Densely folded spectral images of a CCD spectrometer working in the full 200–1000 nm wavelength range with high resolution

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Abstract: A new charge-coupled device (CCD) spectrometer has been studied and constructed by using a two-dimensional CCD detector and an integrated grating consisting of 10 subgratings. Effective spectral images of 268 mm along the dispersion direction have been densely folded 10 times to cover the full 200–1000 nm working wavelength range without any mechanical moving elements. The results show that the system has a spectral resolution and acquisition time of better than 0.07 nm and less than 100 ms, respectively, in the entire spectral range after system calibration.

OCIS codes: (120.4640) Optical instruments; (300.6550) Spectroscopy, visible; (110.2960) Image analysis; (050.2770) Gratings; (040.1520) CCD, charge-coupled device.

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1. Introduction

The advanced optical spectrometer has played a significant role in modern science and technology for extracting rich physical information of materials in nature [1]. In the traditional design of the spectrometer, optical dispersion elements such as gratings or prisms have to be rotated continuously in very fine steps using the mechanical process in order to scan the wavelength and to achieve high spectral resolution in measurements [2–4]. Usually it takes several minutes to complete the wavelength scanning in the entire working spectral range because of this slow mechanical process. With the application of new types of one- or two-dimensional array detectors, researches have resulted in the design of a spectrometer with high data-reading speed and high resolution [1, 3–7]. One of the most important

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improvements is the use of the advanced Si-based charge-coupled device (CCD) or complementary metal oxide semiconductor (CMOS) detectors to measure spectral distribution in the focal plane [6–9]. The CCD or CMOS array detectors can record many spectral lines at the same time in parallel data acquisition mode. Because of technical limitations in array detector design and fabrication, measurement will be restricted to a narrow spectral range in most situations. For example, for the spectrometer having a typical dispersion of about 3 nm/mm in the visible range, we can only measure an effective wavelength window of about 80 nm by using a CCD detector that has an active area of 26.8 mm × 26 mm [10]. In application, therefore, a mechanical scanning process with fewer scanning steps will still be needed to perform a full coverage of the 200–1000 nm working spectral range with respect to the Si-based array detectors. However, the advantage of using a two-dimensional array photon detector is that it will help to develop a spectrometer in which the dispersed spectral lines imaged on the focal plane of the array detector can be densely folded in terms of proper system design. The actual working spectral range can be extended effectively without reducing the resolution.

In this work we study the CCD spectrometer to pursue high spectral resolution greater than 0.1 nm in the full working spectral range. The width of the effective spectral images in the dispersion plane has been densely folded 10 times to extract spectra in the entire working wavelength range at a speed of less than 100 ms without any mechanical moving elements. The detailed results with regard to the system design and construction of the spectrometer are given in the following sections.

2. Principle and system construction

In the spectral dispersion system using a plane grating, light with a wavelength λ that enters onto the grating at the incidence angle i will be diffracted at the angle θ as [12]

$$m\lambda=d(\sin\theta\pm\sin i), \tag{1}$$

where m is the order of diffraction and d is the space distance between two neighboring grooves of the grating. In this work, the positive sign is taken since i and θ are located on the same sides of the grating normal in the design; otherwise the sign will be negative. For the given grating structure, d is a fixed value and sin i is a constant related only to the incidence angle of the light entering onto the grating. When we consider the first-order (m=1) diffraction, the diffracted spectral lines will be distributed in a wavelength window $\Delta\lambda$ corresponding to the diffraction angles ranging from θ_1 to θ_2

$$\sin\theta_2-\sin\theta_1=(\lambda_2-\lambda_1)/d=\Delta\lambda/d. \tag{2}$$

For the two-dimensional array detector, the certain diffraction wavelength window of $\Delta\lambda$ can be fitted into the physical size of the image plane of the CCD detector. This can be achieved by using the multiple-grating structure to arrange several spectral zones with different wavelength windows in sequence along the direction perpendicular to the spectral distribution so that all spectral zones can fill the focal image plane of the CCD detector. In the system design, we made an integrated grating structure with 10 subgratings fixed at different incidence angles. The groove density of all gratings is 1200 g/mm. The spectral resolving power R in the first order is given by $R=\lambda/\Delta\lambda=N$, where N is the total number of grooves on the grating. Assuming that gratings will have a useful width of 60 mm in the design, the ideal wavelength resolution $\Delta\lambda$ will be about 0.008 nm at the 600 nm wavelength. In practical application, the resolution will not be as high as expected due to some physically restricted factors.

The designed spectrometer in this work had a linear dispersion of about 3.2 nm/mm at the focal plane of the CCD detector. We used an advanced back-illuminated CCD camera to have high quantum efficiency and an effective photon sensing area of 26.8mm x 26 mm (1340 x 1300 pixels) with the pixel size of 20 μm x 2 0 μm and 16-bit A/D signal converting capability [10]. To take advantage of the Si-based CCD detector that has the optimal 200–1000 nm working spectral range, at least 10 subwavelength windows were required to be distributed uniformly in the region. Each individual subwavelength window was equal to about 80 nm. The incidence angle of each subgrating was carefully adjusted, with the result that the diffracted light with the different wavelength window $\Delta\lambda$ was distributed within the same range of the diffraction angle

$$\Delta(\sin\theta) = \sin\theta_2-\sin\theta_1 = \sin\theta_3-\sin\theta_2=......\sin\theta_{10}-\sin\theta_9$$

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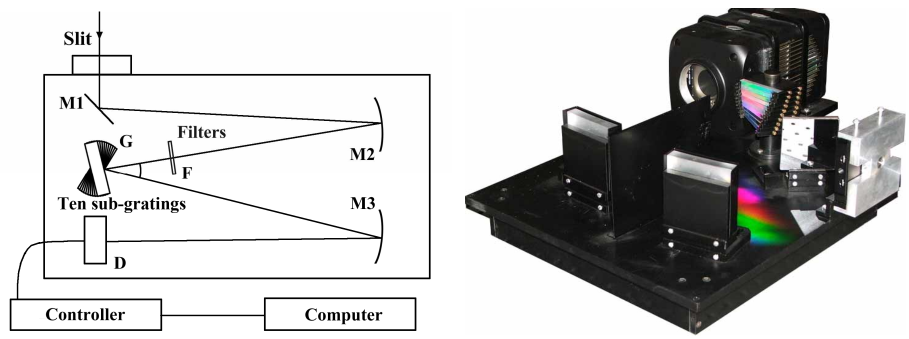
$$=(\lambda_2-\lambda_1)/d =(\lambda_3-\lambda_2)/d =......=(\lambda_{10}-\lambda_9)/d = \Delta\lambda/d. \quad (3)$$

The image plane of the CCD array detector was placed at the focus position of the spectrum. Therefore, when we adjust the orientation of each grating, 10 spectral image zones corresponding to the 10 wavelength windows can be formed on the focal plane of the CCD detector. Each zone will had about 1340 × 130 pixels equivalent to the photon sensing area of 26.8 mm x 2.6 mm, resulting in that there was a total of 13,400 pixels along the spectral direction in the 200–1000 nm wavelength range. In the two-dimensional focal plane, the physical spectral width has been effectively extended to about 268 mm with the resolution better than 0.1 nm for each pixel in the limitation.



(a) (b)

Fig. 1. Schematic structure of the spectrometer. (a). Optical configuration of the spectrometer: M1, the plane mirror; M2, the spherical mirror; M3, the toroidal mirror; G, the integrated grating consisting of 10 subgratings; F, the filters; D, the CCD detector. (b). Detailed photo picture to show the internal configuration of the spectrometer.

The configuration of the spectrometer is shown in Fig. 1. To enhance diffraction efficiency, 10 plane subgratings were blazed at different wavelengths: 250 nm (200–280 nm), 300 nm (280–360 nm), 400 nm (360–440 nm), 500 nm (440–520 nm, 520–600 nm, 600–680 nm), 750 nm (680–760 nm, 760–840 nm, 840–920 nm), and 1000 nm (920–1000 nm), respectively, with respect to each subwavelength window [11]. The dimension size of the subgrating was 60 mm × 5 mm with the grooves parallel to the short side. The integrated grating had an effective grating size of about 60 mm x 50 mm. Although these 10 subgratings were arranged with different orientations, the value of $(\theta+i)$ is the same for each grating to make the diffraction light form on the focal plane of the detector.

Eight pure fused silica fibers working in the 200–1000 nm wavelength range were made to form a spot-to-slit type fiber bundle and to guide the light signal into the spectrometer. Each fiber had the diameter of about 0.125 mm. The light source was focused and coupled into the spot end and existed from the slit end of the fiber with the size of about 0.125 mm x 1 mm placed at the entrance slit of the spectrometer. The long side of the fiber slit was adjusted parallel to the entrance slit with a fixed width of about 10 μm. The light exiting from the entrance slit was reflected by the plane mirror M_1 and collimated by the spherical mirror M_2 with a focal length of 250 mm. The collimated light beam was incident onto 10 subgratings at different incidence angles. A toroidal mirror M_3 with the focal lengths of 250 mm and 500 mm along the direction parallel and perpendicular to the spectral distribution, respectively, was used to make the diffracted light focus and to fill into the image plane of the detector.

According to Eqs. (1) and (3), the first order of the diffracted light will be distributed in ten spectral zones with a window of about 7° along the spectral distribution. When we use the advanced CCD camera, spectral data acquisition time can be controlled by the program depending on the signal-to-noise ratio. The minimum exposure time to capture the full frame of the spectral image can be set to 1 ms. The real data acquisition time, however, is about 100 ms limited by the data transferring from the CCD camera to the computer through the A/D converting process. The three high-pass optical filters with the wavelength threshold at 310 nm (360–520 nm), 450 nm (520–680 nm), and 620 nm (680–1000 nm), respectively, were used to cut off the high-order diffraction light. The system was controlled by the personal computer running with the Microsoft Windows operation system. The

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software program was written in Visual C++ using PVCAM [10] to read and analyze the spectral data.

3. Results and discussion

The image of spectral lines of the Hg lamp was measured, with the result shown in Fig. 2. It is clear to see that there are 10 spectral regions corresponding to 10 sub-gratings.

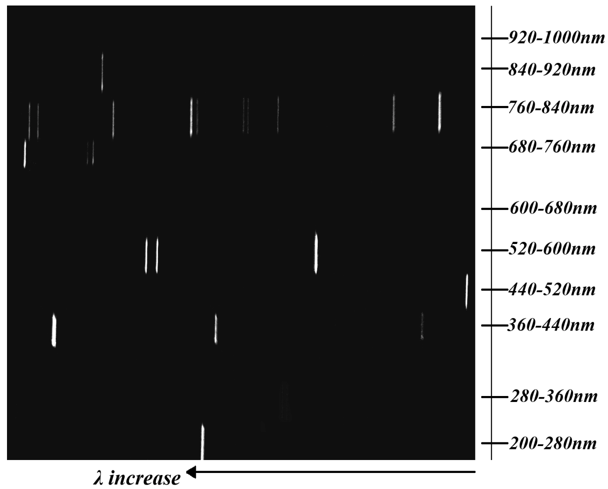

Fig. 2. Spectral pattern of Hg lamp with 10 sub-wavelength regions was imaged on the focal plane of the CCD detector.

From the bottom to the top, the 10 subwavelength regions are almost uniformly distributed in equal space from 200 to 1000 nm along the direction perpendicular to the spectral diffraction. When we analyze the image pattern of the spectral lines, the completed spectral information can be obtained without any ambiguity. A standard 0.5 m focal-length monochromator was used to calibrate the spectrometer. According to Eqs. (1)–(4), although the pixel position may be not exactly linear to the wavelength, the error is small since the spectrum from 200 to 1000 nm has been folded 10 times to make each individual wavelength region be imaged on a relatively narrow physical region of about only 7^o. To correct the dispersion error, a mathematical polynomial function was used to fit the wavelength λ to the pixel position x regarding to the 10 sub-spectral regions in the calibration procedure of the system:

$$\lambda(x)=a_0+a_1x+a_2x^2+a_3x^3. \tag{4}$$

The typical calibrated coefficients in the 440–520 nm wavelength range are a_0=211.97, a_1=0.063, $a_2=9.72\times 10^{-7}$, and $a_3=-8.05\times 10^{-11}$. Because of the longer focal length of the mirror as compared to the dimension of the image plane of the CCD detector, it can be seen that the non-linearity terms arising from the higher order of errors are quite small and can be ignored. The value of the coefficient a_1 indicates the average spectral resolution of each pixel in its limitation. The calibrated wavelength-to-pixel curves are shown in Fig. 3. Afterwards, the completed set of the polynomial coefficients was stored in the program to be used in the experiment. The entrance slit of the spectrometer with the fixed width of about 10 μm will be imaged on the focal plane of the CCD detector. This width is narrower than the pixel size (20 μm) along the spectral direction. When we take the average of the dispersion curves in the entire wavelength region, the spectral resolution is equal to about 0.065 nm/pixel in the 200–1000 nm wavelength range and is in good agreement with the system design expectation.

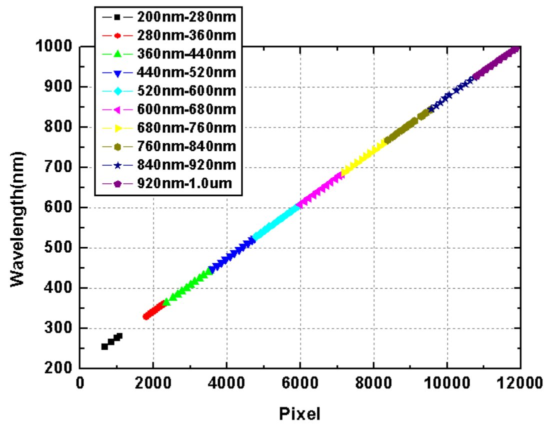

Fig. 3. Calibrated curves of the wavelength to pixel positions for the 10 subgratings fixed at different incidence angles.

In experiments, the spectral resolution can be measured by the full-width at half maximum (FWHM) of the spectral line. We tested the system by measuring the width of the 632.8 nm line of the He–Ne laser. As seen in Fig. 4, the FWHM of the spectral line is covered by about three pixels and is equal to about 0.12 nm. This indicates that two spectral lines with a wavelength separation of $\Delta\lambda$=0.12 nm can be clearly resolved. In terms of the characteristic spectral lines of the Hg lamp as shown in Fig. 2 for its image pattern, the spectral position of each line has been determined and shown in Fig. 5. It is clear to see that the two sets of spectral lines located at (312.5 nm, 313.1 nm) and (577.0 nm, 579.0 nm), respectively, are well resolved with fine resolution. The results are in good agreement with the Hg spectral data.

4. Conclusion

We have studied and constructed a new CCD spectrometer by using a two-dimensional CCD detector and an integrated grating consisting of 10 subgratings. The spectral width in the 200–1000 nm wavelength range has been effectively extended to about 268 mm in the focal plane along the dispersion direction by densely folding the spectral image 10 times without any mechanical moving elements. The results show that the system has a spectral resolution and acquisition time of better than 0.07 nm and less than 100 ms, respectively, in the spectral range after system calibration. The spectrometer will have the advantage and potential to be used for rapid spectral extraction and analysis in many applications.

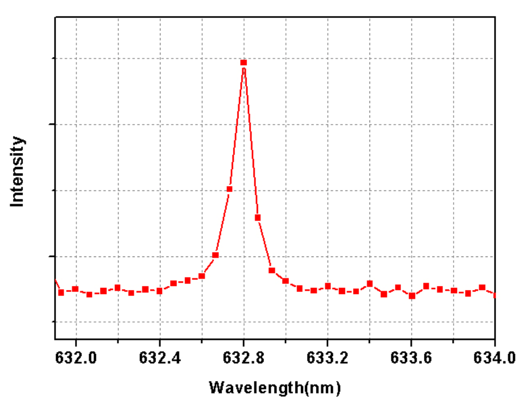

Fig. 4. Measured 632.8 nm spectral line of the He-Ne laser light source having the FWHM value of about 0.12 nm.

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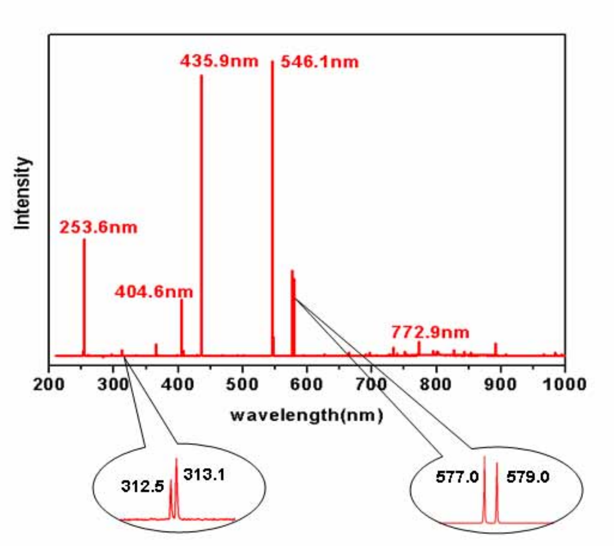

Fig. 5. Measured spectral lines of the Hg lamp to show those well-resolved lines with fine resolution.

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