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Broadband astigmatism-corrected spectrometer design using a toroidal lens and a special filter

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ABSTRACT

In the paper, a method to obtain a broadband, astigmatism-corrected spectrometer based on the existing Czerny–Turner spectrometer is proposed. The theories of astigmatism correction using a toroidal lens and a special filter are described in detail. Performance comparisons of the modified spectrometer and the traditional spectrometer are also presented. Results show that with the new design the RMS spot radius in sagittal view is one-eightieth of that in the traditional spectrometer over a broadband spectral range from 300 to 700 nm, without changing or moving any optical elements in the traditional spectrometer.

1. Introduction

The Czerny–Turner spectrometer, which consists of two spherical mirrors, a plane grating, and a detector is widely used in many areas, for example, Raman spectroscopy measurement [1], retrieval of ultraviolet skylight radiances [2], spatiotemporal characterization of laser pulses [3], and laser-induced breakdown spectroscopy [4,5]. However, the traditional Czerny–Turner spectrometer, introducing the astigmatism due to the off-axis incidence to spherical mirrors, wasting energy and the signal to noise ratio decreases as a linear array detector is used, which is very harmful for weak signal applications, such as frequency-domain optical coherence tomography (FD-OCT) [6] and biological fluorescence detection [7]. Making use of two-dimensional array photodetectors makes it possible to improve the situation to some extent with the reason that the signals on the focus line can be added together, but the possibilities that parallel operation with several detection channels are reduced and the signal-to-noise ratio decreases since the illumination distributes on many pixels, is unacceptable for the signals close to the sensitivity threshold of the detector.

Some methods have been investigated to reduce or remove astigmatism [8], for example, using freeform mirrors [9], taking toroidal focusing mirror [10], compensating optics before the entrance slit [11], and introducing divergent illumination [12,13]. However, these methods are limited because they all need to satisfy a(some) condition(s) of the parameters of the Czerny–Turner spectrometer as compensating the astigmatism.

Using a cylindrical lens is a good way to eliminate the astigmatism, this method was introduced by Lee et al. [14] and has developed to other forms [15,16], but in all these designs the cylindrical lens, spherical mirrors, grating and detector are a complete system, if the cylindrical lens is taken out, the system cannot work. In actual designs we all know that some spectrometers did not consider astigmatism in the initial design owing to the cost and applications, and cannot achieve a 'real' broadband spectrum detection due to the spectral overlaps. In this paper, we present one novel solution to eliminate the astigmatism and spectral overlaps for the existing Czerny–Turner spectrometer making use of a toroidal lens and a special filter, without moving or changing any optical elements on the original spectrometer. This method provides low-cost modification for the existing spectrometer and supplies a variety of cost choices for the spectrometer design. From the design example described in Section 4, with the new design the RMS spot radius can be compressed to 1/82 in sagittal view compared with the traditional system, enhancing the energy collection efficiency and improving the signal to noise ratio. In the following part we present how a toroidal lens and a filter can correct the astigmatism over a broadband spectral range and describe the spectrometer with the new design.

2. Broadband astigmatism correction using a toroidal lens and a filter

2.1. Structure design for astigmatism correction

In the classic Czerny–Turner spectrometer, for the collimating light incident on the mirror, if the chief ray makes an off-axis angle

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α with the mirror vertex whose radius is r, the sagittal focal length and tangential focal length are [15]

$$f'_s = \frac{r}{2\ \cos\ \alpha} \quad (1)$$

$$f'_t = \frac{r\ \cos\ \alpha}{2} \quad (2)$$

When the off-axis incident angle is not large, the difference in astigmatic focus yielded by the two off-axis spherical mirrors of Czerny–Turner can be derived as [17]:

$$\Delta f' = \frac{r_1\ \sin\ \alpha_1\ \tan\ \alpha_1}{2} + \frac{r_2\ \sin\ \alpha_2\ \tan\ \alpha_2}{2} \quad (3)$$

where r_1 is the radius of the first spherical mirror, r_2 is the radius of the second spherical mirror, α_1 is the off-axis incident angle on the first mirror, and α_2 is the off-axis incident angle on the second mirror.

In this design, the toroidal lens and the filter are both located between the focusing mirror and the detector, as shown in Fig. 1. The toroidal lens is mainly used to eliminate the astigmatism, the filter is taken to remove high diffraction order spectrum. The filter is close to the detector because it is easier to cut off the high-order light from the low-order light at such position. In Fig. 1 there are two views displayed: (1) tangential view and (2) sagittal view.

In Fig. 1, we assume the detector locates at the tangential focus point. The toroidal lens can be seen as the combination of a thin lens with no thickness and a plate glass with thickness t_l, then the change of focus introduced by the filter and the plate glass can be written as

$$P_f = (n_f - 1)t_f / n_f \quad (4)$$

$$P_l = (n_l - 1)t_l / n_l \quad (5)$$

where n and t are the index refraction and the thickness, the subscripts f and l represent the filter and toroidal lens, respectively.

In Fig. 1(1), the change of tangential focus introduced by the toroidal lens is given by

$$\frac{1}{l'_{tl}} - \frac{1}{l_{tl}} = \frac{1}{f'_{tl}} \quad (6)$$

where l_{tl}, l'_{tl} are tangential object and imaging distances of the toroidal lens, f'_{tl} Represents the tangential focal length of the toroidal lens. Because the focus location in tangential view does not change and the change of focus introduced by the filter is P_f, then the imaging distance l'_{tl} can be calculated as $l'_{tl} = l_{tp} - P_f$; analogously, the change of focus caused by plate glass is P_l, then the object distance l_{tl} can be expressed as $l_{tl} = l'_{tl} + P_l$, here l_{tp} is the distance from the toroidal lens to the focal point of tangential view, the subscript p represents the focal point. Then Eq. (6) can be rewritten as

$$\frac{(l_{tp} - P_f)^2}{f'_{tl} - (l_{tp} - P_f)} = P_l \quad (7)$$

In Fig. 1(2), the change of sagittal focus follows the formula:

$$\frac{1}{l'_{sl}} - \frac{1}{l_{sl}} = \frac{1}{f'_{sl}} \quad (8)$$

where l_{sl}, l'_{sl} are the sagittal object and imaging distances of the toroidal lens, respectively, f'_{sl} Stands for the sagittal focal length of the toroidal lens. From Fig. 1(2) it is obvious that as $l_{sp} - l'_{sp} = \Delta f'$, the astigmatism is corrected. Just like the analysis in the tangential view, the object and imaging distances can be written as $l_{sl} = l'_{sl} + P_l + \Delta f'$ and $l'_{sl} = l'_{sp} - P_f$. Because the focus locations in the tangential view and sagittal view are the same after adding the toroidal lens and the filter, $l'_{sp} = l_{tp}$, Eq. (8) can be written in another form:

$$\frac{(-P_f + l_{tp})^2}{f'_{sl} - (-P_f + l_{tp})} = P_l + \Delta f' \quad (9)$$

The incident angles to the second mirror are different for different wavelengths, as shown in Fig. 2, and the variation of the incident angle α_2 leads to the change of astigmatism $\Delta f'$. Here we define H as the distance between the chief ray of the central

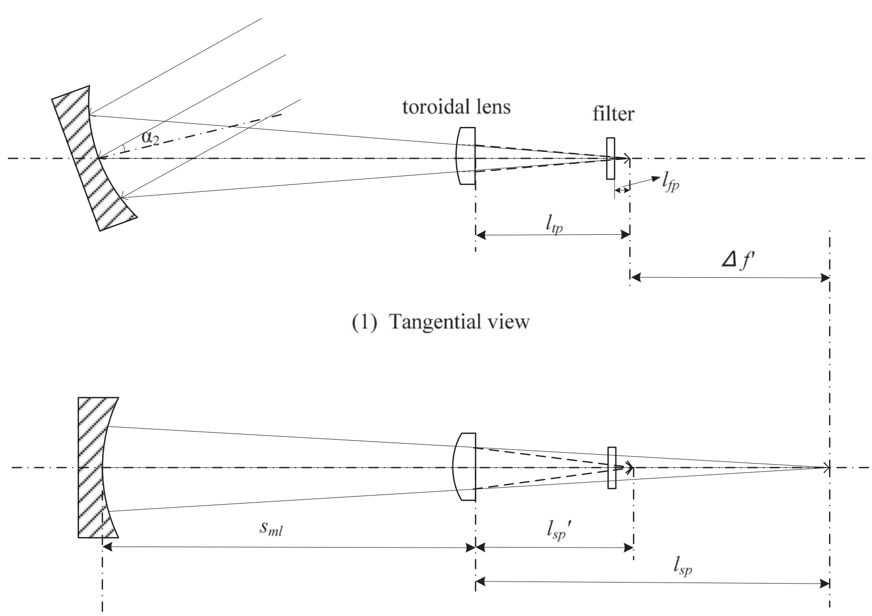

Fig. 1. Astigmatism is corrected by a toroidal lens and filter in (1) tangential view and (2) sagittal view; the high order diffraction lights are cut off by the filter, the toroidal lens and the filter are both located between the second mirror and the detector. The solid rays denote the rays not using a toroidal lens and a filter, and the dashed rays denote the rays using them.