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A METHOD ON IMPROVEMENT OF WAVELENGTH RESOLUTION OF GRATING SPECTROMETERS

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Abstract

A novel concept on the optical structure of the grating spectrometer is introduced to improve the wavelength resolution. Having entering the spectrometer from the entrance, the light is transformed into the parallel beam by a lens and a concave mirror in order to compress the size on the image plane of spectrometer, which efficiently reduces the full width at half maximum of the spectral lines. Having been dispersed by the grating, the beam is converged on the image plane by a concave mirror and a lens with a spectrum range smaller than that only by a concave mirror. By using a spectrometer home-developed and a Charge Coupled Device camera, the lines of 588.9951nm and 589.5924nm from a hollow cathode lamp with sodium element are recorded with three types of optical structure, respectively, and a Charge Coupled Device camera. The experimental results are well in agreement with theoretic results.

Keywords: Spectrometer; wavelength resolution; CCD ; lens

1 Introduction

For a traditional grating spectrometer, the light from the entrance slit or fiber is collimated by a concave mirror and the parallel beam dispersed by the grating is then focused on the image plane of the spectrometer by another concave mirror[1]. The free spectrum range (FSR) is determined by both the grating constant and the focal length of the second mirror. The shorter the focal length, the larger FSR, but the lower the wavelength resolution (WR) of the spectrometer[2]. By using a Charge Coupled Device (CCD) camera to record the spectrum information for the spectral structure, the narrower FSR, the longer the focal length (FL) of the concave mirror for the dispersed beam. Thus, to get the fine structure of the spectrum in a small FSR is bound to increase the length of the spectrometer dimension. This not only greatly increases the cost and the difficulty making, and it is inconvenient to use due to the huge size of the spectrometer. In some special experiments and researches, the aim is for the fine structure of the emission such as some of the typical the molecular spectra, which deal with the excitation of the oscillation and rotation levels[4,5]. Although the spectrometers with the extraordinary combination can be used to record the spectrum with a small FSR and a high WR, the characteristics of the structure limits the further improvement of WR.

As the band width of the light is narrow in an optical device, the chromatic aberrations of the lens are so small that the refraction index of the material is nearly a constant[6]. In a grating spectrometer, the lens can be used to collimate, converge, and transform the light beam as the wavelength range is as narrow as several nanometers.

2 Experimental details and Analysis

For a typical grating spectrometer, FSR $\Delta\lambda$ and WR can be obtained from the grating diffraction equation and the object-image equation.

$$d(\sin\theta_0 - \sin\theta_1) = \lambda \tag{1a}$$

$$d\cos\theta_1 \Delta\theta_1 = d\cos\theta_1 \frac{N\delta}{F_2} = \Delta\lambda \tag{1b}$$

$$\Delta' = (F_2 / F_1)\Delta \tag{1c}$$

$$\Lambda \approx d\cos\theta_1 \frac{\Delta'}{F_2} \tag{1d}$$

where d is the grating constant, θ_0 is the incident angle of the parallel beam from the collimated concave mirror, θ_1 is the diffraction angle from the grating and changes with the wavelength λ . N and δ are the transverse pixel number of CCD camera and dimension of one pixel, respectively. F_1 and F_2 are the focal lengths of the concave mirrors for the collimation and convergence of the light, respectively, as shown in Fig.1(a). Δ and Δ' are the sizes of the light source at the entrance of the spectrometer and of the image on the CCD camera, respectively. And Λ is the full width at half maximum (FWHM) for a beam with a single wavelength.

In the spectrometer developed by ourselves, the pixel size and number of the CCD camera are $6.45\mu m \times 6.45\mu m$ and 1392×1080 , respectively. The grating constant is with $1800^{-1} mm$. Under the case of $F_1 = F_2 = 400mm$ and $\cos\theta_1 \approx 1$, FSR $\Delta\lambda$ is about 12.5 nm . On the other hand, the quartz fiber with a core diameter of $200\mu m$ is used to input the light measured into the spectrometer, as shown in Fig.2. The size of the entrance is thus $200\mu m$. The spectral line width of a monochromatic light is 0.278 nm from equations (1). In order to decrease the line width to 0.139 nm, FLs of both the concave mirrors should be increased to $F_1 = F_2 = 800mm$ and the corresponding FSR is decreased to 6.25 nm , if the line width decreases to 6.25 nm but the structure dimension of the spectrometer increases obviously. In this paper, a new concept for the spectrometer is introduced where both the lenses are used in the process of the collimation and convergence of the light beam for the improvement of WR. A special experiment for the recording of the spectral lines of sodium from a hollow cathode lamp (588.9951nm and 589.5924nm) is carried out to prove the feasibility of this method[3].

The schematic diagram of the typical grating spectrometers is displayed in Fig.1(a) where the light entrance locates at the focal point of the concave mirror F_1 and the parallel light dispersed by the grating converges on the plane of the recording medium by the concave mirror F_2 . The smaller transverse size of the light entrance is, the narrower FWHM of the lines is. Therefore, in order to increase the wavelength resolution of the spectrometer, the concave mirrors with a long focal length have to be employed. However, the introduction of such mirrors makes the structure dimension of the spectrometer increase obviously.

In the region of the collimation and convergence of the light, the introduction of the lens with the special focal length not only impresses FSR of the spectrometer but also improves the corresponding WR. Such structure is shown in Fig.1(b). The light from the slit or the fiber firstly passes through a lens with a negative focal length and, then, collimate by the concave mirror and this transformation minifies the size of the light entrance. Having been dispersed by the grating, the parallel all the directions are converged by the second concave mirror. Before the beams reach the focal point of this mirror, they are transformed by another lens with a negative focal length. Thus, the corresponding image plane is extended to the position farther from the mirror than its focal plane. In this optical structure, the transformation of the sizes of the light entrance and the image on the recording medium and the spectral range follows as:

$$\Delta' = \left| \frac{l_1'}{l_1} \cdot \frac{l_2'}{l_2} \cdot \frac{F_2}{F_1} \right| \cdot \Delta \qquad (2a)$$

$$\Delta\lambda = d \cdot \cos\theta_1 \cdot \frac{N\delta}{F_2} \cdot \left| \frac{l_2}{l_2'} \right| \qquad (2b)$$

From Fig.1(b), it is seen that there are relation of $|l_1| > |l_1'|$ and $|l_2| < |l_2'|$. Therefore, by comparing the case without the lens, the spectral range decreases to $|l_2 / l_2'|\Delta\lambda$ and the image size of the light entrance image depends on $|l_1' / l_1|$ and $|l_2' / l_2|$. For a symmetry system, i.e. $|l_1' = l_2|$ and $|l_2' = l_1|$, the size of the image equals to that of the entrance ($\Delta' = \Delta$). However, WR increases by a factor of $|l_2' / l_2|$.

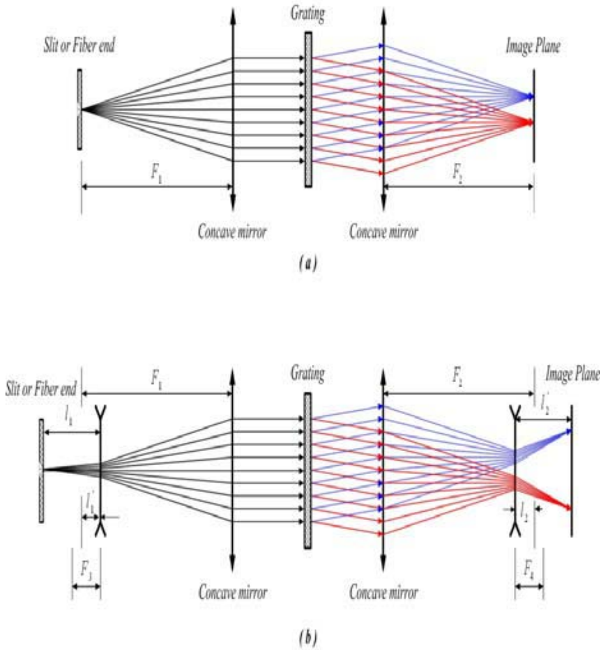


Figure 1 The optical schematic diagram of grating spectrometer (a) normal structure and (b) with two lens with negative focal lengths.

Figure 2 is shown the optical structure of the spectrometer home-developed by ourselves and the setup for the recording of the spectral lines of 588.9951nm and 589.5924nm from a hollow cathode lamp with sodium element and the figure inserted this figure is the corresponding spectral result of the lines. From the experimental results, it is easy to find that FSR is 12.99 nm, FWHM of the lines is 0.177 nm , and the amount of the wavelength each pixel is *0.0093328 nm / pixel*.

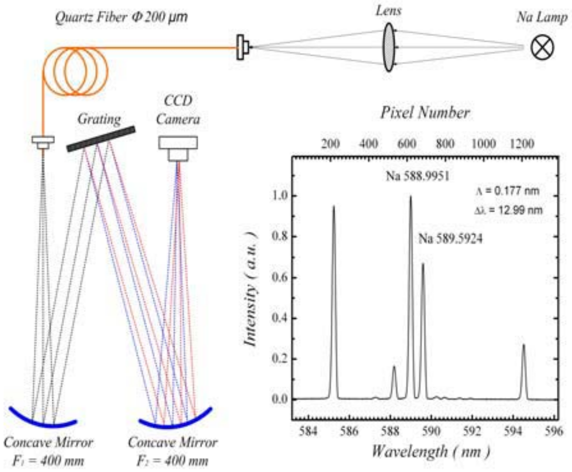


Figure2 The optical structure of the spectrometer home-developed and experimental setup for the recoding of the spectral lines of sodium element and the experimental spectrum where the focal length of both the concave mirrors are $F_1 = F_2 = 400\ mm$.

Between the CCD camera and the second mirror, a lens with a focal length of *- 80 mm*, F_4, is inserted and its distance from the CCD camera is *130 mm*, shown in Fig.3. Then the careful adjusting is required for the minimum of FWHM of the spectral lines of 588.9951nm and 589.5924nm. The distance of the lens F_4 from the second mirror F_2 is finally *350 mm*. From the experimental results shown in the figure inserted in figure 3, FSR $\Delta\lambda$ and FWHM Λ are $4.862\ nm$ and $0.140\ nm$, respectively. The wave range each pixel of CCD camera is *0.0034930 nm / pixel*.

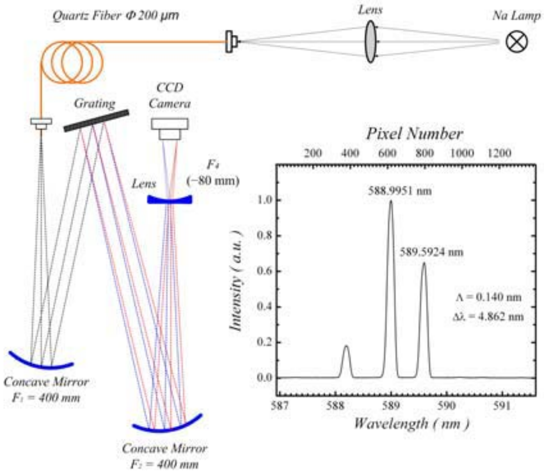
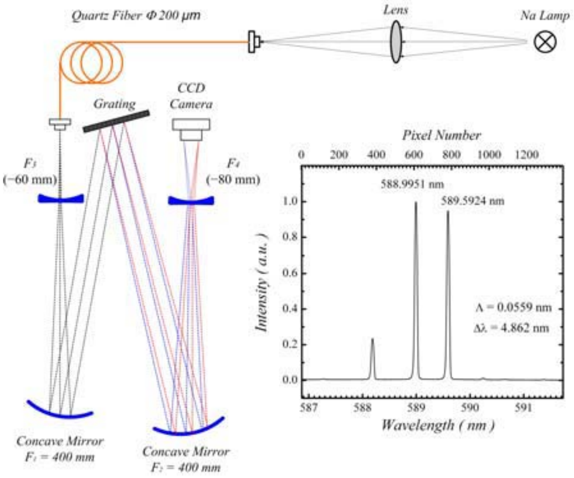


Figure 3 Customer Figure 3 the optical structure of the spectrometer and experimental setup for the recoding of the spectral lines of sodium element and the experimental spectrum where a lens with a focal length of $-80mm$ is inserted between the CCD camera and the second concave mirror

Under $l_2' = 130\ mm$ and $F_4 = 80\ mm$, one can easily obtain $l_2 = 49.5\ mm$ from the relation of object distance and image distance. From equation (2b), the compression factor of FSR is equal to $\left| l_2 / l_2' \right| = 0.380$. The actual ratio is 0.374, which is well in agreement with the former. On the other hand, the image of the light entrance is magnified as 2.67 time as the size of the light entrance, which is advantageous to find the position of the second mirror F_2 for the minimum of FWHM of the spectral lines.

In the device shown in Fig. 3, a lens with a focal length of *- 60 mm*, F_3, which is with a distance of *95 mm* from the light entrance, is inserted and the first mirror is moved backward *60 mm*, as shown in Fig. 4. The spectrum above recorded by this device is shown in the figure inserted in Fig.4. The values of FSR and the wavelength range each pixel are all as same as those without the lens F_3. However, FWHM of the lines are all reduced to $0.0559\ nm$.



Figture4 Flows of ITSM implementation strategy aiming at customer service

The size of the image on the plane of the recoding medium can be estimated by Eq. (2a) and FSR can be calculated by Eq. (2b). The FWHM of the lines calculated is 38.7% of that without the lens F_3 and the actual value is 39.9%. Both the values are well in agreement with. Therefore, by comparing to that shown in Fig.2, WR of the spectrometer with the optical structure in Fig.4 is efficiently improved but the dimension of the spectrometer only slightly increases.

From the experimental and analytic results, WR depends on FL of F_3 and its distance from the light entrance. The longer this distance is, the narrower FWHM of the spectral lines. The ratio of both

FWHMs with and without the lens F_3 is $F_3/\left(F_3+l_1\right)$. At $l_1=F_1=9F_3$, it is only required to double the optical structure length of the spectrometer. WR increases by 100% without F_3 but by 1000% with F_3. On the other hand, FSR is a function of FL of the lens F_4 and its distance from the plane of the recording medium. The larger this distance is, the smaller the free spectrum range. By comparing the case without the lens F_4, FSR decrease by a factor of $F_4/\left(F_4+l_2^{'}\right)$. Under the case of $l_2^{'}=F_1=9F_4$, FSR decreases to $1/10$ of that without the lens F_4 where the dimension of the spectrometer along the optical axis is only 200% of the latter. Therefore, the introduction of both the lens can efficiently increase WR of the spectrometer but it is unessential to increase the structure dimension of the spectrometer.

3 Conclusions

In summary, in a traditional grating spectrometer, FWHM of the lines can be decreased and WR is efficiently improved as a lens is used to minify the image size of the light entrance on the plane of the recording medium. Having been focused on the plane of the recording medium, the light dispersed by the grating first passes through a lens with a negative focal length. Thus the distance of the image plane from the second concave mirror is extended and the profile of the spectrum is obviously magnified. Thus, it is avoided that the improvement of the wavelength resolution and the spectral structure is with the greatness of the dimension of the spectrometer.

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