Method for improving the quality of focusing in optical spectrometers used for the diagnosis of plasma spectra

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Abstract. As a recording element in spectrometers with an optical scheme built on the Rowland circle, as a rule, a multi-element photodetector is used. Such a receiver has a flat surface and therefore the best focusing can be achieved at no more than two points. As a result of the research it was proposed to overcome this drawback by mounting a fiber-optic plate of a special design on the surface of a multi-element photodetector, which allows to obtain the best focus on the entire field of radiation detection, or to eliminate dead zones in multi-channel spectrometers.

1. Broadening of the spectral lines due to defocusing along the photodetector surface

Most modern optical spectrometers are constructed using concave diffraction gratings [1–4]. Such gratings have both dispersing and focusing properties, which can significantly reduce the number of optical elements in devices based on them. In a spectrometer with a concave diffraction grating, the focus is on the Rowland circle [7]. The input slit of the device and its image should be on the circle concerning the top of the diffraction grating.

As a recording element in spectrometers with a similar optical scheme, as a rule, a photodiode or charge-coupled device (CCD) multi-element photodetector is used [8, 9]. Such a receiver has a flat surface and therefore the best focusing can be achieved at no more than two points. On the rest of the surface of the photodetector focusing deteriorates, which leads to a decrease in the real spectral resolution of the device compared to theoretically possible. Thus, in figure 1, the spectral lines of mercury have a half-width $\Delta \lambda = 0.5$ nm at the edges and $\Delta \lambda = 0.6$ nm at the center.

To calculate the value of the broadening of spectral lines, we use the following geometric constructions (figure 2): the distance from the center of the diffraction grating to the Rowland circle $a$, half the length of the sensitive zone of the photodetector $b$, half the length of the photodetector plane $d$, the distance from the Rowland circle to the surface of the photodetector at the point of maximum defocusing $c$, the width of the diffraction grating section $e$, the broadening of the spectral line $f$.

The angle $\beta$ can be found from the known sides of the triangle $aab$:

$$\beta = \arccos(\frac{a^2 - b^2}{2a^2})^{-1}.$$  \hspace{1cm} (1)

The angle $\gamma$ of the triangle $bcd$ can be found from the $\beta$ angle value:

$$\gamma = (\pi - \beta)/2.$$  \hspace{1cm} (2)
Figure 1. Different half-width of mercury spectral lines.

Figure 2. Points of the best focusing of the spectrum in the photodetector plane.
The length $c$ is calculated by the expression:

$$c = \frac{b \cos \gamma}{\sin \alpha}.$$  \hspace{1cm} (3)

The broadening $f$ is calculated from the similarity of triangles $aab$ and $bcd$ using formulas (1–3):

$$f = \left. \frac{eb}{a} \cos \left( \frac{\pi}{2} - 0.5 \arccos \left( 1 - \frac{b^2}{2a^2} \right) \right) \right|_{a = \text{constant}}.$$  \hspace{1cm} (4)

The numerical value of the broadening calculated with the expression (4) for an optical scheme having a diffraction grating with a 10 mm hatched section width, a diameter of a Rowland circle of 125 mm and a photodetector with a length of a photosensitive zone of 27 mm was 58 µm, which means a broadening by 4–7 pixels with a pixel width of the most common multi-element CCD photodetectors of 8–14 µm. This effect can be reduced if the focus is provided at points at a distance of 1/3 and 2/3 of the photodetector width, then with the same initial data, the broadening is 6 µm.

As a result of the research, it was proposed to mount a fiber-optic plate of a special design on the surface of a multi-element photodetector to overcome this deficiency. Fiber-optic plates are usually used for direct image transmission from one end of the plate to another without lenses. They consist of a large number of optical fibers combined together in a regular structure. In such plates, individual light guides have light-insulating shells, which ensure the preservation of the geometry in the transmission of radiation from one end of the plate to the other, since optical radiation can’t penetrate into the adjacent light guides. The fiber-optic plate mounted on the multi-element photodetector shall be flat at one end and the other end shall be concave with the radius of the Rowland circle (figure 3). With this design of the fiber-optic plate, provided that the surface of the input end face is located directly on the Rowland circle, the spectrum will have the best focus across the surface of the concave end of the plate.

![Figure 3. The design of the fiber-optic plate mounted on the multi-element photodetector.](image)

Thus, when using the fiber-optic plate of the proposed design, it becomes possible to provide the best focusing of the recorded spectrum along the entire length of the multi-element photodetector.

2. Dead zones in the multi-channel optical systems

The optical design of the registration system with several photodetectors has the so-called "dead zones" between them. The presence of these zones is explained by the fact that in the design of photodetectors there is a sufficiently large distance from the edge of the crystal to the edge of the body in which it is mounted. As a result, when assembling a structure of several photodetectors in the field of radiation detection, there are zones in which the photosensitive elements are simply absent (figure 4).
Figure 4. Dead zones in multi-channel spectrometers.

This problem can be solved in at least two ways. The first method is that the registration system is made on the basis of unselfish crystals of multi-element photodetectors mounted on a common basis, instead of using standard packaged photodetectors. Another well-known method of eliminating dead zones involves the presence of flat mirrors in the design of the device. Half of the multi-element photodetectors are rotated 90° relative to the rest of the photodetectors, and the rotary plane mirrors design the necessary fragments of the spectrum on them. This method does not eliminate dead zones completely, but only minimizes them.

Figure 5. Design of the fiber-optic focons.

Almost completely eliminate dead zones can be mounted on a multi-element photodetector fiber-optic focon (focusing cone) of the proposed design. Focons same as fiber optic washers have a large number of optical fibers connected together.

The developed design of the fiber-optic focon, which is mounted on the photodetector, from one end touching the surface of the photodetector, has a size $d$, which is slightly less than the width of the...
sensitive zone of the photodetector. The other end of the focom is of size \(a\), and it must exceed the size of the case of the photodetector \(b\) (figure 5). The end, which is connected directly to the photodetector, has a size smaller than the size of the sensitive area of the photodetector. This is necessary to simplify production and installation, because otherwise, when positioning the focom on the surface of the photodetector, it would be required to comply with the accuracy up to the size of a single pixel that is technologically difficult to provide. The width of the proposed focom slightly exceeds the width of the photodetector, which also simplifies installation.

The input ends of the tapers are located in the focus area of the spectrum (the Rowland circle), and their edges are touching. As a result, the spectrum image of the focus area with the input ends of the tapers is transmitted on a separate optical waveguide to the surface of the multi-element photodetectors. This changes the scale of the image, and the spatial energy distribution of optical radiation is preserved, which almost completely eliminates the appearance of dead zones.

3. Conclusion
Thus, it can be concluded that the calculated and developed designs of fiber optic plates installed on the surface of a multi-element photodetector make it possible to obtain the best focus over the entire radiation detection area, or to eliminate dead zones in multi-channel spectrometers.

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