

Structural analysis of a new type lightweight optical mirror blank

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ABSTRACT

To reduce the cost and increase the feasibility of the astronomical optical telescope, modern large optical telescope is normally required to be as light as possible. Therefore lightweight mirror is always pursued by large telescopes development. In this paper, a new type lightweight optical mirror blank, the evaluation of its technical feasibility and the reduction of cost are introduced. For the purpose of applying active optics with this lightweight mirror blank, the structural analysis, thermal analysis and optical performance simulation by the finite element method have been presented.

Key words: Large telescope, Lightweight mirror, Active optics, Structural analysis, Finite element method

1. INTRODUCTION

With the development of modern science and technology, thin mirrors have been applied widely more and more in large telescopes. In this paper, a new type thin mirror will be introduced. There are two thin mirror panels in the upper and lower blank, and between the two thin mirror panels are arranged in rows of thin tubes(see Fig.1). Panels and tubes are fused together by high temperature in electric furnace, using the same glass material (such as Pyrex, its low coefficient of expansion for the 3.3ppm). Therefore, we call such type thin mirror “hollow tubular light mirror”. This thin structure mirror has the following three significant advantages. First, comparing with the corresponding solid mirrors, this thin mirror with the characteristic of its light weight not only significantly reduce the weight and cost of the whole telescope, but also greatly reduce its demand for expensive mirror material. To adopt the zero-expansion glass ceramics, Zerodur or ULE, for example, mirror blanks for each decrease of 1kilogram, can save 250 to 500 U.S.dollars. Thus,when mirror blanks have the total decrease of hundreds of kilograms, the funds can be saved will be considerable. Secondly, the temperature inside the thin mirror can be more quickly to keep up with environmental temperature changes, i.e., the temperature lag time is short. So it can quickly get rid of thermal deformation and maintain its original surface shape. Thirdly, it is more important than above two, the thin mirror with its “soft” characteristic makes it possible that “active optics” which can real-time change mirror surface can be applied in large telescopes. In order to active optics technology can be implemented on this hollow tubular lightweight mirror blank, the structural analysis, optimization of mirror support, some theoretical analysis of thermal response and thermal deformation analysis should have been performed in this paper. Such as the optimization of the number and distribution of axial support points, simulation active correction of different spatial frequency aberration with finite element method, etc. This paper also mainly concerns of its technical feasibility and practicability in future telescopes.

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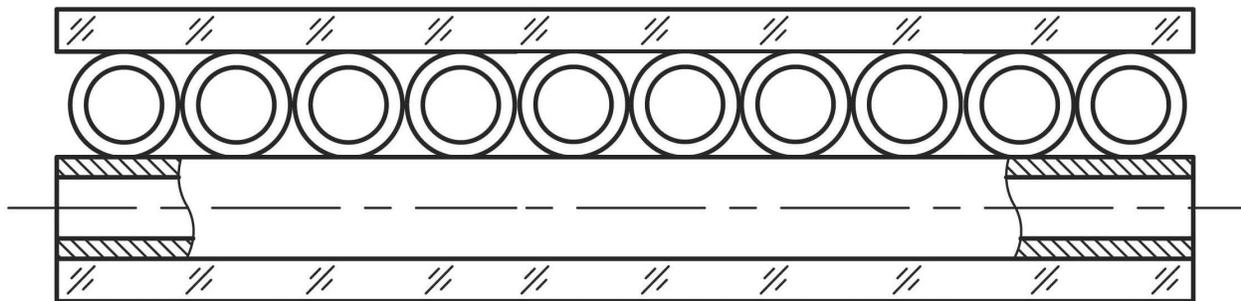


Fig. 1 Hollow tubular light mirror

2. DEVELOPMENT STATUS OF HOLLOW TUBULAR LIGHT MIRROR

People ever had used “honeycomb” structure to replace the solid light mirror, but because the large cellular structure would result in irregular deformation and active optics technology couldn’t be implemented on a cellular hollow mirror. In the past year, after numerous of failures and technology to explore, Professor Ningsheng Hu finally had succeeded in trial-produce a variety of light mirror blanks made of Pyrex material. These light mirror blanks are in diameter from 12cm to 70cm and all parts are welded very satisfactorily. After the process of annealing in precision, the residual stress within the mirror blanks have reached to almost undetectable levels. This new type lightweight mirror, “hollow tubular light mirror”, not only has good temperature characteristics of small delay, but also active optics can be used on it. In May 2009, Professor Hu applied for a Chinese patent on the hollow tubular light mirror. Some similar foreign patents are the 2003 U.S. patents 6,598,984. In their patents, a number of circular holes drilled along the horizontal are in the thick solid mirror blanks in order to achieve the purpose of hollow. Obviously, we use the pipe to replace the drilled holes would be better.

3. ANALYSIS OF HOLLOW TUBULAR LIGHT MIRROR SUPPORT

First of all, we will build the finite element model of hollow tubular mirror. In the model, a hollow tubular light mirror which is 1m in diameter and 32mm in thickness, is composed of two thin mirror panels and two rows of thin mirror tubes. The upper and lower panels are both 4 mm in thickness and the tubes are 10mm in diameter and 1mm in thickness(see Fig.2). There are three axial fixed supports which are distributed in 120° symmetry, to define the position of the mirror. The number and distribution of axial support points should not only satisfy the surface accuracy of the mirror under the gravity load, but also could carry out the accurate active correction for eliminate the low spatial frequency aberration, such as thermal deformation of the mirror and residual surface error of the optical polishing. To reduce the complexity and lower the cost of the active support system, it is better to reduce the number of the axial support points. Considering about above reasons, an axial support system with 35 points has been optimized finally. Excluding 3 fixed points, there are only 32 actuators needed for mirror (see Fig.3). The surface accuracy of the mirror due to maximum gravity deformation is PTV 48.5nm and RMS 10.0nm (see Fig.4). Comparing with the same size of solid mirror, the hollow tubular mirror results in a reduction of mass of about 60%(see Table.1). The change in weight is shown the following chart. Even this mirror is not difficult to achieve weight loss 70%, that is, its weight is only 30% of solid mirror after the size and thickness of panels and tubes would have been optimized.

Table.1 Information on mass of solid mirror and hollow tubular mirror

Item	Mass
Solid mirror blank	55.4566 kg
Hollow tubular mirror blank	22.9459 kg

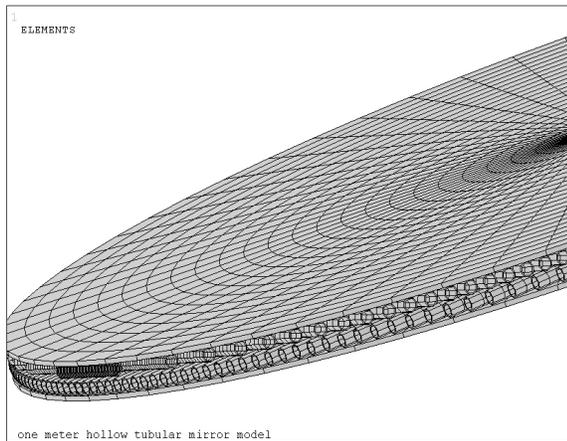


Fig. 2 Finite element model of hollow tubular mirror

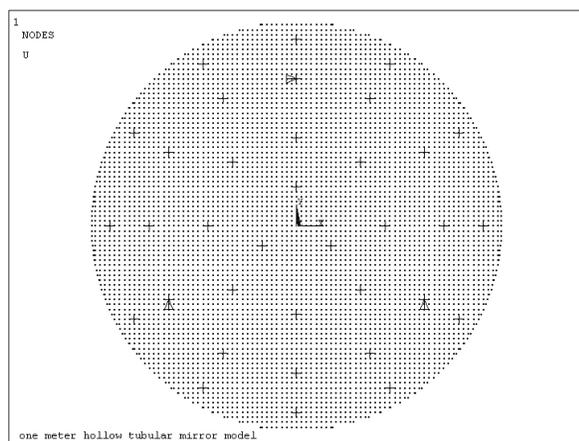


Fig. 3 Distribution of support points (35 axial support points)

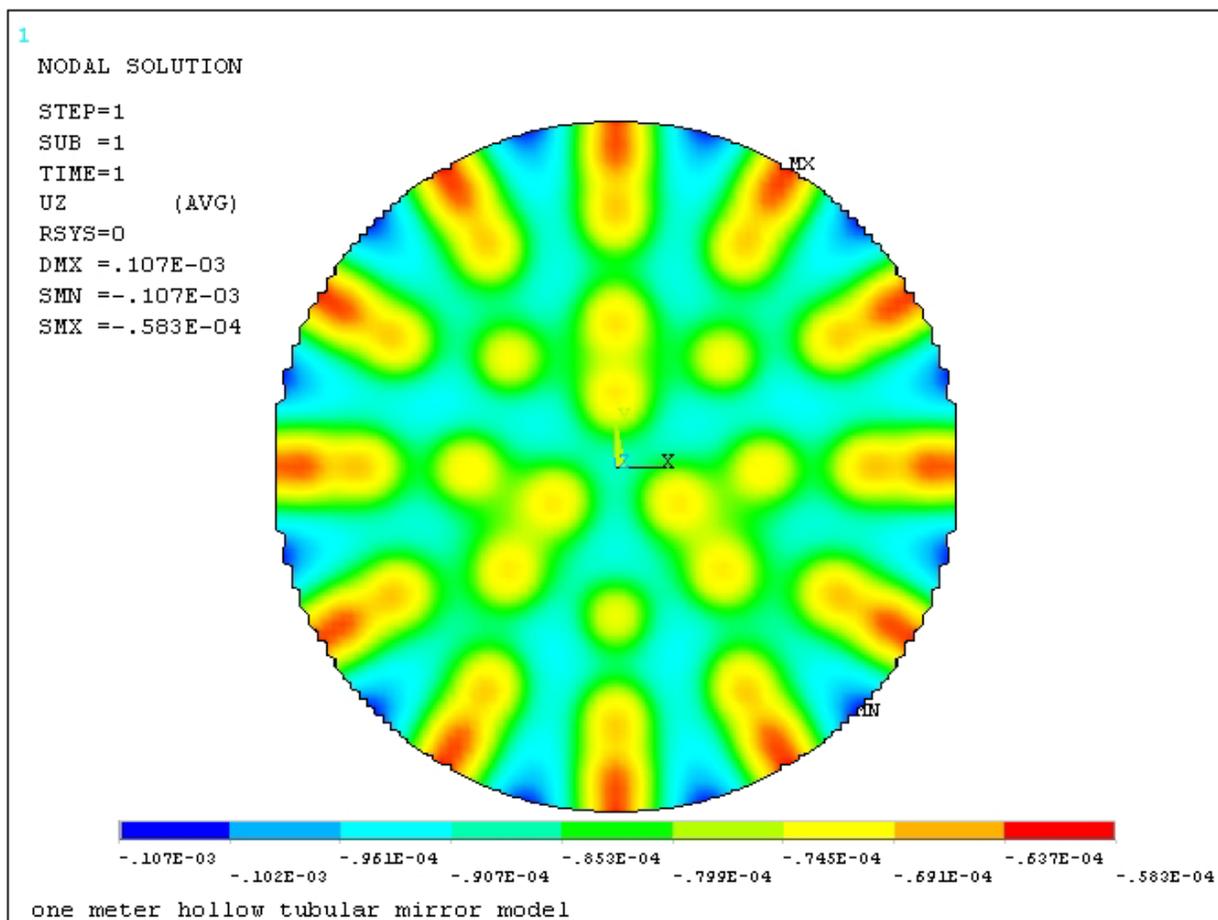


Fig.4 Maximum gravity deformation with 35 axial support nodes(including 3 fixed nodes)

The lateral support system is a kind of local lateral support system, combined with axial actuator and located at the same place. Using this type of lateral support system is because of the difficulty to put the lateral supports at the out edge of the mirror. The problem is also difficult to drill a blind hole at each support place to put the lateral support point at the center plane of the gravity of the mirror because of the very thin (4mm) mirror and the tubes in blank. Additionally, the active support system has to correct the moment, which is created on the mirror by the lateral support system. This kind of lateral support system has been succeeded in LAMOST. The surface accuracy of the mirror due to maximum lateral gravity deformation is PTV 37.7nm and RMS 4.8nm (see Fig.5).

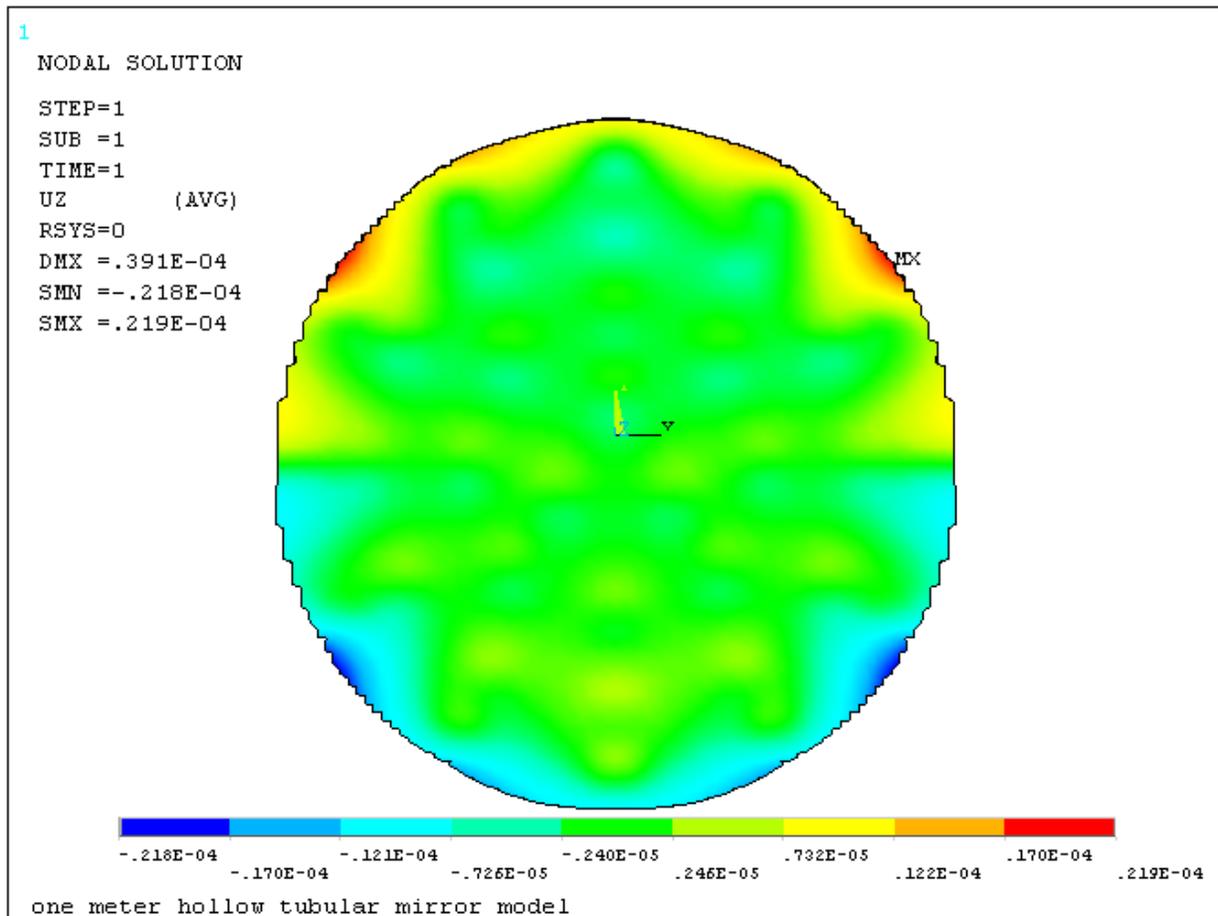


Fig.5 Maximum lateral gravity deformation

4. SIMULATION ACTIVE CORRECTION

In order to test the effect of active optics on the tubular mirror, we will simulate correction a variety of mirror shapes derived from theoretical aberration. Here, we will simulate the low spatial frequency aberration correction, such as spherical aberration, coma and astigmatism. According to the following formula (1-1), (1-2), (1-3), we can respectively get the surface of the low-level spherical aberration, the low-level coma, the low-level astigmatism. The coefficient in the formula, A, B, C, Φ_A , Φ_B and Φ_C , can be assumed constant.

$$W = A * r^2 + B * r^4 + C * r^6 \quad (1-1)$$

$$W = A * r^3 * \cos(\theta + \Phi_A) + B * r^5 * \cos(\theta + \Phi_B) \quad (1-2)$$

$$W = A * r^2 * \cos(2 * \theta + \Phi_A) + B * r^4 * \cos(2 * \theta + \Phi_B) + C * r^6 * \cos(2 * \theta + \Phi_C) \quad (1-3)$$

And then we obtain the active forces, F, according to the following matrix equation:

$$K F = W \quad (2)$$

Here, K is influence function and can be obtained by the finite element model in advance. Then we apply the forces to the finite element model of the hollow tubular light mirror and finally get the simulated surface W1. Comparing with W, we can infer the effect of active correction from W-W1. In other words, by the analysis of residual surface errors(Fig.6) (Fig.7) (Fig.8), we can draw the conclusion that it is no problem that application active optics to the hollow tubular light mirror, but we can also find the residual errors are not so small and there are still some low spatial frequency aberration required being corrected. Although the result of active correction is not so perfect, we think the active forces are so small and we may have an iteration correction based on the current result. On the other hand, we can say that the hollow tubular mirror is more responsive to the changes of force than the solid mirror. By the way, the residual surface errors of coma are bigger than the other two because the the low-level coma is related to the tip-tilt aberration which is not corrected.

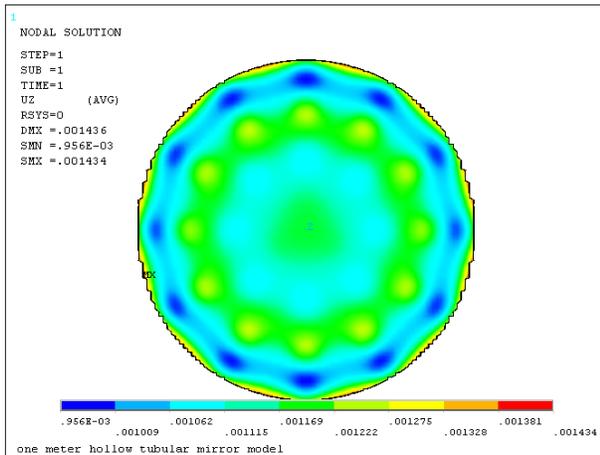


Fig.6 Residual surface errors of spherical aberration

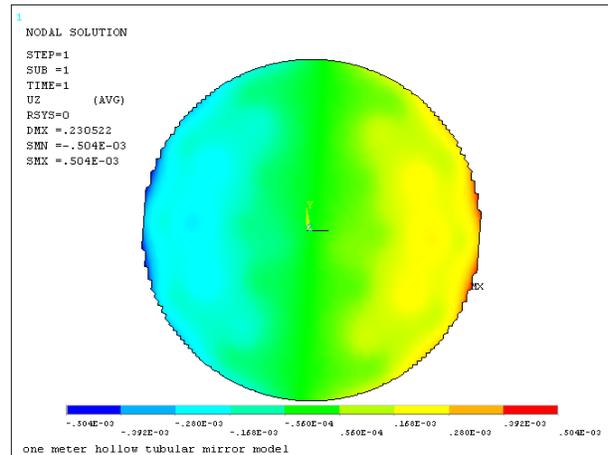


Fig.7 Residual surface errors of coma

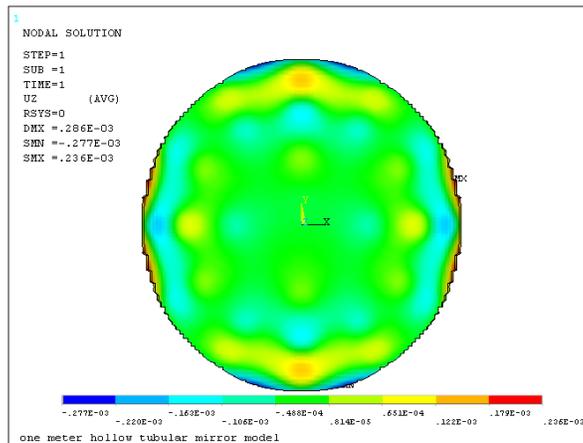


Fig.8 Residual surface errors of astigmatism

Table.2 Information on simulation active correction based on the finite element model

Item	Initial surface (W)	Simulated surface (W1)	Residual surface(W-W1)	Maximum active force(F)	Maximum stress
Low-level spherical aberration	PTV=300 nm RMS=90.4 nm	PTV=294.5 nm RMS=90.0 nm	PTV= 47.7nm RMS= 8.3nm	Fmax= 3.698 N Fmin= -2.466 N	0.132 N/mm^2
Low-level coma	PTV=393.6 nm RMS=65.9 nm	PTV=301.7 nm RMS=51.1 nm	PTV=100.8 nm RMS=16.9 nm	Fmax= 2.529 N Fmin= -2.529 N	0.089 N/mm^2
Low-level astigmatism	PTV=581.4 nm RMS=102.5nm	PTV=570.2 nm RMS= 102.3nm	PTV= 51.3nm RMS= 5.9 nm	Fmax= 3.954 N Fmin= -4.188 N	0.151 N/mm^2

5. THERMAL DEFORMATION ANALYSIS

As we know, temperature changes can bring about the changes of the shape of mirror surface. We will calculate the thermal deformation by finite element method and compare the hollow tubular light mirror blank with the solid mirror blank. And a coarse analysis of thermal performance will be provided.

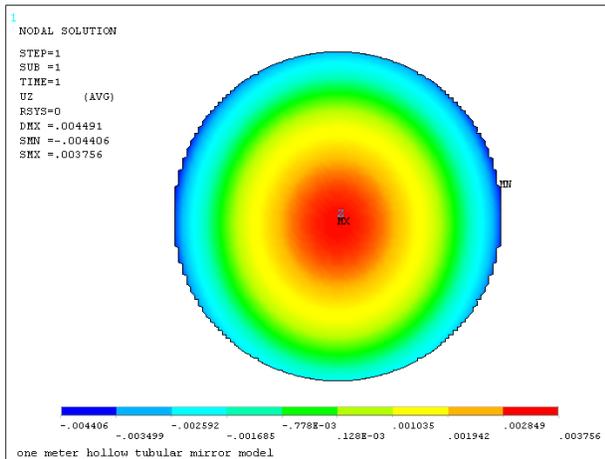


Fig.9 Thermal deformation of hollow tubular mirror blank

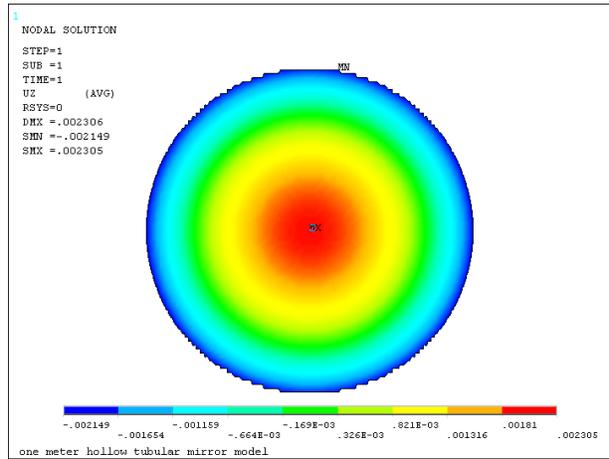


Fig.10 Thermal deformation of solid mirror blank

With a 1° C temperature difference in axial direction , we respectively get the shape of mirror surface of the two kinds of mirror blank, with surface accuracy of the mirror: PTV=8.04 μ m, RMS=2.16 μ m (Fig.9) and PTV=4.45 μ m, RMS=1.31 μ m (see Fig.10). we can see that the former is more responsive to the changes of temperature than the latter. That is to say, the hollow tubular mirror is more seriously affected by temprature, which is disadvantage in telescope. If it is well ventilated or made from fused silica glass (its coefficient of expansion for the 0.55ppm), the adverse effects of thermal deformation will be greatly improved. Only, the cost of using fused silla glass will be higher than using Pyrex material. And if considering that the tubes are open at both ends, the air around can flow freely and also easier to fan ventilation, the hollow tubular mirror can reach the balance of thermal and temperature stability quickly. The thermal diffusivity (α) of Pyrex and the mirror blank thickness, L, a time delay, τ , depends on the following relation:

$$\tau \approx \frac{L^2}{a} \quad (3)$$

Now considering the hollow tubular light mirror blank panel 4 mm thickness and the solid mirror blank 32 mm thickness, the former's temperature lag time can be shortened to 1/64. It is very important to telescopes. When dome is open and telescope is in use, the external cold air enters into the dome and encounters hollow thin mirror, the thin mirror can quickly reach equilibrium with the air temperature and the time of thermal deformation will be shortened. On the other hand, the adverse effects of mirror seeing, which is generated by the air mass above the thin mirror surface due to the temperature difference of mirror surface, also will be reduced and will be helpful to obtain the good image quality of large mirror telescopes.

6. CONCLUSIONS AND EXPECTATION

As we have described above, this new type lightweight optical mirror blank has significant advantages because of its particular structure. The studies and coarse analysis have shown that this structure mirror should be used in large astronomical telescope in the future. But there are still many works have to be done carefully, such as more effective active correct, further analysis of the temperature deformation and how to get rid of the adverse effects of high sensitivity for changes. A coarse summary of characteristics of the hollow tubular light mirror is provided as follows: 1. Lighter than usual lightweight solid mirror, 2. Smaller temperature lag, 3. Deformation characteristics similar to lightweight solid mirror, 4. Various curvature of the meniscus mirror that can be manufactured, 5. Low cost, 6. Fast delivery. Now, it will not encounter too much difficulty to manufacture a 4 meters hollow tubular light mirror of Pyrex material in technology.

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