The characteristics of compound diffractive telescope

Hua Liu[1], Zhenwu Lu[1*], Jinying Yue[12], Honxin Zhang[1]

[1]State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Changchun 130033, China
[2]Graduate School of the Chinese Academy of Sciences, 100039, China
[*]Corresponding author: luzhenwu55@yahoo.com.cn

Abstract: Compound diffractive telescope is a new type of space optical system. It applies the structure of compound eyes into diffractive telescopes. With the help of diffractive optical element, the optical system could become lighter in weight, lower in cost, and looser in sensitivity to manufacturing tolerance. And with the help of compound eyes structure, the field of view is expanded. A demonstrated system of compound diffractive telescope is given. It is composed of one 50mm aperture primary diffractive lens and twenty-one eyepieces. The characteristics of the system are analysed by testing its star image and resolution. It is shown that the whole system can provide about diffraction limit imaging within 4.2 degree field of view.

OCIS codes: (220.3620) Lens system design; (050.1965) Diffractive lenses.

References and links

1. A. Eamonn, "A new membrane mirror for infrared telescopes" SPIE **5489**, 1173-1177 (2004).
2. W. W. John and S. A. Gregory, "Optical Metrology Of Adaptive Membrane Mirrors" SPIE **4327**, 13-23 (2001).
3. C. Surya, D. M. James, G. P. Brian, D. Brett, and K. M. Dan, "Design, fabrication, and validation of an ultra-lightweight membrane mirror" SPIE.**5894**, 1-12 (2005).
4. M. B. Lan, A. B. Jerald, and N. D. Shanasundar, "Fabrication of Large-Aperture Lightweight Diffractive Lenses For Use in Space " Appl. Opt. **40**, 447-451 (2001).
5. A. Hyde, "Eyeglass. 1. Very large aperture diffractive telescopes" Appl. Opt. **38** , 4198-4212 (1999).
6. G. A. Horridge, "The compound eye of insects" Scientific American **237**, 108-120 (1977).
7. G. A. Horridge, "Apposition eyes of large diurnal insects as organs adapted to seeing" Proceedings of the Royal Society of London B **207**, 287-309 (1980).
8. F. Land, "Compound eyes: old and new optical mechanisms" Nature **287**, 681-686 (1980).
9. L. Zhenwu, Z. Nan, L. Hua, L. Fengyou, and S. Qiang, "Compound telescope," SPIE **6289** 1-5 (2007).

1. Introduction

Recent advances in small satellites have brought higher requirements for space optical system. For example, low launching cost limits the weight of optical system to be lighter; high ground resolution limits the image quality of optical system to be better; atrocious working environment limits the performance of optical system to be stabler. Conventional optical systems are difficult to meet these demands. To deal with the mass and launchability problems, two methods are developed. The first one is to use membrane mirrors as the primary optics to form reflective telescope [1-3]. However, it is hard to control their shape to the λ /20 scale precision to attain λ /10 optical tolerances. The source of this difficulty is that mirrors reflect light, thereby doubling the optical-pathlength errors associated with their surface ripples. The second one is to use diffractive lens as the objective to form transmissive diffractive telescope [3-5]. Its optical tolerances are loosed greatly, because the optical-pathlength errors for the thin transmissive film are avoided, as light first arrives-at and then departs-from surface ripples. However, the primary diffractive lens of this space telescope tends to be very weak, large field of view results in eyepiece too large and too heavy to launch. So this type of telescopes may get only very narrow field of view.

A new type of space telescope optical system—compound diffractive telescope is proposed. It combines the structure of compound eyes with diffractive telescopes. This can widen field of view of space telescope effectively, while maintaining small aperture of eyepiece. A demonstrated system of compound diffractive telescope is given, which is composed of one 50mm aperture primary diffractive lens and twenty-one eyepieces. One eyepiece can provide 0.2 degree field of view, so the whole telescope has 4.2 degree field of view. Although the field of view is consists of twenty one small segments, it is continuous in one direction after data jointing. The characteristics of the system are tested by viewing star image and resolution factor, and the results agree well with the theory ones.

2. Diffractive telescope

Diffractive optics works by applying small, local corrections to a light beam. They are implemented by a series of shallow, closely spaced grooves on the surface of an aperture, so the material holding them can be thin and lightweight. In addition, they are transmissive, the optical-pathlength errors associated with their surface ripples could be cancelled as long as the material holding them has uniform thickness. So the diffractive telescope based on diffractive optics can deal with both the mass-and-launchability and the optical-precision problems. It tends to have two parts as shown in Fig. 1. One is the primary diffractive lens to gather light, and the other is eyepiece to correct aberration.

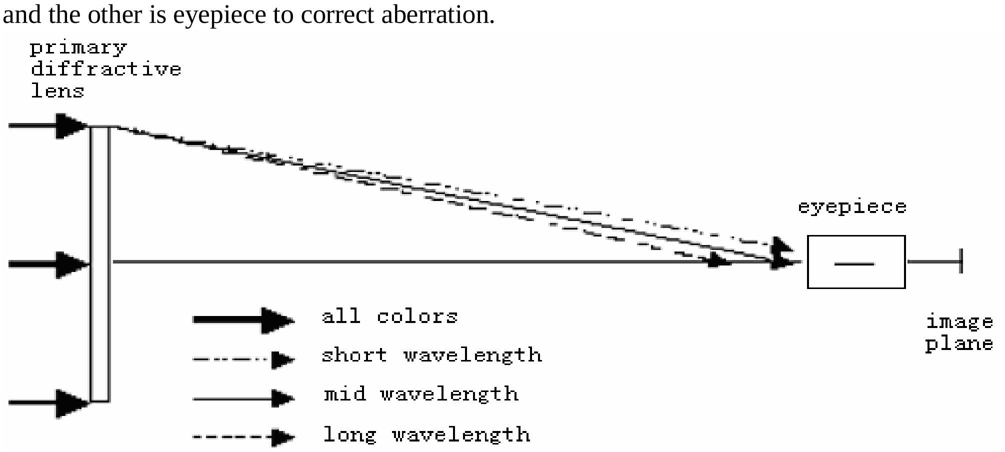


Fig. 1. The structure of single-eye diffractive telescope.

The big drawback to use a diffractive optics as objective is its chromatic dispersion. Its focal length varies inversely with wavelength:

$$f(\lambda) = f_0 \frac{\lambda}{\lambda_0} \tag{1}$$

Where λ_0 is the main wavelength, f_0 is the focal length at λ_0, f is the focal length at λ. So it only accurately focuses light within a narrow spectral bandwidth. In order to achieve broadband application, another structure such as eyepiece must be added to correct chromatic aberration. In order to correct chromatic aberration better, a hybrid refractive/ diffractive lens is designed to substitute the diffractive lens. Although this will tighten the optical tolerance, compared with diffractive lens, this may lighten and minish the eyepiece effectively. As long as one selects proper power shared by the refractive lens and the diffractive elements, both the

#98579 - $15.00 USD Received 10 Jul 2008; revised 14 Aug 2008; accepted 13 Sep 2008; published 26 Sep 2008

optical tolerance and the weight of the eyepiece can be controlled well. A diffractive telescope includes the structure of hybrid primary diffractive lens and eyepiece as shown in Fig. 1. In this system, the parameters of the hybrid primary lens are as follows: aperture is 50 mm, f-number is 49, and total length (the distance between it and the eyepiece) is 2.416 m. While the parameters of eyepiece are as follows: aperture is 8mm, and total length is 43 mm. The eyepiece is composed of a doublet lens and two single elements. The spectrum of this system covers from 0.5 um to 0.7 um, while the full field of view is only 0.2°. The optical tolerances of the diffractive telescope are very loose as shown in table 1, on the condition that the value of MTF at 50 lp/mm falls to 0.5 with focus compensation.

Table 1 Tolerance of diffractive telescope

Distance between primary lens and eyepiece	±40 mm
X decenter of primary lens	±4 mm
Y decenter of primary lens	±4 mm
X tilt of primary lens	±2°
Y tilt of primary lens	±2°

3. Compound diffractive telescope

When the diffractive telescope is of narrow field of view, the aperture of eyepiece can be decided by two parameters: the focal length of the hybrid primary lens and the broadband application. It is not large even with large aperture and weak hybrid primary lens. When the diffractive telescope is of wide field of view, however, the aperture of eyepiece is then decided by the focal length of the hybrid primary lens and the field of view. This may lead to eyepiece too large and heavy to launch with large aperture and weak hybrid primary lens. From the optical tolerances of the diffractive telescope, we know that the image quality of the diffractive telescope is good enough, even when the hybrid primary lens is tilted 2 degree from the eyepiece. This gives us a good way to widen field of view. In order to solve the conflict between lightweight and wide field of view, we integrated many eyepieces with one primary lens to form a new type of space telescope—compound diffractive telescope. As we know, compound eye has two models: apposition compound eye and superposition compound eye [6-9]. The former, the rhabdoms receive light only from their own corneal facets, in other words, each rhabdom will receive light from one facet, that is to say the ommatidia are optically isolated; the latter, each rhabdom will receive light from many facets, that is to say the ommatidia are not optically isolated. So the compound diffractive telescope could also be designed in the same way. According to the characteristic of diffractive telescope, we design and set up a compound diffractive telescope as shown in Fig. 2.

#98579 - $15.00 USD Received 10 Jul 2008; revised 14 Aug 2008; accepted 13 Sep 2008; published 26 Sep 2008

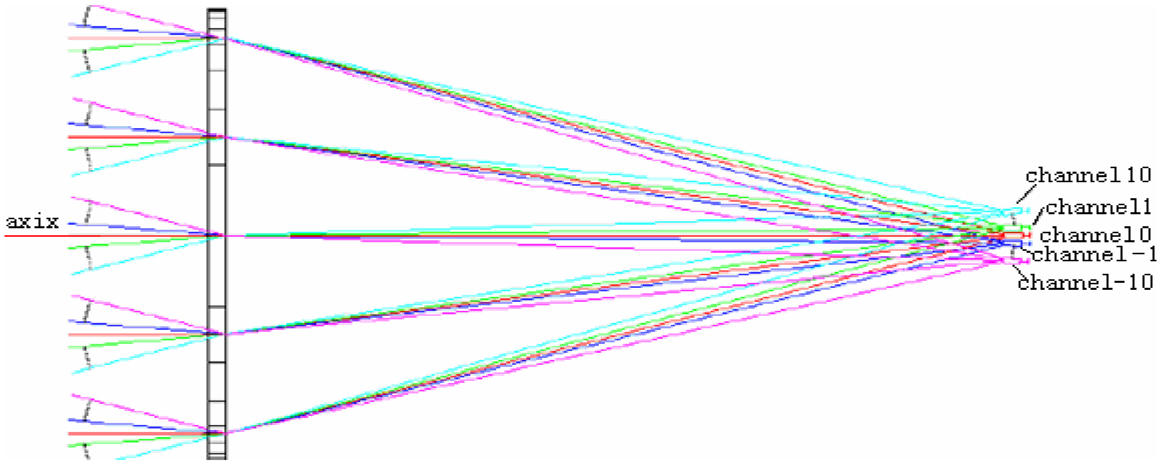


Fig. 2. Compound diffractive telescope of the later model structure.

The hybrid primary diffractive lens is shared, and array structure of the eyepieces is used to form many channels. Channel 0 is for central field of view and cover a small field of view about 0.2 degree with one eyepiece; channel 1 is obtained by axial rotating the eyepiece of channel 0 with 0.2 degree, and accordingly, channel 10 is obtained by axial rotating the eyepiece of channel 0 with 2 degree. Channel -1 is obtained by axial rotating the eyepiece of channel 0 with -0.2 degree. Accordingly, channel -10 is obtained by axial rotating the eyepiece of channel 0 with -2 degree. The entire compound diffractive telescope can attain the field of view 4 .2 degree with 21 eyepieces. This kind of structure can simplify the system greatly to reduce the weight. In fact, its field of view is limited by the tilt tolerance of the objective. When it goes beyond the tilt tolerance of the objective, the image quality of the system will not meet the requirement of use. Table 1 indicated that it should be within ±2°. Although the field of view consists of twenty one small segments, it is continuous in one direction after data jointing. The space structure of the adjacent eyepieces can be viewed well in Fig. 3. It is indicated there is enough space for fixing eyepieces even with mechanism. The modulation transfer function (MTF) curves of channel 0 and channel 10 in theory are shown in Fig. 4. The two-dimension schemes of point spread function of channel 0 and channel 10 in theory are shown in Fig. 5. It is clear that the image quality even of the marginal channel is good enough.

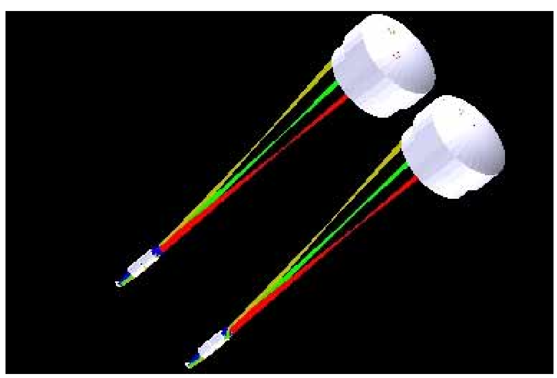
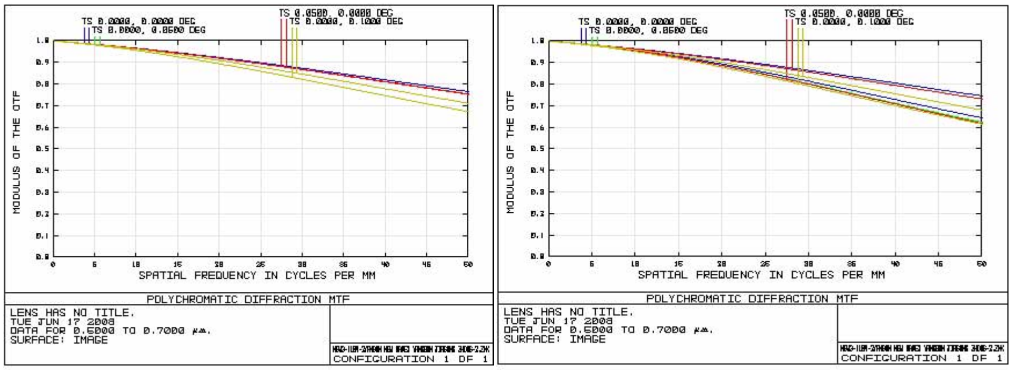


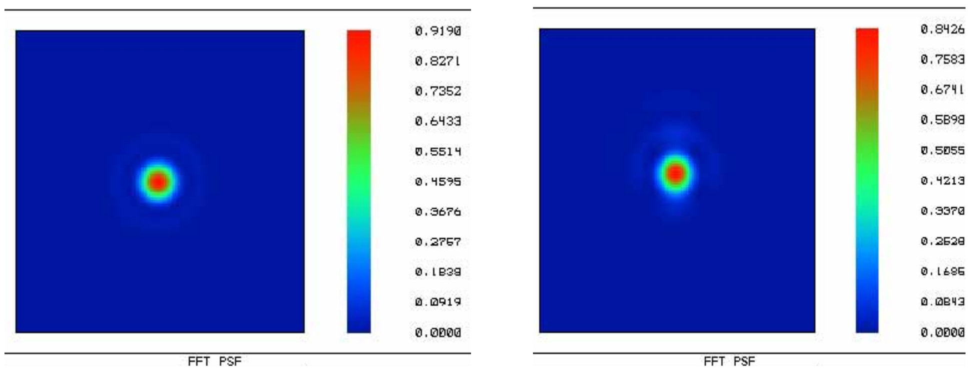
Fig. 3. Space structure of the adjacent eyepieces.

#98579 - $15.00 USD Received 10 Jul 2008; revised 14 Aug 2008; accepted 13 Sep 2008; published 26 Sep 2008



(a) (b)

Fig. 4. (a) MTF plot of channel 0 (b) MTF plot of channel 10.



(a) (b)

Fig. 5. (a) Point spread function of channel 0 (b) Point spread function of channel 10.

4. Test results

We have fabricated a hybrid primary lens and four eyepieces. With these components we have set up a demonstration system of compound diffractive telescope. In this system, eyepieces are put in channel 0, 1, 9 and 10, respectively. Though this demonstration system does not include all 21 eyepieces, it is enough to view the characteristics of the compound diffractive telescope. The image of its central and marginal field of view can be obtained with channel 0 and channel 10.

The star image of the system is tested by using the set-up as shown in Fig. 6. One He-Ne laser with 632.8nm wavelength is put in front of a microobjective. A pinhole with 10um diameter is just put at the focus plane of the microobjective. So a point source is formed by this way. By adjusting the collimator to make the point source to be at its front focus plane, a uniform plane wave is obtained. The uniform plane wave illuminates the hybrid primary lens, and focuses to the eyepiece. A star image is formed at the image plane of the telescope. By using the microscope and CCD receiver, a magnified star image is obtained. The uniform plane wave illuminates the hybrid primary lens with 0 degree, 0.2 degree and 2 degree for channel 0, 1, and 10. The star images of channel 0 and channel 10 are shown in Fig. 7. They agree well with the theory results as shown in Fig. 5.

#98579 - $15.00 USD Received 10 Jul 2008; revised 14 Aug 2008; accepted 13 Sep 2008; published 26 Sep 2008

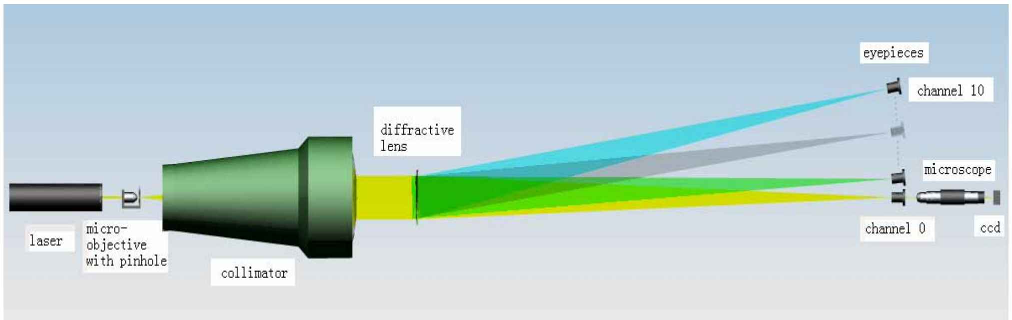


Fig. 6 Layout for testing star image.

(a) (b)

Fig. 7. (a) Star images of channel 0 (b) Star images channel 10.

The resolution of the system is tested by using the set-up as shown in Fig. 8. A white light source with wave filter is put in front of a resolution power test target. And the resolution power test target is placed at the front focus plane of a collimator. Then the light from the collimator illuminates the hybrid primary lens, and focuses to the eyepiece. By using the microscope and CCD receiver, a magnified image of the resolution power test target is obtained. In this experiment, one part of the resolution power test target can be viewed by one channel. For channel 0, the central part can be viewed. For channel 10, the marginal part can be viewed. In order to compare easily, here we use the same part with 200pl/mm space frequency as the target of channel 0 and channel 10. The results of channel 0 and channel 10 are shown in Fig. 9. Here due to some astigmatism, the horizontal image quality is not as good as the vertical one.

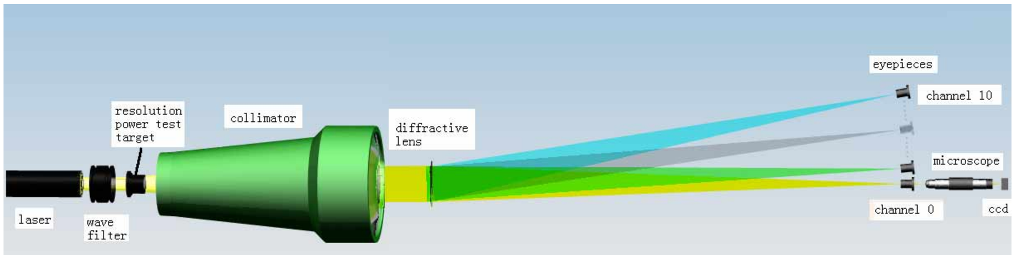
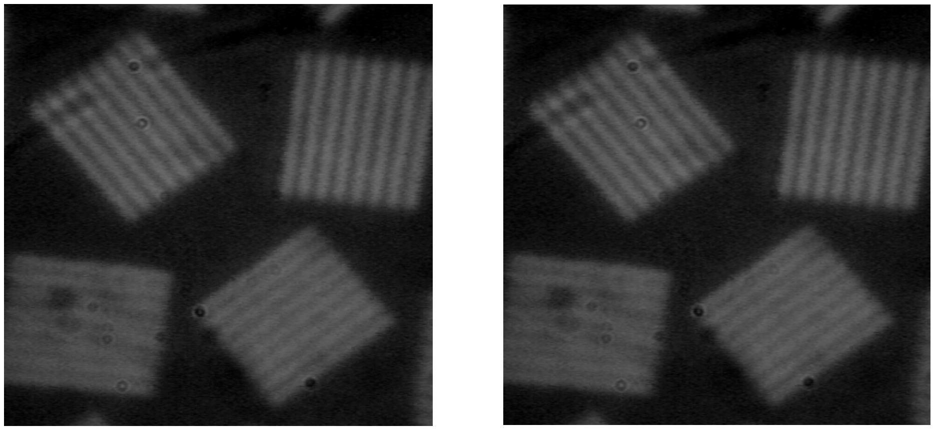


Fig. 8. Layout for testing resolution.

#98579 - $15.00 USD Received 10 Jul 2008; revised 14 Aug 2008; accepted 13 Sep 2008; published 26 Sep 2008



(a) (b)

Fig. 9. (a) Resolution test result of channel 0 (b) Resolution test result of channel 10.

5. Conclusion

In this paper, a new kind of space optical system—compound diffractive telescope is given. It has high resolution, light weight and wide field of view. In contrast with other optical systems, the compound diffractive telescope solves the conflict between lightweight and wide field of view well, since it combines the structure of compound eyes with diffractive telescope. The demonstrated system given in this paper agrees well with those characteristics.

Acknowledgement

This study is supported by the National High Technology Research and Development Program of China under Grant (2006AA12Z127) and National Natural Science Foundation (10704072) (60577044).