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GENERAL EXPERIMENTAL TECHNIQUE

Investigation of Spectral Resolution in a Czerny Turner Spectrograph[1]

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Abstract—This article describes a smiple and low-cost Czerny–Turner spectrograph capable to operate in spectral range from approximately 350–900 nm. A sine drive assembly was used for linearizing the wavelength scale. The wavelength and pixel position calibration problem have been solved using light sources with known wavelength emission lines, and a polynomial fitting method to find the relationship between diffraction wavelengths and pixel numbers. The pixel resolution ~0.015 nm/pixels and FWHM ~0.1 nm at 170 μm entrance slit width are sophisticated enough to serve well in a research laboratory, yet is simple and inexpensive enough to be affordable for educational use.

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1. INTRODUCTION

Spectroscopic investigation of the physical parameters of plasma and other luminous sources is one of the primary diagnostic techniques for the better understanding of the real systems. Atomic transitions with optical wavelengths are regularly used as indicators of plasma parameters such as temperature and density in a variety of plasma devices. The needs of our current study in the chemistry-physics of plasma lead to design and build an optical spectrometer efficient enough, while remaining uncomplicated and versatile [1, 2].

Diffraction grating based instruments are a good compromise between cost and instrumental flexibility. The diffraction grating type instruments can be divided into two groups based on wavelength tuning mechanisms, namely, scanning monochromator and spectrograph [3]. The resulting instrument is simple and inexpensive because the major components are all commercially available. The most common Czerny-Turner configuration [4, 5] has advantage over other configuration like Littrow and Fastie Ebert [6]. By using an asymmetrical geometry, a Czerny-Turner configuration may be designed to produce a flattened spectral field and good coma correction at one wavelength. Spherical aberration and astigmatism will remain at all wavelengths. The resolution and spectral bandpass of the instrument can be easily altered to suit a specific experiment by swapping plane reflective diffraction gratings or changing the CCD detector.

The main component of the spectrometer is diffraction grating. Detailed treatments of the theory of the diffraction grating can be found in any standard optics text [7, 8]. When parallel light is normally incident on a diffraction grating, one can derive the familiar "grating equation":

$$m\lambda = d(\sin\theta_i + \sin\theta_d), \quad (1)$$

where λ is the wavelength of the diffracted light, θ_i and θ_d are the angle of incident and diffracted light relative to the grating normal respectively, d is the grating constant (i.e., the spacing between lines on the grating), and m is the diffraction order. A variety of spectral and pixel resolution modes can be provided by combinations of CCD and optical components.

In this paper, first we describe the technical specifications of the experimental arrangement and wavelength calibration procedure. Then the concepts of spectral and pixel resolution are discussed.

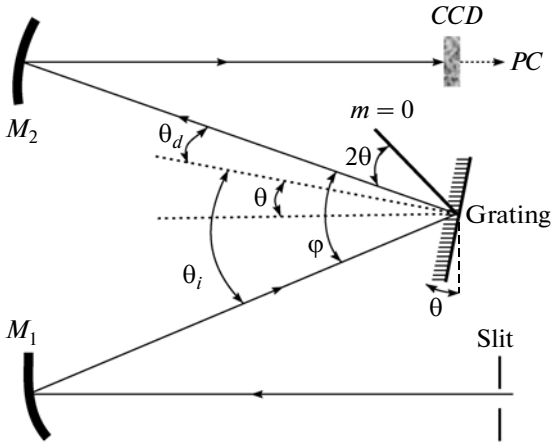

Fig. 1. Optical path in Czerny–Turner spectrograph.

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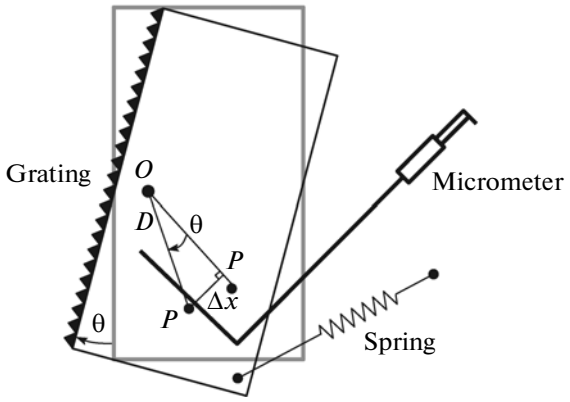

Fig. 2. Sine drive mechanism.

2. INSTRUMENT LAYOUT

A Czerny–Turner mounting using a plane grating is shown in the Fig. 1. The incident radiation passes through the entrance micro-changeable slit and strikes the concave collimating mirror M_1. This mirror produces a collimated light beam reflected onto the grating (600 groves/mm and ruled area 30 × 35 mm), which spatially disperses the spectral components of the incident radiation. The blaze angle is about 6°. Collimated rays of diffracted radiation strike the concave focusing mirror M_2. The focal point of two mirrors is about 57 cm. The dispersed radiation is focused at the surface plane of a CCD image detector (TV lines 420) to provide a one-to-one image of the light source.

Necessary software has been developed to convert the recorded image to a wavelength spectrum. By a grating movement system, the various spectral lines of different sources in the wavelength range of 350–900 nm have been recorded. In fact, the spectral range is determined by the efficiency of the grating and maximum permissible angle of rotation of the grating.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Wavelength Calibration

Finding an exact relation between the wavelength and pixel positions of a spectrum using a known light emission source is a usual problem of any spectrometers. The general procedure is a polynomial fitting method between diffraction wavelengths and pixel numbers [9]. When the grating is rotated, the wavelength is changed nonlinearly. We used therefore a typical sine drive mechanism for linearizing the wavelength scale. The principle of sine drive mechanism is shown schematically in Fig. 2. A lever of length L is rotated through an angle θ about one end, the other end moves through a distance $\Delta x = L\sin\theta$ perpendicular to the initial position of the lever. So the corresponding wavelength is carried out by rotating the diffraction grating by modifying (1) as

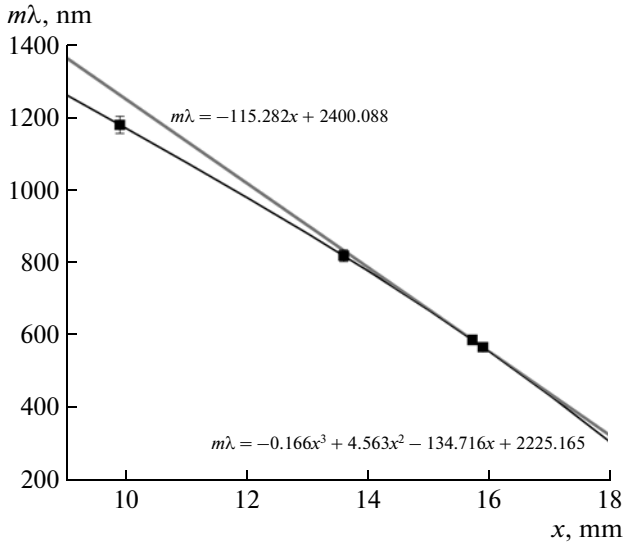

Fig. 3. Relationship between the wavelength and micrometer position.

$m\lambda = 2d(\Delta x/L)\cos(\varphi/2)$. Here, φ is the angle of the incident and diffracted beams of light.

This equation can be simply expressed as $m\lambda = ax + b$. In our experiment in the first positive order of diffraction $a = -115.282$ and $b = 2400.088$ were determined by using two specific green and yellow sodium lines at 568.820 and 588.995 nm, respectively. The corresponding line has been shown in Fig. 3. Because of mechanical error, this dependence is not exactly linear and a polynomial fit has been done by means of more atomic sodium transition lines at 819.482 and 588.995 nm in 1^+ and 2^+ order of diffraction respectively. It means the calibration curve can also be extended to 2^+ order of diffraction. It is worth to notice the spectral range of the spectrograph is determined by the efficiency of the grating and maximum permissible angle of rotation. In our case, the wavelength interval 350–900 nm can be easily achieved.

3.2. Pixel Resolution

Spectral resolution is a key factor in unmixing multiple spectra. An element of dl on the CCD has a specific line width $d\lambda$. The linear dispersion of spectrometer is defined as:

$$\frac{dl}{d\lambda} = f_2\frac{d\theta_d}{d\lambda}, \qquad (2)$$

where f_2 is the focal length of secondary mirror and $\frac{d\theta_d}{d\lambda} = \frac{m}{d}\frac{1}{\cos\theta_d}$ is the angular dispersion of spectrometer [8].

Combined with the grating equation yields:

$$\frac{dl}{d\lambda} = f_2\frac{m}{d}\left[\cos\left(-\frac{\varphi}{2} + \sin^{-1}\left(m\lambda/2d\cos(\varphi/2)\right)\right)\right]^{-1}. \qquad (3)$$

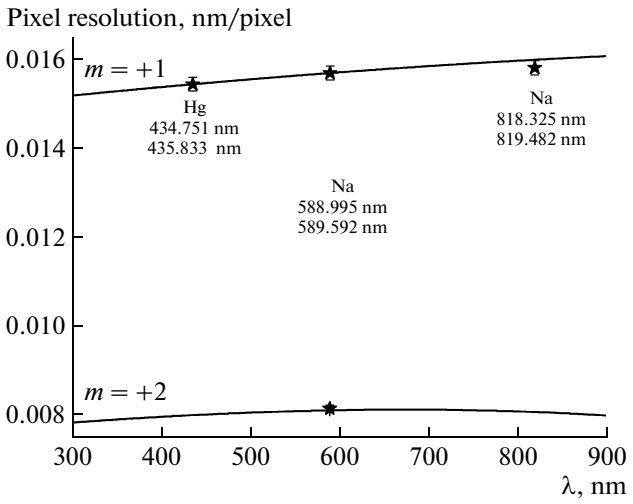

Fig. 4. The wavelength and pixel position calibration curve.

The linear dispersion can also express as the form of pixel resolution $\frac{dl}{d\lambda} = \Delta p \frac{dp}{d\lambda}$, where Δp is the pixel to pixel spacing of image on CCD. The Eq. (3) is therefore modifying to:

$$\frac{d\lambda}{dp} = \frac{d}{m}\frac{\Delta p}{f}\cos\left(-\frac{\varphi}{2} + \sin^{-1}\left(m\lambda/2d\cos(\varphi/2)\right)\right). \quad (4)$$

It is obvious from this equation that for the fixed parameters of detection system, the pixel resolution, $d\lambda/dp$, is reduced about 50% in second order of diffraction for the same diffracted wavelength. This feature is shown in Fig. 4. In our experimental arrangement φ was about 54° and the pixel to pixel spacing of CCD detector with 720 pixels was about 3.6 μm.

For validating the above calculation, experimental values were also derived from sodium and mercury atomic lines. These points indicated by (×) on Fig. 4, have a good agreement with theoretical values both in 1^+ and 2^+ diffraction orders. As expected the pixel resolution in the first order, 0.015 nm/pixels, is about twice higher than compared to the second order of diffraction.

3.3. FWHM of the Instrumental Profile

The instrumental bandpass of an optical spectrometer depends on both the dimensions of the image of the entrance slit (w'_{en}) and the exit slit dimensions (w_{ex}) [10]:

$$\text{FWHM} = \left(\frac{dl}{d\lambda}\right)^{-1} \max\{w'_{en}, w_{ex}\}. \quad (5)$$

Where $(dl/d\lambda)$ is the linear dispersion on exit slit and $\max\{w'_{en}, w_{ex}\}$ due to the slits, is determined by either the image of the entrance slit or the exit slit, whichever is greater. While a CCD detector is used in exit slit, the width of an individual element (few microns) is not wider than image of the entrance slit and the FWHM of the spectral profile could be expressed as:

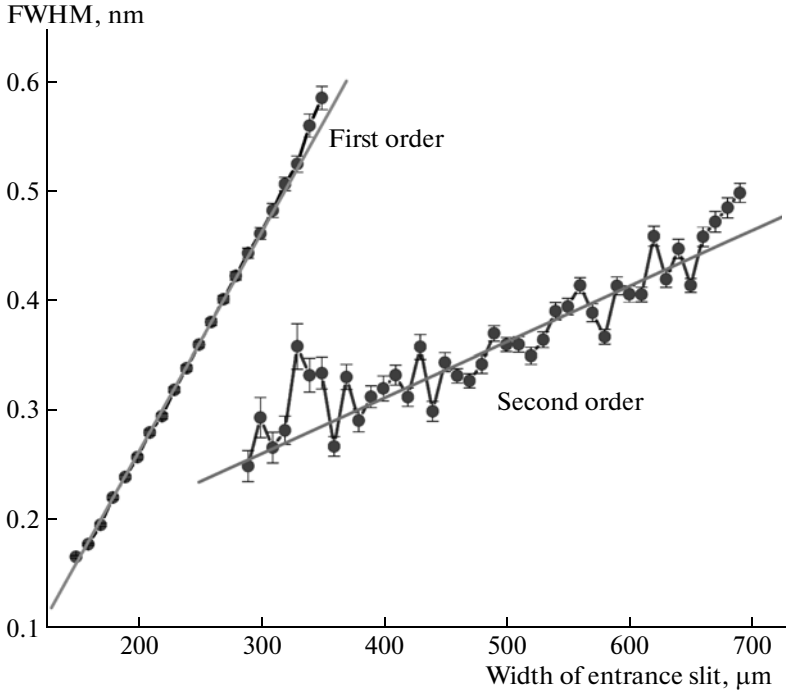

Fig. 5. Relationship between FWHM and entrance slit width.

$$\mathrm{FWHM} = \left(\frac{1}{\Delta p}\frac{d\lambda}{dp}\right) M w_{en}, \quad (6)$$

where $M = w'_{en}/w_{en}$ is the tangential magnification image of the entrance slit.

As mentioned before, the digital dispersion is relatively linear the whole wavelength range. Then for the unchanged mirrors (fixed image magnification), the FWHM is expected to change linearly with entrance width both in 1^+ and 2^+ orders of diffraction. To confirm this assumption, a Gaussian profile was used to fit an individual spectral line of sodium at 588.995 nm. Figure 5 shows the evolution of the FWHM versus the entrance slit width. In practice the FWHM is determined by the convolution of the various causes of line broadening including, the limiting resolution of the spectrometer, bandpass determined by finite spectrometer slit widths, natural line width of the spectral line and Doppler line width. At room temperature the Doppler shifted wavelength and natural line width are relatively low. So the influence of the slits plays important role in the line profile.

4. CONCLUSIONS

In this work, we have demonstrated the performance of an asymmetrical Czerny–Turner scanning spectrograph using spherical mirrors and a low blaze angle grating. A sine drive mechanism was used to calibrate the movement of grating in the absolute scale of wavelength both in 1^+ and 2^+ order of diffraction. This arrangement shows an approximate linear and smooth evolution of the resolution in the wavelength range of 350–900 nm. The pixel resolution was found about 0.015 and 0.008 nm/pixel at first and second order of diffraction respectively. These results yield also a linear dependency of the FWHM versus the entrance slit width. At the lower slit width ~170 μm the FWHM of individual atomic line was found ~0.1 nm.

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