The optical design of solar spectrograph

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ABSTRACT

At the beginning of this paper, we simply describe the theories of spectrograph and the operating principle of grating. Based on the Spectrometer theory and optical theory we design a solar spectrograph by analyzing and calculating. And the working waveband of this solar spectrograph is between 510nm and 540nm. Besides, according to the design data, we ensure the blaze level of grating and the focal length of collimate. Due to the presence of the collimate in the optical structure, astigmatism exists in the system. For this reason, we add a cylindrical lens to the structure to correct. The optical system is characterized by using white-pupil design and folding light path to make the whole system simple. In the end, according to the calculated design parameters, we use the Zemax software for simulation, then the result is RMS only has 4μm at the 520nm. It's worth nothing that the resolution merely near the reference wavelength (520nm)meets the design requirements.

Key words: solar spectrograph; resolution; white-pupil; aberration;zemax

1. INTRODUCTION

The reason of solar atmosphere has broken up is solar magnetic field, for example macula, granule, chromospheric eruption, CME and so on[1][2].As base on the prediction of solar activity, the goal that solar physicists have been relentless pursuit is getting violent solar activity clear picture understanding the outbreak of the mechanism. At present, we have obtained the general physical picture and mechanism of the outbreak of the sun, i.e. the solar material and energy are still during transmission which is from photosphere to chromosphere and then corona and in this transmission the magnetic field energy is released by the magnetic reconnection mechanism. Although getting the process of picture, we lack the accepted evidence of the transmission process and the magnetic reconnection of the physical process. In order to study the fine structure of the basic physical reaction process, usually we need to ensure the thermal parameters, as magnetic field, temperature, pressure, etc. The grating spectrograph can deal with the goal.

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Spectrograph is an important testing instrument by spectroscopy principle to observe, analyze and deal with the material structure and composition[3]. As the spectroscopic methods, the spectrograph can be divided into different type, prism dispersion spetrograph, interference spetrograph, filter spetrograph, grating dispersion spetrograph and calculate tomography spetrograph[4]. Researchers has been wide attention to the grating dispersion spetrograph, it has a simple principle, stable performance, uniform dispersion, hign spectral resolution, small spectral curvature, small color distortion, etc.

G.R.Harrison has made a new kind of diffraction grating in 1949, it is called echelle grating, and the score of echelle grating method of pioneering work[5][6][7]. Echelle grating is a kind of coarse grating, it has a larger blaze angle, and can be used to high orders of diffraction, therefore it can obtain high resolution. Echelle grating is usefully in many fields of spectroscopy, especially, the echelle grating has the characteristics of wide band, high dispersion, high resolution and so on. There is very important applications in astronomy[8].

2. THE THEORIES OF SPECTROGRAPH

The operating principle of grating spectrograph as show in figure 1. There are entrance slit, collimating, dispersion element, focus lens and CCD in it. From the light source through a slit and collimating to the dispersion element on the main direction of dispersion, by focusing mirror after the dispersion of light by the CCD to the detect after the light convergence.

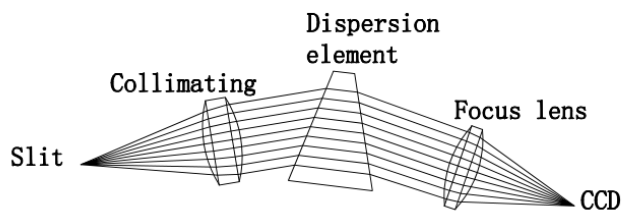

Figure 1. The theories of spectrograph

Dispersion element is the most core components of spectrograph, for the spectrograph, the dispersion element usually using the grating. If there is an angle between grating and the incident parallel light is α, grating diffraction angle is β, grating constant is d, as show in figure 2. So the grating equation is

$$d(\sin\alpha + \sin\beta) = m\lambda \tag{1}$$

m=0,1,2,…, the spectrum orders is m. When α and β in grating normal ipsilateral, β is positive; on the opppsite side, β is negative.

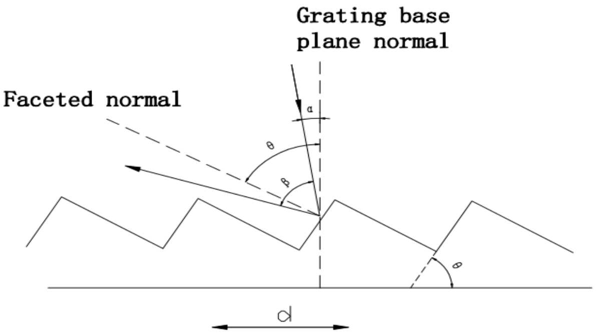

Figure 2. The theories of echelle grating

In order to get large amount of information, high effciency and high resolution spectrum, the solar echelle spectrograph should be used echelle grating, as show in figure 2. When the angle between the incident light and diffraction light is hour, the echelle grating through increased the blaze angle, the grating constant and the spectrum orders to improve resolution.

Angular dispersion:

$$\frac{d\beta}{d\lambda} = \pm \frac{m}{d\cos\beta} \tag{2}$$

Free spectral range:

$$1 \cdot \lambda_1 = 2 \cdot \lambda_2 = 3 \cdot \lambda_3 = \Lambda = m \cdot \lambda_m \tag{3}$$

Signle dispersion angle:

$$\Delta\beta = \Delta\lambda \cdot \left(\frac{d\beta}{d\lambda}\right) = \pm \frac{\lambda}{d\cos\beta} \tag{4}$$

The characteristic of echelle grating:

(1)Every orders can get higher angular dispersion;

(2)When many orders overlap together, separate the orders need the horizontal dispersion, after the separation can be obtained the two-dimensional spectrum. So single-exposured can be obtained wide wavelength range of the spectrum;

(3)signle dispersion angle is small, usually only a few degrees, the wavelengths in the free spectral range will be appeared in the order near the blaze peak. So an echelle grating is effective for all wavelengths, the echelle grating has become efficient blazed grating.

3. THE DESIGN OF THE OPTICAL SYSTEM

The grating spectrograph using the echelle grating, the working wavelength is 510-540nm, the groove density of grating is 31.6lp/mm, the resolution is 110000@520nm.

3.1 Blaze order of grating

In order to the grating obtained the highest efficiency, the grating worked in Littrow condition, so

$\alpha=\beta=\theta$. The design choosed the groove density of grating is 31.6lp/mm, so the grating constant is 1/31.6; the blaze angle of grating is 76 degree; The design requirements of the reference wavelength is 520nm; the wide of entrance slit is 0.08mm. By the formula (1), we can calculation the blaze orders about 118 order.

3.2 Focus length of collimating

Slit is the main factors to influence the resolution in the spectrograph. If the wide of entrance slit is a_1, the wide of entrance slit's image is a_1'. By the geometrical optics

$$a_1 = f_1 \tan\omega_1 \tag{5}$$

$$a_1' = f_1' \tan\omega_1' \tag{6}$$

Where ω_1 is the angle between the incident slit and the optical axis, ω_1' is the angle between the exit slit and the optical axis. Finishing formula (5) and (6) are:

$$a_1' = a_1 \frac{f_1' \tan\omega_1'}{f_1 \tan\omega_1} = a_1 \frac{f_1'}{f_1}\gamma \tag{7}$$

The image of incident slit have produced spectral broadening is:

$$\Delta\lambda_1 = a_1' \times \frac{d\lambda}{dl} = a_1' \times \frac{1}{\frac{d\theta}{d\lambda}\times f_1'} = \gamma \frac{a_1}{f_1}\frac{d\lambda}{d\theta} \tag{8}$$

Where $d\theta/d\lambda$ is the rate of dispersion, the angular dispersion can be considered linear in a small range.

Similarly, the image of exit slit have produced spectral broadening is:

$$\Delta\lambda_2 = a_2' \times \frac{d\lambda}{dl} = a_2' \times \frac{1}{\frac{d\theta}{d\lambda}\times f_2'} = \gamma \frac{a_2}{f_2}\frac{d\lambda}{d\theta} \tag{9}$$

In Littrow condition, the collimating lens and the converging lens are equal in focal length and the angle magnification is 1. When the wide of incident slit is equal to the wide of exit slit, so

$$\Delta\lambda = \Delta\lambda_1 + \Delta\lambda_2 = \frac{2a}{f}\frac{d\lambda}{d\theta} = \frac{2ad\cos\theta}{mf} \tag{10}$$

The resolution of spetrograph is:

$$R = \frac{\lambda}{\Delta\lambda} = \frac{\lambda mf}{2ad\cos\theta} \tag{11}$$

For formula (11) can be known the focal length of the collimating lens is 2250mm.

3.3 Cylindrical lens optimize astigmatism

Developed the structure of spectrograph has astigmatism, which is caused by the inclined spherical mirrors, as the shown in figure 3. The system uses off-axis light. When shaft light enters the system, because the curvature of sagittal and tangential is different and the sagittal image and the tangential image do not coincide , result in astigmatism. At the same time, grating spectroscopy will result in different astigmatism values at different wavelengths, so we need to correct the entire wavelength astigmatic. And the projections of the cylindrical lens on the tangential plane and the sagittal plane are different. And the projection curvature of second surface in the tangential plane is zero, and in the sagittal plane, the value of projection curvature is not zero, so there is a convex spherical surface in the sagittal plane. In the tangential plane ,the cylindrical lens is equivalent to a parallel plate, so the focus will move back; in the sagittal plane, the cylindrical lens is equivalent to a plano - convex lens which has focusing effect, so the focus will move forward[9], as shown in figure 3.

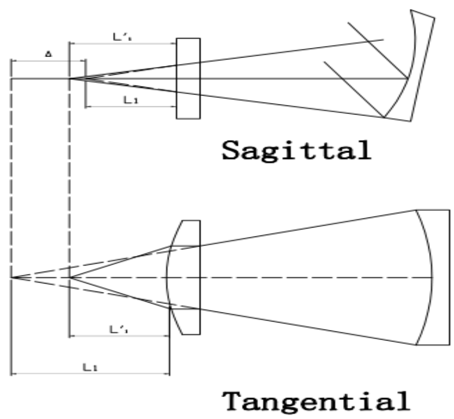

Figure 3. The theories of cylindrical lens optimize astigmatism

3.4 Spectrograph structure design

For spectrograph, the structure is generally a classic and white-pupil design. The white-pupil design developed by the littrow spectrograph, the field mirror is added to the focal plane of the littrow spectrograph. At present, the spectrograph of the large-caliber telescope is used white-pupil design in the world; the spectrograph of KECH telescope is used classic design, the collimating focal length is 4.2m; the spectrograph of the VLT telescope is used white-pupil design,the collimating focal length is 3.05m; the spectrograph of the LAMOST telescope is used white-pupil design,the focal length is 2.6m[10].

For the domestic and foreign astronomical spectrograph design experience, the optical system of the developing grating spectrograph is used white-pupil design. As the spectral overlap occurs in higher order sub-spectra, usually, we will add a filter or prism to increase the lateral dispersion, separate the overlapping spectral levels. But the resolution of the developing spectrograph is 110000@520nm, it is necessary to separate the two wavelengths of $\lambda_1 = 519.997636nm$ and $\lambda_2 = 520.0023636nm$. Obviously, the felter can't reach such a narrow band. When used the prism, in order to achieve the processing accuracy requirements, the costs will greatly increase , so the design does not join the cross-dispersive components. the design of the optical system is shown in figure 4.

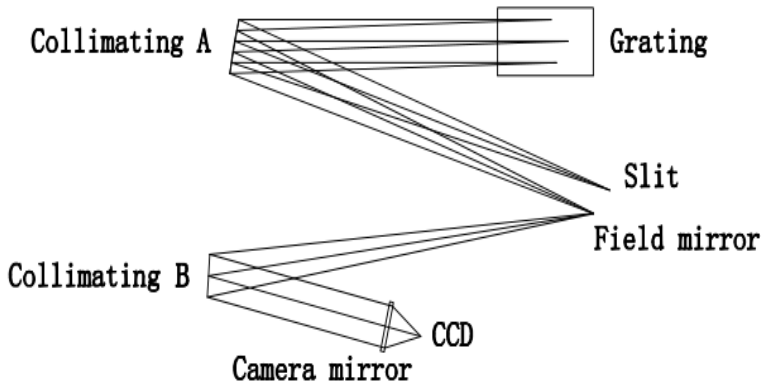

Figure 4. The optical system of spectrograph

3.5 Design results

According to the above analysis and calculation, the solar spectrometer was developed, the optical design parameters are as follows:

Reference wavelength: $\lambda = 520nm$

Grating constant: d=1/31.6mm

Incident angle of grating: α=76°

Focal length of the collimating lens: $f_1 = f_2 = 2250mm$

The above parameters are input to the simulation of zemax, the results shown in figure 5.

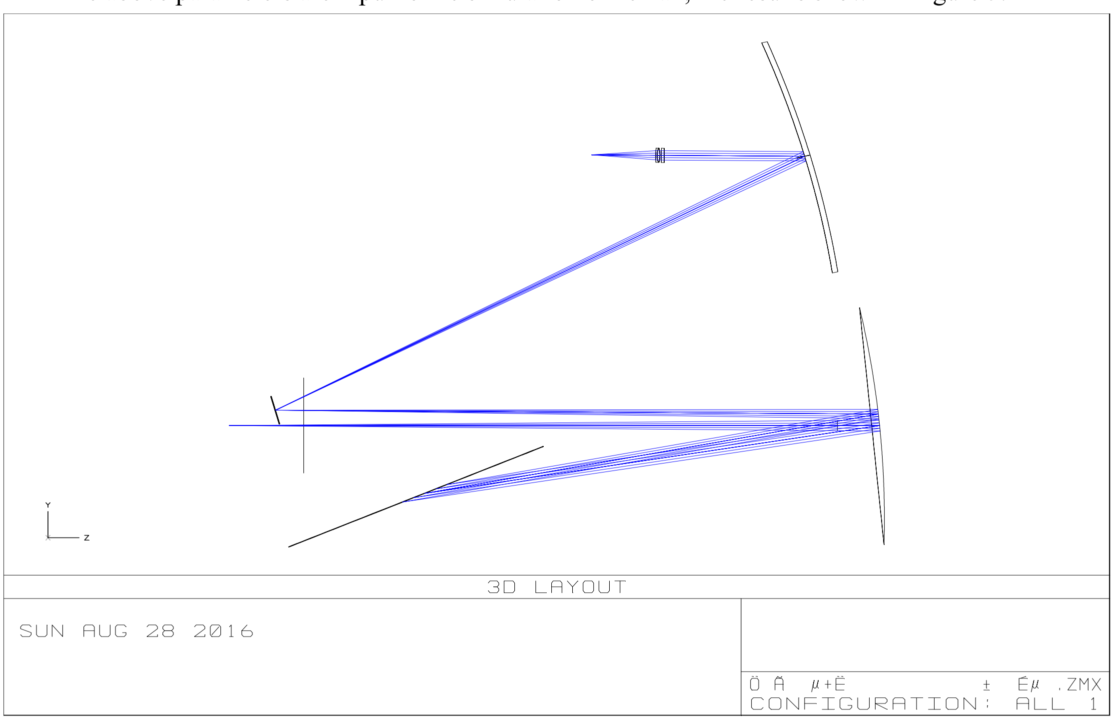

Figure 5. the simulation of zemax

The reference chart of the wavelength $\lambda = 520nm$ is shown in figure 6.

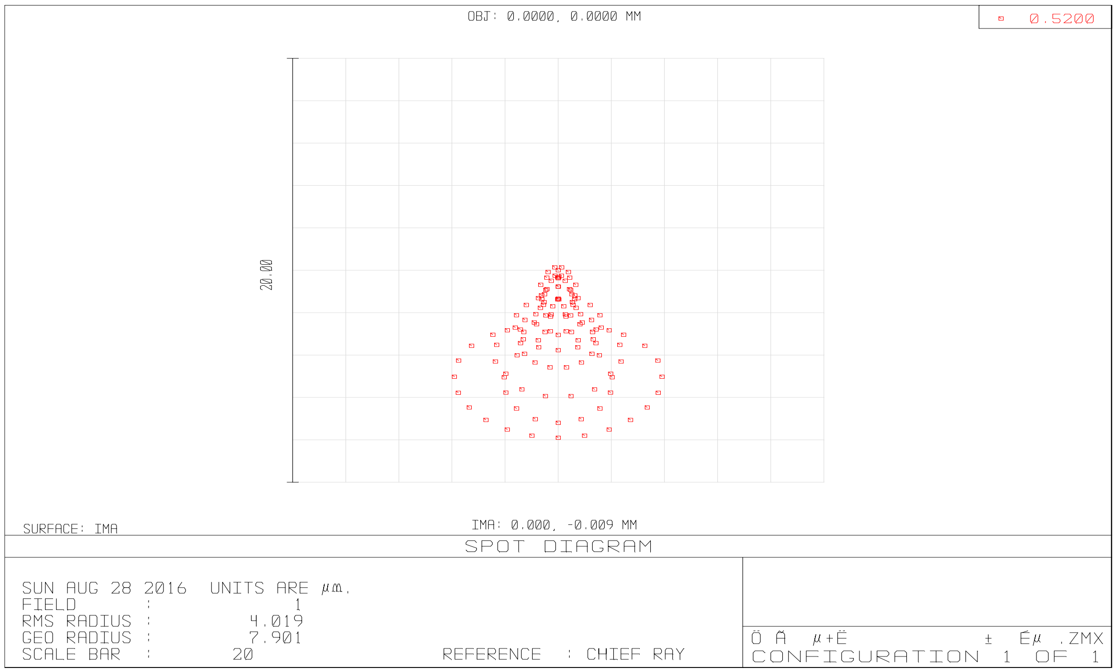

Figure 6. Spot diagrams

As we can be seen from the spot diagrams, the aberration correction at the reference wavelength position is better, with RMS only $4\mu m$. In order to verify whether the resolution of the system to meet the requirements, input the wavelength $\lambda_1 = 519.997636nm$ and $\lambda_2 = 520.0023636nm$, the spot diagrams is shown in figure 7.

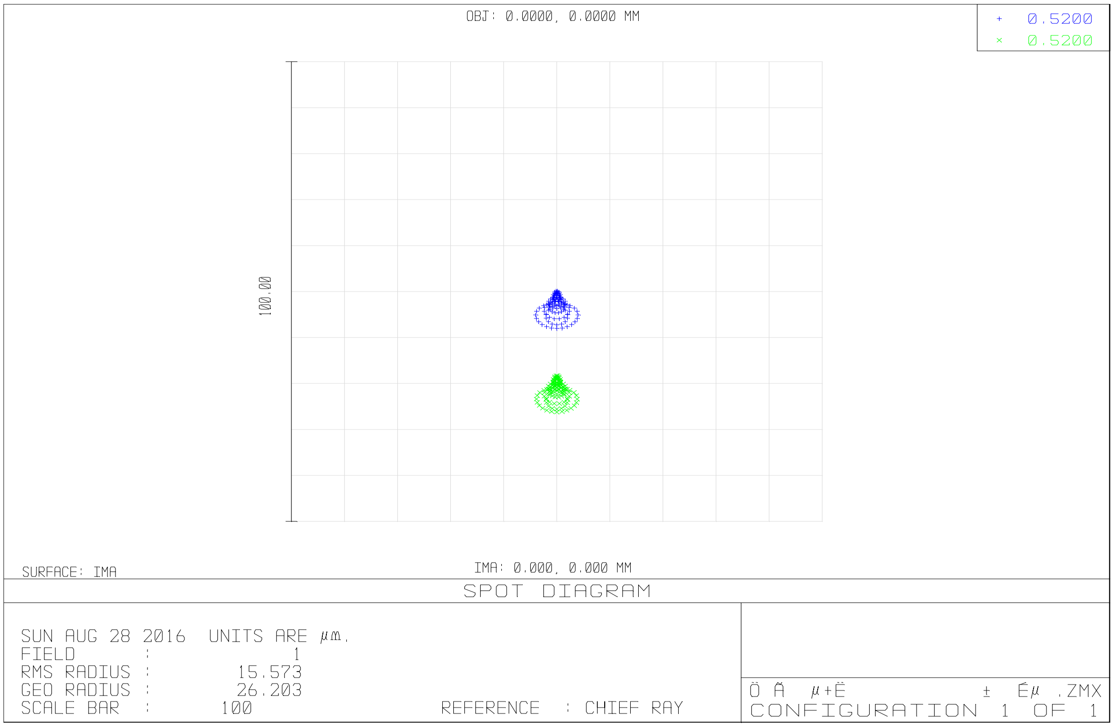

Figure 7. The resolution of spectrograph

As the size of the solar spectrometer is large, so the axis of light is difficult to correct. We needed the deeper level to design the camera separately to meet the design requirement.

4. SUMMARY

Accoarding to the theoretical and analysis to developing the solar grating spectrograph. The optical system used the white-pupil design, reduced the size of the spectrograph; at the same time, we used cylindrical lens optimize astigmatism, improved the image quality. After the zemax software simulation, at the reference wavelength of 520nm, the resolution has meet the design requirements. The whole structure is simple and compact, no mechanical structure, easy to install. However, because of its axis of view field of light is difficult to correct, so the design of the camera still needs further study.

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