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Optical system research of multi-object fiber spectroscopic survey telescope

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Abstract In the first part of this paper, four different Cassegrain optical systems with their correctors are designed and studied for multi-object fiber slit spectroscopic survey. The aperture in 6.5 m and field of view 3° are taken for these optical systems. Assuming observation wavelength range is 0.365–0.95 µm, the maximum zenith distance for observing is 60°, the maximum diameter of these lenses is 1.66 m, the altitude of the telescope site is 2500 m, two correctors are composed of 4-piece lenses and the other two are 5-piece lenses. The results obtained are: f-ratio about 3.7, the image quality for all four systems with EE80D $\leq 0.60''$, the linear diameter of the focal surface is about 1.2 m and 11 000 fibers can be set on it. Considering the limit of size of fused silica and optical glass, the maximum diameter for lens is about 1.7 m. Such a 6.5 m telescope is about the largest one if using the above correctors. Considering the multi-object spectroscopic survey is greatly important, we also studied some telescope optical systems having their aperture near or larger than 10 m used for the multi-object fiber spectroscopic survey. Such ideas are introduced in the last section of this paper.

Key words: telescopes — techniques: miscellaneous — techniques: spectroscopic — methods: miscellaneous — surveys — instrumentation: miscellaneous

1 INTRODUCTION

In 1980's, a hundred of optical fibers for multi-object fiber spectroscopy have been developed. Based on it, Shouguan Wang put forward that must be implemented thousands or even tens of thousands of optical fiber spectrum survey in every observation, we called this idea an extra-large scale spectroscopic survey. In 1994, Shouguan Wang and Ding-qiang Su put forward the basic configuration of the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) with diameter 4 m, field of view(FOV) 5° and the focal surface with linear diameter 1.75 m (Wang, Su & Hu 1994; Wang et al. 1996). A special fiber positioning system put forward by Xiaozheng Xing (Xing et al. 1998) for LAMOST. The 4000 fibers and their fiber positioning unit with 24 mm gap are installed on the focal surface of LAMOST. If the newly developed compact fiber positioning system with fiber unit gap 10 mm is adopted, 23 000 fibers can be installed on the LAMOST focal surface. Led by Xiangqun Cui, the LAMOST was successfully completed in 2008 (Cui et al. 2012), which is mainly dedicated to the research of the Galaxy structure and evolution. Now more than 17 000 thousand spectra were detected and many major achievements were made. The active optics have greatly advanced to get through to completion LAMOST (Su et al. 1986; Lemaitre 2009; Cui et al. 2012). Together with the other two fiber spectroscopic survey telescope as SDSS with diameter 2.5 m, field of view 3° and 640 fibers (Gunn et al. 2006), and 2dF with diameter 3.9 m, field of view 2° and 400 fibers (Lewis et al. 2002), these three telescopes are making momentous contributions on the research of the galaxies, AGN, and cosmology, the Galaxy structure and evolution, stellar physics, discovery of new-type celestial objects and so on. Currently extra-large scale slit spectra survey is becoming an extremely important direction of astronomy.

Today Shouguan Wang's extra-large-scale spectroscopic survey idea has been of great importance and many telescopes with thousands or even tens thousands fibers are under development or planned. WHT Enhanced Area Velocity Explorer (WEAVE) with 2° diameter field (Agócs et al. 2010), Dark Energy Spectroscopic Instrument (DESI) with 3.5° diameter field (Doel et al. 2014), the Subaru Prime Focus Spectrograph (PFS) with 1.3° diameter field (Nariai & Takeshi 1994) and 4-metre Multi-Object Spectroscopic Telescope (4-MOST) with 2.5° diameter field (Azais et al. 2016). All these telescopes are matched with thousands of fibers in which DESI is on commissioning, PFS, WAVE and 4-MOST are under development. Other two large aperture spectroscopic survey telescopes with diameter around 11 m are under plan with thousands and tens of thousands of fibers (McConnachie et al. 2016; Pasquini et al. 2016).

In this paper, a Cassegrain-type telescope with diameter 6.5 m was taken as an example, and four types of optical systems with different correctors were researched and designed for multi-object fiber spectroscopic survey purpose. All these four optical systems are with the same primary f-ratio 1.25 and diameter of field of view 3°, so their etendue equals 234 $\mathrm{m^2deg^2}$, which is defined as the product of the effective aperture area and the solid angle of FOV of telescope. Both the primary and secondary mirror are rotationally conic surface. Assuming the altitude of the astronomical site is 2500 m, the observation wavelength range is from 0.365 to 0.95 μm and the maximum zenith distance is 60°, then the atmospheric dispersion is about 2.6″. For multi-object fiber spectroscopic observation, light in all wavelength band should be within the fiber. Considering a good seeing condition on the assumed astronomical site, the fiber diameter is supposed to be 1.4″. Thus, the atmospheric dispersion needs to be compensated. That means the correctors should be used for both aberration correction and atmospheric dispersion compensation. The designed image quality for all four systems EE80D (the diameter of 80% encircled geometric light energy) is less than or equal to 0.60″.

Epps (Epps, Ange & Anderson 1984) proposed to insert a pair of zero-deviation prisms in the image field corrector of the telescope, and let the prisms relatively counter-rotate around the optical axis to compensate the atmospheric dispersion according to different zenith distance. If two single prisms are put in collimated light path, no extra coma generates.

The following three atmospheric dispersion compensator units (abbreviated as ADC) were adopted in our research and design.

(1) Lensm (lens-prism) type ADC. It is proposed by Ding-qiang Su (Su 1986; Su & Liang 1986; Liang & Su 1988; Wang & Su 1990). The ADC includes two cemented lenses. Each cemented lens is made of two kinds of glasses, of which the indexes of refraction are close and the dispersion are different. The cementing surface is tilted. Su calls such a cemented lens a "lensm" (lens-prism). Two lensms relatively counter rotate around the optical axis to compensate the atmospheric dispersion at different zenith distance. With AAT-2dF (Jones 1994), WHT (Agócs et al. 2010), and 4-MOST (Azais et al. 2016), these telescopes all adopted lensms type ADC.

(2) A pair of wedged single lenses as ADC. It is proposed by Ming Liang and is used in DESI (Doel et al. 2014). The two wedged single lenses relatively counter-rotating around the optical axis compensate the atmospheric dispersion at different zenith distances.

(3) Lateral shift type ADC. This type ADC is developed in the primary corrector for the Subaru telescope (Nariai & Takeshi 1994). In the Subaru telescope, this ADC is composed of two lenses, laterally shifted them perpendicularly to the optical axis to correct atmospheric dispersion.

We think: a perfect optical system should be without the lateral chromatic aberration, because the lateral chromatic aberration of any part has the same amount and opposite direction with the other lenses of this system. If moving this part laterally, one can find that the same size and same direction (parallel with the connecting line between two centers of these two parts) spectra can be obtained in whole field of view. Such spectra can be used to correct the atmospheric dispersion.

Furthermore, one or more single lenses can be served as lateral shift ADC or only rotating corrector to correct atmospheric dispersion, which are very good idea proposed by Saunders (Saunders et al. 2014; McConnachie et al. 2016).

Considering that the multi-object spectroscopic survey is very important, we still need to develop a much larger and powerful spectroscopic survey telescope with aperture of ten meters in order to observe much darker and farther objects. Our proposed configurations, such as the multi-6.5m telescopes on one mounting or scaling the current 6.5 m telescope and adopting fan-shape segmented correctors et al., are introduced in the last section of this paper.

2 DESIGNS OF FOUR OPTICAL SYSTEMS WITH DIFFERENT CORRECTORS

For the telescope optics system design, the correctors should have two functions for both aberration correction over wide field of view and atmospheric dispersion compensation. Under this guideline, four compact optical systems with good image quality and simple structure were obtained. The optical layouts of four optical systems are given in Figure 1, and the properties of four optical

Table 1 The Properties of Four Optical Systems

	Number of lenses	Number of aspheric surface	ADC movement (from ZD 0°–60°)	Secondary mirror tilt (from ZD 0°–60°)	Focal surface tilt (from ZD 0°–60°)	Focal surface type	Image quality (EE80D)	ADC induced distortion changes (from ZD 0°–60°)
System I	4	4	Rotation	None	None	Spherical	0.58″	0.04 mm
System II	5	3	Rotation	0–0.014°	0–0.071°	Aspheric	0.59″	0.2 mm
System III	5	4	Lateral shift (0–50 mm)	0–0.006°	0–0.086°	Aspheric	0.60″	0.5 mm
System IV	4	3	Lateral shift (0–22 mm)	0–0.021°	0–0.110°	Aspheric	0.60″	0.34 mm

ZD is zenith distance.

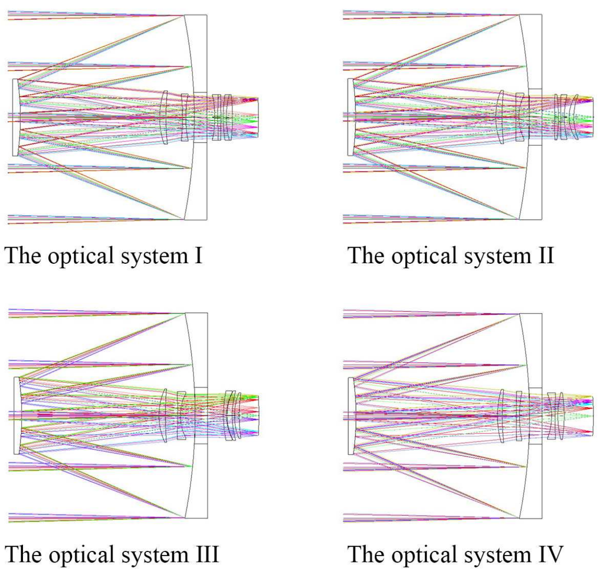

Fig. 1 The layout of four designed optical systems.

systems are listed in Table 1. There are some common features of these four optical systems: the primary mirrors are standard hyperboloid (without high-order terms) with the diameter 6.5-m, the conic constants are close to –1 and the secondary mirrors are hyperboloid with the diameters of 2.4-m. The system f-ratio is about 3.7. Most of the optical surfaces of the correctors are spherical surfaces plus aspheric surfaces, which is an important factor for good image quality for large field of view. The ZEMAX software is used in this article.

Considering a compact configuration and enough space for fiber positioners, the distances between the primary and focal plane are set to about 2.0 m, and the focal plane is set at 600–950 mm behind the last piece of corrector. In order to reduce the risk and cost of the correctors, the largest effective aperture of elements is limited to 1.66-m and the slope of aspheric lenses is constrained to less than or equal to 0.03. Some ADC will produce coma, but in a Cassegrain system if the secondary mirror has a tilt or decenter that will also produce coma (for example Su 1989; Wilson 1999), which can be used to compensate the ADC's coma. For some ADC if the focal surface is tilted the image quality will be increased. During these correctors design, both these two methods are used. Considering the baffles, the linear obscuration of all the four system is about 50%. There is not vignetting in the four optical systems except the effects of baffles. In this section, we describe the designs of all four systems. For brevity, we just present the image spot diagrams of two recommended systems in Section 2.1 and Section 2.4.

2.1 Optical System I

The corrector layout for optical system I is shown in Figure 2. The clear aperture of first lens is 1.65 m and others are about 1.4m. The lens materials are fused silica for first and secondary lenses, Schott BK7HT and LLF1HT for two lensms which are all available for high transparent and homogeneous blanks. Since each lensm is made of two kinds of glasses, of which the refracting indexes are close, so this corrector works like a coaxial system. The extra coma introduced by this corrector is small, thus there is no need to tilt or decenter the secondary mirror to compensate coma or put the lensms in collimated light path. The focal surface also need not tilt. There are four aspheric surfaces in lenses, with 4th, 6th and 8th order terms adding on the spherical surface. The maximum slope of aspheric lenses is 0.03, and the maximum asphericity of lenses corrector is 5.1 mm. The focal surface is spherical. The maximum incident angle between the principal ray and the normal line of the focal surface is 0.2°, For the diameter of field of view 3°, EE80D is 0.58″. If the diameter of field of view is 2.5°, the image quality EE80D is 0.43″ and EE85D is 0.48″. Figures 3, 4, 5, 6 and 7 show the spot diagrams at 0°, 40°, and 60° zenith distances. The field positions selected for the spot diagrams are presented in Figure 8.

2.2 Optical System II

The corrector layout for optical system II is shown in Figure 9. The ADC is composed of two wedged single lenses, nested within the second and third lens of the corrector. The clear aperture of the first lens is 1.65 m and the others are about 1.4 m. The material for ADC is Schott LLF1HT, and fused silica for other lenses. In order to correct atmospheric dispersion, ADC need to counter-

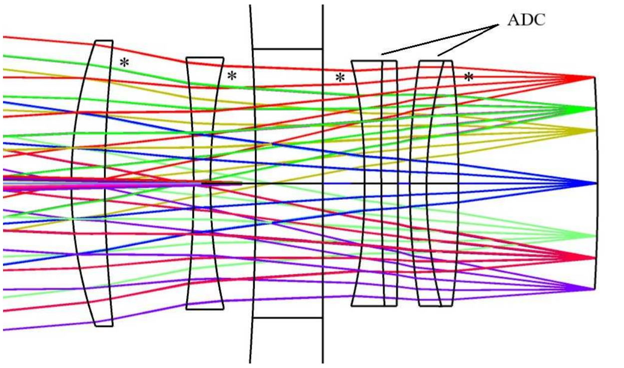

Fig. 2 The layout of corrector obtained for optical system I design. $*$ indicates the aspheric surface.

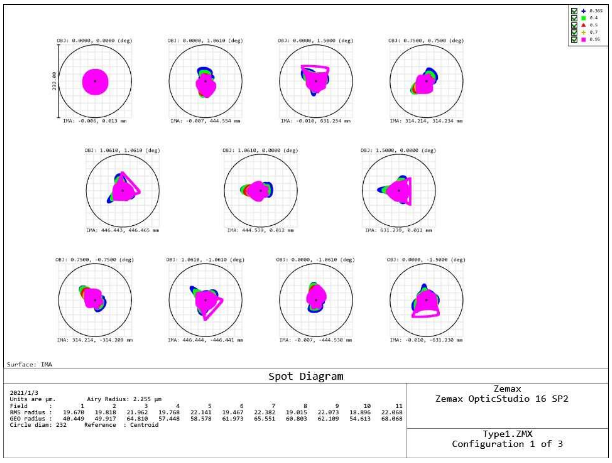

Fig. 3 The spot diagrams of optical system I at 0° zenith distance. The circle diameters correspond to 232 μm (2 arcsecond).

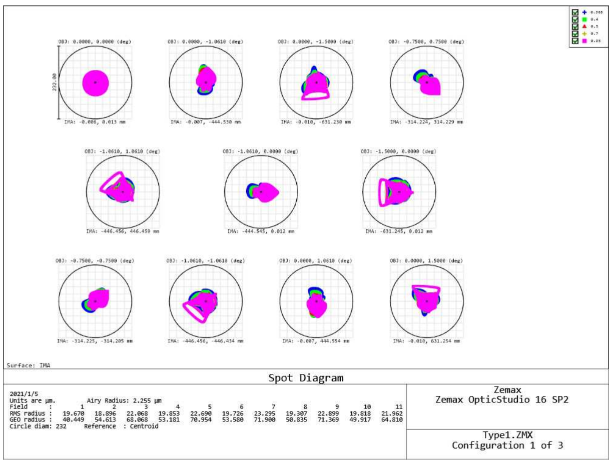

Fig. 4 The spot diagrams of optical system I at 0° zenith distance with the opposite direction FOV in Fig. 8. The circle diameters correspond to 232 μm (2 arcsecond).

rotate around the optical axis for different zenith distances, meanwhile the secondary mirror and the focal surface need to be tilted at the same time. There are three aspheric surfaces in lenses with the 4th, 6th and 8th order terms

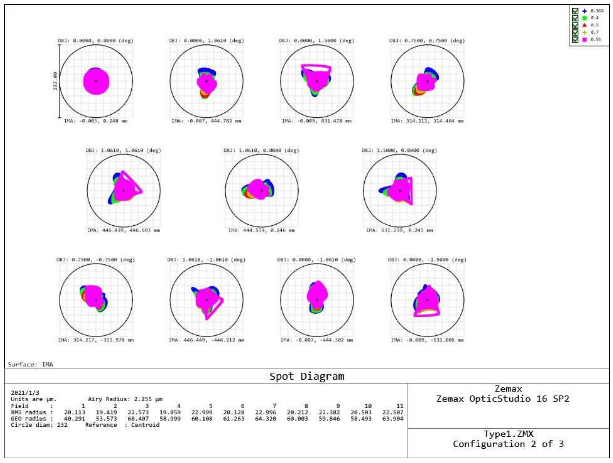

Fig. 5 The spot diagrams of optical system I at 40° zenith distance. The circle diameters correspond to 232 μm (2 arcsecond).

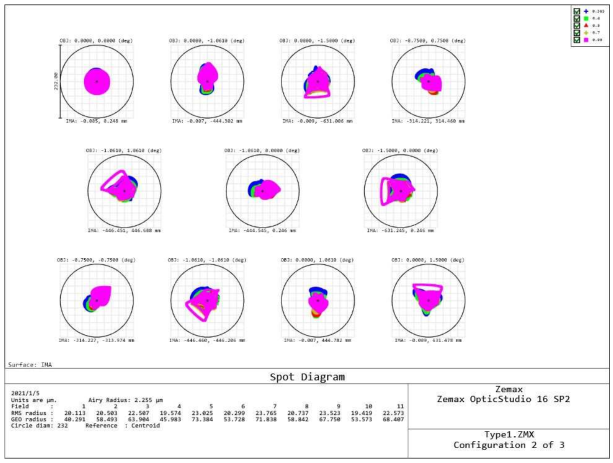

Fig. 6 The spot diagrams of optical system I at 40° zenith distance with the opposite direction FOV in Fig. 8. The circle diameters correspond to 232 μm (2 arcsecond).

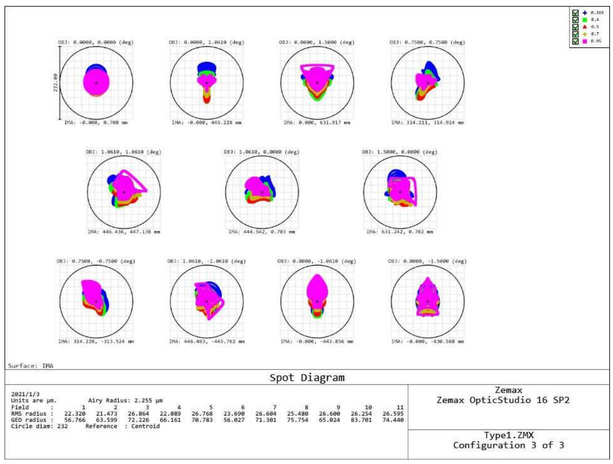

Fig. 7 The spot diagrams of optical system I at 60° zenith distance. The circle diameters correspond to 232 μm (2 arcsecond).

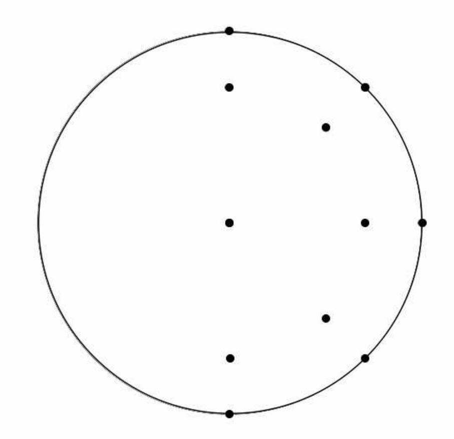

Fig. 8 Field positions selected for the spot diagrams. The diameter of the circle represents FOV 3°.

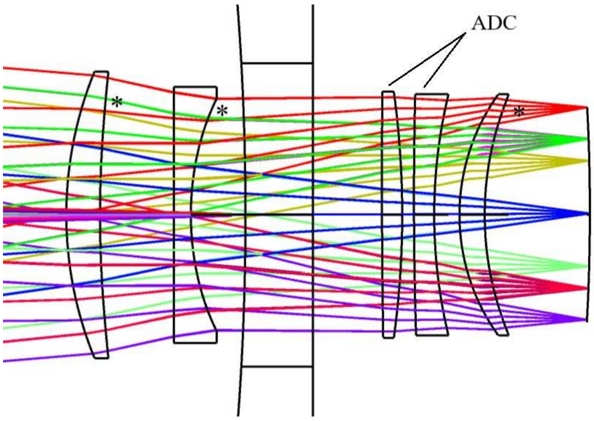

Fig. 9 The layout of corrector obtained for optical system II design. ∗ indicates the aspheric surface.

adding on the spherical surface. The maximum slope of aspheric lenses is 0.03, and the maximum asphericity of lenses corrector is 2.3 mm. The focal surface is a high-order aspheric surface up to the 8th term, and the maximum asphericity is 0.32 mm. The shape of focal surface does not change during observation. The maximum incident angle between the principal ray and the normal line of the focal surface is 0.3°. For the diameter of field of view 3°, EE80D is $0.59''$.

2.3 Optical System III

The corrector layout for optical system III, composed of five single lenses, is shown in Figure 10. The third and fourth lenses serve as ADC which need lateral shift perpendicular to the optical axis to correct atmospheric dispersion for different zenith distances, at the same time, the secondary mirror and focal surface need to be tilted. The distance between two elements of ADC is 10 mm, thus they can be set at one supporting cell. The clear aperture of first lens is 1.65 m and the others are also

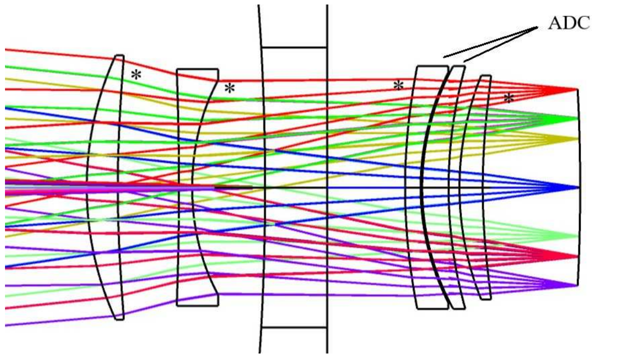

Fig. 10 The layout of corrector obtained for optical system III design. ∗ indicates the aspheric surface.

about 1.4 m. The materials for ADC lenses are Schott LLF1HT and BK7HT, fused silica for other lenses. There are four aspheric surfaces in lenses, with the 4th, 6th and 8th order terms adding on the spherical surface, and the maximum slope of aspheric lenses is 0.03, and the maximum asphericity of lenses corrector is 2.4 mm. The focal surface is a high-order aspheric surface up to the 8th term, and the maximum asphericity is 0.09 mm. The shape of focal surface does not change during observation. The maximum incident angle between the principal ray and the normal line of the focal surface is 0.45°. For the diameter of field of view 3°, EE80D is $0.60''$.

2.4 Optical System IV

The corrector layout for optical system IV, composed of four single lenses, is shown in Figure 11. In this design, the fourth lens serves as ADC which need lateral shift perpendicular to the optical axis to correct atmospheric dispersion for different zenith distance, at the same time, the secondary mirror and focal surface need to be tilted. The clear aperture of the first lens is 1.66 m and the others are also about 1.4 m. All lenses are made from fused silica. There are three aspheric surfaces in lenses with the 4th, 6th and 8th order terms added on the spherical surface. The maximum slope of aspheric lenses is 0.019, and the maximum asphericity of lenses corrector is 1.8 mm. The focal surface is a high-order aspheric surface up to the 8th term, and the maximum asphericity is 0.12 mm. The shape of focal surface does not change during observation. The maximum incident angle between the principal ray and the normal line of the focal surface is 0.3° . For the diameter of field of view 3°, EE80D is $0.60''$. If the diameter of field of view is 2.5°, the image quality EE80D is $0.41''$ and EE85D is $0.44''$. By setting both the Lens-3 and Lens-4 as lateral shift units, the image quality can also be slightly improved. The spot diagrams at 0°, 40°, and 60° zenith distances are shown in Figure 12, Figure 13, and Figure 14. The field positions selected for the spot diagrams are presented in Figure 8.

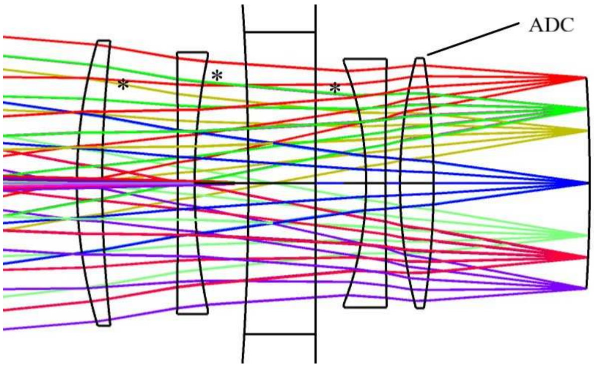

Fig. 11 The layout of corrector obtained for optical system IV design. ∗ indicates the aspheric surface.

3 DISCUSSIONS

(1) In this article most of the optical surfaces of the correctors are spherical surfaces plus aspheric surfaces with the 4th, 6th and 8th order terms. This is an important factor for obtaining excellent image quality.

(2) If the primary mirror f-ratio is set to be any value from 1.2–1.3, all results obtained are about the same as in this paper.

(3) An innovative parallel controllable optical fiber positioning system was put forward by Xing in 1994 for LAMOST (Xing et al. 1998). The focal surface is divided into several thousands or tens of thousands areas, each has two driving motors to move an optical fiber to the required position. There are two important advantages for this optical fiber positioning system: one is all fibers can aim at all observing celestial objects at the same time, another is during observation time the optical fibers can be moved if necessary. Such an optical fiber positioning system has been used or considered in DESI, Subaru and SDSS.

(4) During observing time, the relative positions of celestial objects are changeable, which are caused by differential atmospheric refraction and the distort of corrector, especially differential atmospheric refraction, and both these two factors are decided by the changeable amount of zenith distance during observation time and what zenith distance is observed. The relative positions of celestial objects can be calculated and can be corrected by using the above optical fiber positioning system to move the optical fiber. An optical fiber 0.2 arcsecond positional accuracy is necessary, so the optical fiber positioning system must have this high accuracy.

(5) When celestial bodies pass through the meridian the change of zenith distance is least, the observation should be done in this situation if possible. LAMOST does so.

(6) In Table 1 both values of the secondary mirror tilt and focal surface tilt are from zenith distance 0°–60°. In general, during observation the changeable amount of

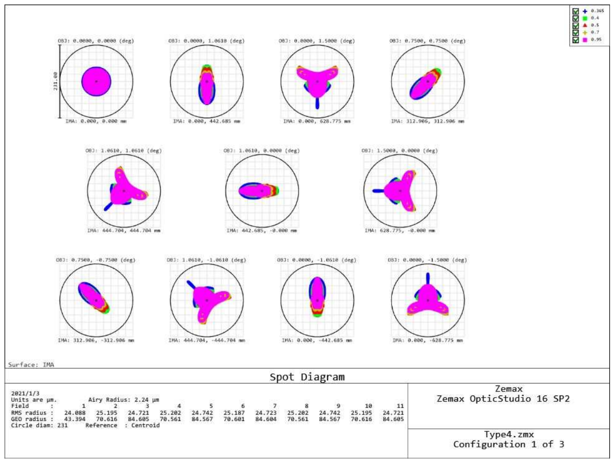

Fig. 12 The spot diagrams of optical system IV at 0° zenith distance. The circle diameters correspond to 231 µm (2 arcsecond).

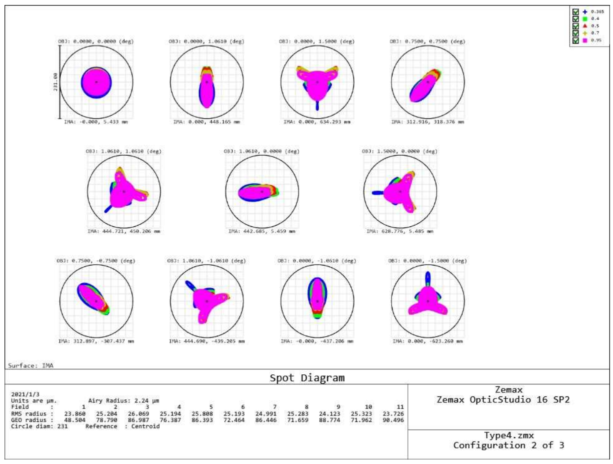

Fig. 13 The spot diagrams of optical system IV at 40° zenith distance. The circle diameters correspond to 231 µm (2 arcsecond).

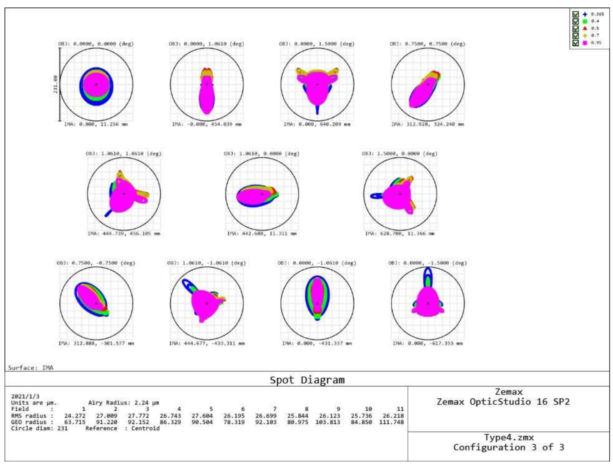

Fig. 14 The spot diagrams of optical system IV at 60° zenith distance. The circle diameters correspond to 231 µm (2 arcsecond).

zenith distance is not large, and during this time the zenith distance value is also small, the secondary mirror, focal surface, and the ADC can be put to their average positions and do not be moved during observation if the decline of image quality is acceptable.

(7) Currently the largest diameter of the lens is 1.7 m since the material (fused silica and other optical glass) is available in about 1.8 m. The largest corrector diameter in this paper is 1.66 m which is near the limit of the available materials, so the 6.5 m telescope is almost the largest survey telescope with this kind of corrector. That is one of the important reasons for the 6.5 m telescope.

(8) Normally the largest diameter of the lens correctors is about 1.3–1.5 times that of the focal surface. Since the largest diameter of the lens currently existing is about 1.7 m, the largest diameter of focal surface is limited to about 1.4 m for this type telescope.

(9) The etendue defined as telescope aperture area multiplied by solid angle area of the observation sky area is not comprehensive for the slit fiber spectroscopic survey telescope. Suppose the normal etendue is same for two telescopes with different focal surface area, since the accommodated fibers is proportionate to the focal surface area, it is more reasonable to compare the two telescopes with both etendue and the focal surface area.

4 TWO BEST SYSTEMS AMONG ABOVE FOUR SYSTEMS

Based on the above results, we would like to recommend two systems for application. In the corrector of the optical system I, there are eight surfaces in air (same as four single-lens corrector), and the surface reflection loss and ghost are also similar like those of the four single-lens corrector. But there are six lenses needed to be manufactured including two lensms with two glue surfaces, which is the shortcoming of this corrector. The technical problem of gluing was solved in 1970s for the UK Schmidt Telescope (Newell 2002). The lensm type ADC also adopted by 4-MOST with successful gluing (Jonasa et al. 2020). So, the lensm gluing for 6.5 m telescope should be feasible. The cost may be similar to that of the four-single lens corrector since there is no secondary mirror and focal surface tilting required during observation. That makes the atmospheric dispersion compensation and mechanical structure relatively easier.

In optical system IV, there are four important advantages for the corrector including ADC: (1) The total number is only four single lenses. (2) The shift lens is the last one in this corrector; it is easier for installing and movement. (3) Lateral displacement is only 22 mm. (4) All lens materials are fused silica which is easier for blank purchase and important for high transmittance. There are 3-aspheric surfaces and the slopes of all aspheric surfaces < 0.02, which is not difficult for the fabrication. The main shortcomings of system IV is that the secondary mirror and focal surface should be tilted during observation, and the angles of tilting are not tiny.

5 TOWARDS THE FIBER SLIT SPECTROSCOPIC SURVEY TELESCOPE WITH LARGER APERTURE

It is very important for astronomy to build this 6.5 m telescope. But we still need to go further to develop a much larger and powerful telescope with large field area, in order to observe much more darker and farther objects, and enlarge the observation scope of cosmology and galaxies. In fact, the MSE project (McConnachie et al. 2016) and ESO spectroscopic facility (Pasquini et al. 2016) were already proposed with aperture around 11 m for fiber spectroscopic surveys, so building the 6.5 m telescope also serves as our pilot testing telescope for much larger fiber spectroscopic telescope.

We have considered three configurations for the larger telescope:

(1) In 1972, Aden Meinel put forward the MMT project, which is a novel 4.8 m telescope with six telescopes on a single mounting (Meinel et al. 1972). In 1988, Ding-qiang Su put forward a novel idea of four 1.5 m Schmidt telescopes setting on one mounting to generate a 3 m multi-object fiber spectroscopic survey telescope (Su et al. 1988). In this paper, we applied the similar idea to setting four 6.5 m telescopes on one mounting working as one 13 m aperture telescope with the field of view 3° in diameter. The etendue will be $4 \times 234 = 936\,\mathrm{m}^2\mathrm{deg}^2$. The bottom parts of the 4-tubes are neighboring. When observing the same sky area, the four fibers aiming the same object will be sequenced on the slit. The linear diameter of each fiber is half of that of the 13 m equivalent telescope and the sum of the section area of four fibers is equal to one fiber section area of the 13 m telescope. Thus, the number of spectrographs is same for all 4-tubes configuration and one 13 m telescope. If the slit width is setting to be less than the fiber diameter of the 13 m telescope, the light energy within four fibers from the 6.5 m telescopes will be more than that from the 13 m telescope (working as image slicer), which is the outstanding advantage of the 4-tubes configuration. There will be no technical difficulties to develop this type telescope after building one single 6.5 m telescope and the cost will be also cheaper than the 13 m telescope. Since the 4-tubes 6.5 m telescope aiming to the same sky area (otherwise the light collection power cannot reach that of the 13 m telescope), the combined focal surface area and the corresponding sky area is equivalent to that of one single 6.5 m telescope. If four single 6.5 m telescopes are built, the combined focal diameter is also 1.2 m. As

mentioned in the discussion part, the current maximum focal plane diameter is about 1.4 m, so the 1.2 m focal plane of the designed 6.5 m telescope is near the limit. Even further smaller telescopes will deliver smaller focal area and less fibers which will be inappropriate; Our long-term goal is to develop ten meters fiber spectroscopic survey telescope and the 6.5 m sub-telescope is the optimal choice. That is why we firstly need to build such a 6.5 m telescope. We can also set seven 6.5 m telescopes on one mounting to make one 17 m telescope.

(2) Without considering the diffraction effect, enlarging the single 6.5 m telescope will deliver same angular image quality but enlarged linear dimensions with same magnification. Setting the scale factor to be 2 will generate one 13 m telescope, which is the second configuration we proposed. The largest diameter of the double sized correctors will be 3.32 m which is a big challenge. Our approach is: each lens is composed by four fan-shaped sub-lens which are metal-cross supported. The sub-lens surface can also be roughly ground separately, then fine ground and polished together after side gluing. There is a metal-cross on each sub-lens for the two methods which should be feasible for the 13 m telescope with segmented primary and segmented correctors, though higher shape and position requirements are needed for the four fan-shaped lens. The etendue of the 13 m telescope is 936 $\mathrm{m^2deg^2}$ and the linear diameter of the focal surface is 2.4 m which is one outstanding advantage of the configuration with twice the corresponding size of 6.5 m telescope. Then about 44 000 fibers can be mounted.

(3) Take the same configuration as (2), but a scale factor is set to 1.5. In this case, the largest lens diameter is about 2.49 m and the telescope aperture is 9.75 m with etendue 525 $\mathrm{m^2deg^2}$. The corresponding linear diameter of the focal surface is 1.8 m and 24 750 fibers can be accommodated.

IN MEMORIAM

It so happened that right after this article was submitted, on the night of January 28, 2021, Professor Shouguan Wang passed away, who initiated the extra-large scale spectroscopic survey. Here we would like to honor his memory.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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