. The visible spectrum for the point source even without the use of a slit diaphragm.](image)
Fig. 5 shows that the element actually works as we expected. The zero order is build a clear image of the source, + 1, + 2 and -1 the orders of the image of point sources are stretched in the spectral distributions. Thus, we can draw a conclusion about the principle of the element's performance. But to obtain a hypercube it is necessary to use a slit diaphragm in the scheme in Fig. 4. We added a slit diaphragm to the optical scheme. Then we conducted a series of experiments on the formation of hyperspectral images.

We used two lasers with wavelengths of 532 nm and 633 nm for calibration of spectral channels (Fig. 6).

We have formed a hyperspectral image for a black and white lighting table to obtain the optical transfer function. Images at different wavelengths were formed by computer processing. Fig. 7 shows the original image of a black-and-white lighting table.

After we obtained a series of spectral distributions, we formed images at different wavelengths by computer processing. Fig. 8 shows the hyperspectral image layer at the wavelength of 550 nm.
The contrast of the periodically striped images on the black-and-white lighting table with different periods was determined according to the Fig. 8. The contrast of the amplitude grating image was defined by the formula

\[ n = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]

(3)

where \( I_{\text{max}} \) - the intensity of the image of the graphic table amplitude grating at the maximum, where \( I_{\text{min}} \) is the intensity of the image of the graphic table amplitude grating at the minimum.

The section view (Fig. 9) was formed for the amplitude grating shown in the Fig. 8. The \( I_{\text{max}}, I_{\text{min}} \) for the image contrast determination was formed on the basis of this section view.

![Figure 9](image)

**Figure 9.** The section view was formed for the periodically striped image shown in the Fig. 8: a) 17 mm\(^{-1}\); b) 32 mm\(^{-1}\).

Based on the above results a graph of the optical transfer function was obtained (Fig. 10).

![Figure 10](image)

**Figure 10.** The optical transfer function for imaging spectrometer at the wavelength of a) 550 nm; b) 500 nm.

It should be noted that this is the optical transfer function at the calculated wavelength. It is clear that at any other wavelength the optical transfer function will be worse. The optimal number of spectral channels of such a hyperspectrometer should coincide with the number of harmonics of the harmonic lens. In this case, optical transfer function in any spectral channel will be exactly the same. This is an additional argument for the use of reflecting structures, which, while maintaining the height of the microrelief, give a fourfold increase in the number of harmonics of the harmonic lens.
Fig. 11cd shows the hyperspectral image layer at the wavelength of 550 nm.

Fig. 11 shows that the images are quite contrast and completely correspond to the given spectral layer. The microrelief of the element in the future can be optimized to minimize aberration distortions.

3. Conclusion
A diffractive optical element that combines the properties of a lens and a diffraction grating is fabricated. The images of point sources obtained in the experiment confirm the principled operability of such element. An imaging hyperspectrometer based on this element can be used with mobile devices. After series of full-scale experiments on the construction of hyperspectral images, the principal applicability of this hyperspectrometer is shown.

4. References
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