Optical arrangement of a focal monochromator based on a holographic lens for the UV radiometry

S.A. Yushkin, I.I. Ippolitov, and I.G. Polovtsev

Institute of Optical Monitoring, Siberian Branch of the Russian Academy of Sciences, Tomsk

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A focal monochromator based on a holographic lens is proposed as a possible optical arrangement of a spectral device for the UV radiometry. The main analytical equations for making size calculations are given, and the spectral characteristics are described. Some ways to improve the spectral resolution are analyzed.

The UV portion of the solar radiation reaching the Earth's surface has a diversified and often negative effect on living organisms and plants. By the extent to which the radiation in the wavelength region from 200 to 400 nm affects the human beings, it is divided into three ranges: A ($315 < \lambda < 400$ nm), B ($280 < \lambda < 315$ nm), and C ($\lambda < 280$ nm). The UV-A radiation has a beneficial erythemic and sunburn effect. The UV-B radiation possesses higher biological activity: it is useful in small doses, but negative in large doses. The UV-C radiation has strong bactericide effect and is harmful for living organisms and plants.

The instantaneous effective UV irradiation or the dose (exposure) can be determined as

$$E = \int_{\lambda_1}^{\lambda_2} G(\lambda)\ W(\lambda)\ \mathrm{d}\lambda, \qquad (1)$$

where $G(\lambda)$ is the spectral intensity of the UV radiation; $W(\lambda)$ is the weighting function or the spectrum of action for a specific biological or chemical process. The latter two functions can be determined experimentally. Then hourly, daily, or longer doses can be obtained by integration of E over time. It is just these doses and their variability that should be considered as a subject for ecological UV monitoring.

Measurements of the UV radiation, especially, its short-wave part, may face certain difficulties. Optical elements of the devices should be made from quartz or other materials transparent in the UV region. Photodetectors should possess high sensitivity in the UV region. In the case of transformation of the UV spectrum into the visible region with the help of a luminophore, photodetectors should have high sensitivity in the visible region. By the method used for separation of the UV spectrum, UV radiometers can be divided into two groups: (a) spectral devices using quartz prisms or reflecting diffraction gratings as dispersive elements, (b) integral devices that use broadband filters as the spectral selective elements.[3]

The RB-meters that separate out the UV-B region by filters are now used at network of UV monitoring stations. The sensitivity curve of these filters roughly follows the curve of the erythemic spectrum of action. The use of currently available UV radiometers[2,3] for network measurements proves to be inefficient because of their complexity, large size, and high cost. Therefore, it is urgent to develop a simple, compact, and cheap device for such measurements.

One of the ways to simplify the optical arrangement is to use a focal monochromator, in which one element serves as a dispersing element and a collimating objective simultaneously. A diffraction lens being a diffraction grating with a changeable period possesses focusing properties,[1] so it can be used as such a dispersive and focusing element. A particular case of the diffraction lens is a holographic lens obtained by recording an interference pattern generated by two coherent monochromatic beams on a photographic emulsion. According to Refs. 1 and 4, the chromatism of the position of the entrance slit image formed by such a lens is described by the following equation:

$$F(\lambda) = \frac{\lambda_0\ L1\ L2}{k\ \lambda\ (L1 + L2)}, \qquad (2)$$

where λ_0, $L1$, and $L2$ are the parameters of recording the holographic lens; k is the working order of diffraction; λ is the working wavelength.

The classical focal monochromators with the glass optics[6] do not allow efficient operation with the UV component; in the case of a holographic lens, this problem is solved by covering the working surface of the hologram by a reflecting coating. Besides, the holographic lens has the stronger wavelength dependence of the focus than a homogeneous glass lens. The optical arrangement of the focal monochromator based on a holographic lens is shown in Fig. 1.

It includes the entrance slit *1*, the dispersive element *2*, the screen *3* providing for the needed accuracy of separating out the spectral region of interest, and the linear photodetector *4* for the device operation as a spectrograph. The light beam from the entrance slit *1* is incident on the holographic lens *2* made as an off-axis fragment of an axial holographic lens. Because of the pronounced chromatism in the position of the entrance slit image it is formed on the optical axis of the lens. The image consists of spectral lines, which are recorded by the photodetector *4*. In accordance with Eq. (2), the longer the wavelength, the closer the corresponding spectra line to the lens surface. Therefore, short waves are characterized by higher inverse linear dispersion. In the focal monochromator based on classical lens, the higher linear dispersion is observed for long-wave radiation, but here the situation is just reverse. This behavior of the dispersion curve points to the convenient use of this optical arrangement for studying short-wave radiation.

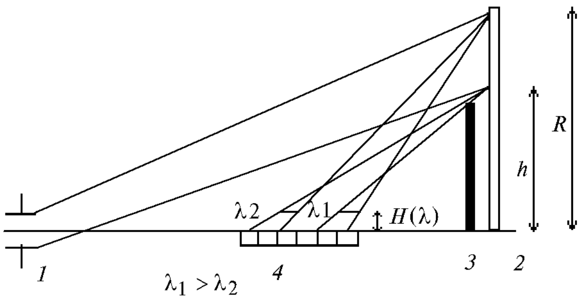

Fig. 1. Optical arrangement of the focal monochromator based on a holographic lens.

Since the off-axis fragment of an axial holographic lens is used, there is no need in using a collimator objective. Thus, the device includes a minimum number of elements. Consequently, radiation losses in the device are reduced to minimum and determined only by the diffraction efficiency of the lens, what is especially important when operating with the UV component of the solar radiation. The use of a multichannel photodetector adds to the convenience of measuring UV fluxes of solar radiation, because this allows all the studied spectral regions (A, B, and C) to fall within the photosensitive area of the photodetector.

The Gauss equation well-known in the geometric optics gives

$$\frac{S'}{S} = \frac{F}{x}, \qquad (3)$$

where S' is the distance from the lens to the image; S is the distance from the object to the lens; F is the lens focal length; $x = S - F$. Thus we can derive the equation describing the dispersion curve in our case

$$S'(\lambda) = \frac{F(\lambda)\, S}{S - F(\lambda)}, \qquad (4)$$

where $F(\lambda)$ is the focal length determined by Eq. (2); S is the distance from the entrance diaphragm to the holographic lens.

Since the reconstruction wavelength is not equal to the wavelength of recording a hologram, the instrumental function has aberration blurring. The instrumental function calculated from the geometry shown in Fig. 1 with regard for the longitudinal spherochromatic aberrations is described by the equation

$$L(\lambda) = \frac{h - H(\lambda)}{\tan\{\arcsin[\lambda\nu(h) - \sin(\arctan((h+d/2)/S))]\}} - \frac{R - H(\lambda)}{\tan\{\arcsin[\lambda\nu(R) - \sin(\arctan((R+d/2)/S))]\}}, \qquad (5)$$

where h is the screen height; R is the height of the holographic lens; d is the width of the entrance slit; $\nu(h)$ and $\nu(R)$ are local frequencies of grooves of the holographic lens at the height h and R, respectively; S is the distance between the entrance slit and the holographic lens; $H(\lambda)$ is the height above the optical axis.

At $H(\lambda) = 0$ we have the equation describing the value of the instrumental function at the optical axis of the holographic lens.

According to Ref. 3, the limiting spectral resolution is determined by the equation

$$\delta\lambda = \frac{L(\lambda)}{2(\mathrm{d}S'/\mathrm{d}\lambda)}. \qquad (6)$$

An important advantage of the proposed optical arrangement is the capability of operating with a wide entrance slit. If usual spectral devices have the entrance slit from several to hundreds micrometers wide, then the focal monochromator based on the holographic lens can employ a slit about 1 mm wide. Thus, for example, for the following optical parameters $d = 1$ mm, $S = 25$ cm, $L1 = 25$ cm, $L2 = 4$ cm, $h = 1$ cm, $R = 3$ cm, $\lambda_0 = 0.63$ μm, we can determine from Eq. 4 that the monochromator has high dispersion (the length of the spectrum for the region from 200 to 400 nm is about 13 cm). The spectral resolution calculated by Eqs. (5) and (6) for the considered spectral region is 2 to 14 nm. Thus, the focal monochromator has not only simple design and wide entrance slit, but gives rather high spectral resolution.

The result obtained is acceptable, because monitoring of the UV solar radiation fluxes does not require very high spectral resolution. Besides, because of the wide entrance slit, we can significantly increase the energy flux of the recorded radiation and neglect losses due to diffraction efficiency of holographic lenses (about 10%). If necessary, the spectral resolution can be improved using the techniques described below.

As was noted above, if a hologram is reconstructed at the wavelength other than the wavelength at which it was recorded, the spherochromatic aberrations arise. Introducing defocusing[5] can decrease them; thus, the spectral resolution will be improved. Studying how the instrumental function varies as its height above the optical axis changes, we can determine the height of the minimum instrumental function. The calculated results for the above optical parameters are shown in

Fig. 2 as a defocusing curve. Fixing the photodetector on this curve significantly (up to 100 times) improves the spectral resolution of the device, all other optical parameters being the same. However, this way of improving the spectral resolution complicates significantly the measurement technique.

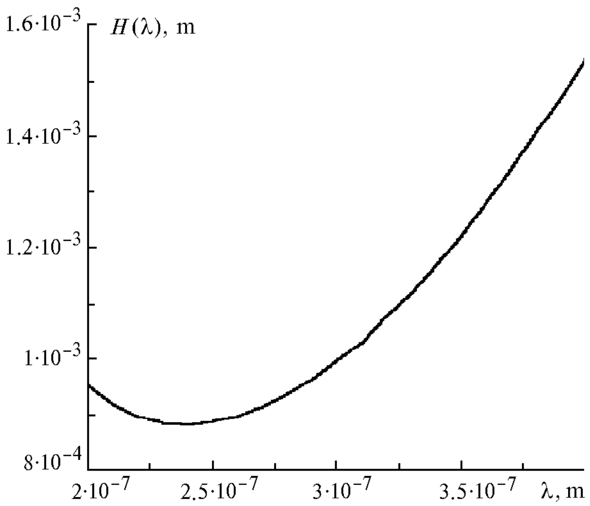

Fig. 2. Defocusing curve.

The other way to increase the spectral resolution is to change the optical parameters of the focal monochromator: to narrow the entrance slit d, to decrease the height of the holographic lens R, or to increase the screen height h. The curves of the spectral resolution at different optical parameters shown in Fig. 3 illustrate the degree of influence of these parameters on the spectral resolution of the device. However, this way of increasing the spectral resolution leads to unwanted decrease of the device's focal ratio.

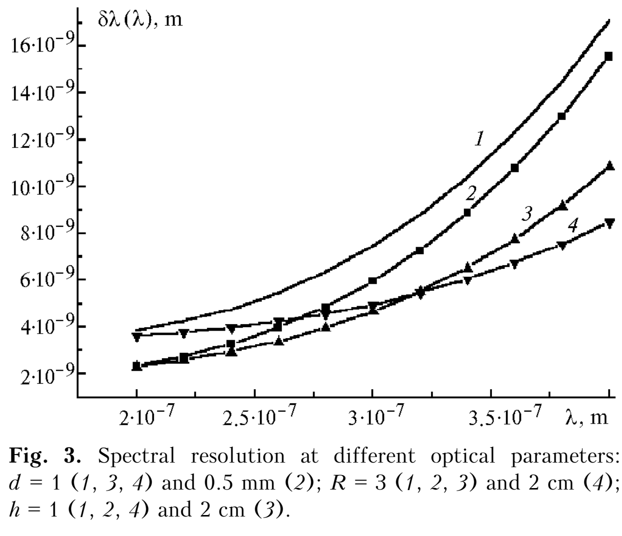

Fig. 3. Spectral resolution at different optical parameters: d = 1 (*1*, *3*, *4*) and 0.5 mm (*2*); R = 3 (*1*, *2*, *3*) and 2 cm (*4*); h = 1 (*1*, *2*, *4*) and 2 cm (*3*).

Changing the parameters of recording the holographic lens, we can improve the resolution keeping unchanged the power characteristics of the device. It is seen from Fig. 4 that the increase of $L1$ and decrease of $L2$ leads to an increase in the spectral resolution. However, the capability of decreasing $L2$ is limited by the technological features of hologram recording, whereas the parameter $L1$ has no such limits. However, the increase of the recording parameter $L1$ leads to an increase in the monochromator size because of the longer dispersion curve. Thus, the problem of improvement of the spectral resolution reduces to the optimal choice of parameters of the focal monochromator based on a particular problem to be solved and the conditions of operation.

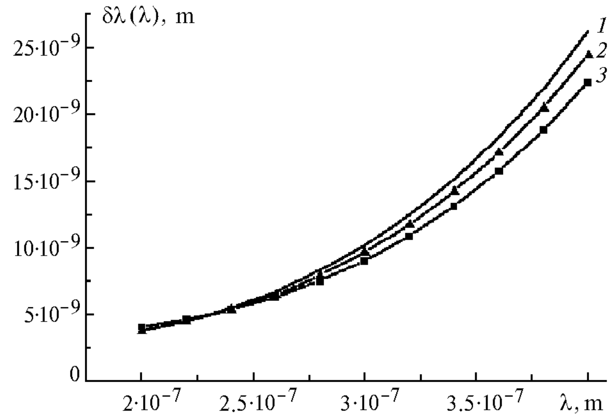

Fig. 4. Spectral resolution at different record parameters of the holographic lens: $L1$ = 35 (*1*) and 25 cm (*2*, *3*); $L2$ = 4 (*1*, *2*) and 3 cm (*3*).

Thus, the use of the focal monochromator based on the holographic lens is an ingenious method to simplify the spectral device for UV monitoring. Since the resulting spectral resolution is sufficient for monitoring of UV solar radiation fluxes, and because of the simple design and low cost, this optical arrangement can become a basis for a small-size and cheap UV spectroradiometer.

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