Polarization Analysis of Fizeau-type Y-4 Prototype

Chaoyan Wang*, Xinyang Chen, Yuanyuan Ding, Dan Zhou
Shanghai Astronomical Observatory,Chinese Academy of Sciences, Shanghai 200030,China

ABSTRACT

Optical synthesis aperture telescope technology can be used to get more rich astronomical information. Interference fringe scanning method is commonly used to eliminate optical path difference between different optical delayed lines, but due to the polarization difference between the interference arms will lead to interference fringe contrast degradation especially in interference type instrument. Especially when observing faint, more distant targets, it is more necessary to consider the polarization effects caused by the instrument itself. In this paper, the Fizeau-type Y-4 prototype developing by Shanghai Astronomical Observatory, Chinese Academy of Sciences is introduced first of all. Based on the principle of the vector-wave superposition, this paper focuses on fringe contrast degradation caused by polarization effects and the changes of polarization states caused by coating of different material. The simulation results show that the interference fringe contrast is sensitive to the polarization effects. Similarly, the changes of polarization state of the beam caused by the coating needs to be considered when designing the optical interferometer. Finally, a polarization compensator is proposed to compensate the polarization difference.

Keywords: Polarization effects, Coating, Fizeau-type, Interference fringe, Contrast

1. INTRODUCTION

Fringe scanning is a common method to detect the relative optical path difference in optical synthesis aperture telescope. After obtaining a set of interference fringes by step scanning, the position of zero optical path difference can be obtained from the change curve of contrast[1]. This method relies heavily on the contrast of fringes, as the information is extracted from the interference fringes. However, the polarization effects can sharply degrade the contrast of the interference fringe and thus reduce the high-resolution imaging. In the scalar theory of optical interference, the polarization difference caused by unpolarized optical elements such as lens, mirrors, film coating are not considered during beam propagation but that can decrease the imaging quality of optical system, just like wavefront aberrations. With the continuous pursuit of high-resolution imaging by astronomers, the effects of polarization on imaging quality will not be ignored.

It has been noted in the world that the polarization difference between the interference arms leads to the decrease of the contrast of fringe. Traub published an article[2] in 1988 about polarization effects in a stellar interferometer, stating that the polarization mismatch between two paths can cause a drop in visibility and proposed the concept of a "directional cosine". In 1996, Perraut et al. modeled the optical sequence of GI2T (Grand Interferometre of 2 Telescopes) through Mueller matrix[3], and pointed out that the horizontal and vertical polarized light caused by asymmetry has different phases. Then he proposed the contrast of the fringes depends on the relative phase between the two polarized states. Elias surpassed classical optical interference in 2004 to develop the theory of polarization interference[4], pointing out that when observing the weaker, more distant targets, very precise polarization control in all optical paths are required. In 2014, Mudge et al. published an article[5] about the polarization of long baseline interferometer, which pointed out that in long baseline interferometer with many folding mirrors, not only to face the problems of wavefront distortion, reflection loss and relative dispersion, but also to minimize polarization effects.

In this paper, I will perform the polarization simulation based on the Fizeau-type Y-4 prototype. This paper could help optical engineer understand how polarization differences affect interference fringe contrast, while providing valuable polarization considerations to designers of optical synthesis aperture telescopes.

*superyan@shao.ac.cn;

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2. Y-4 PROTOTYPE

As the name implies, four identical small-size telescopes form Y-type distribution, with one sub-telescope in the center and three surrounding telescopes at 120 degrees each other. The view of the Y-4 prototype is shown in Figure 1. Target beams collected by four telescopes, which primary and secondary mirrors are still in the classic Cassegrain form, are transmitted to four delay light paths. There is a set of folding mirrors in each delay light path. These beams are directed into a beam combiner, and then the interference image will image on the camera by the imaging lens.

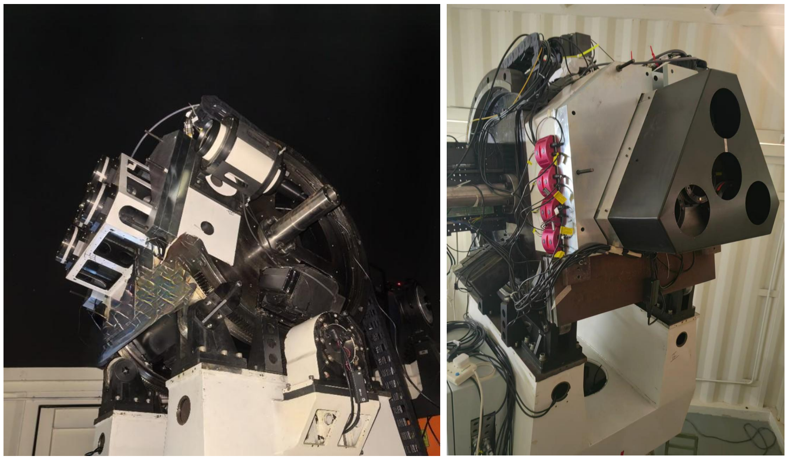

Figure 1. The view of the Y-4 type prototype.

Each sub-telescope is equipped with a delayed light path with tip/tilt mirrors and piston mirrors, see the Figure 2. Through closed-loop operation, the tip/tilt mirrors can make the spots overlap in the focal plane all the time. Piston mirror consists of two mirrors presented at 90 degrees to each other. Before putting it into the delayed light path, piston mirror must be adjustment preciously to ensure that angle error does not exceed 2 arcseconds with the help of the goniometer. Both the tip/tilt mirror and piston mirrors, the microdisplacement actuators are installed under them. See reference[6] for more detail.

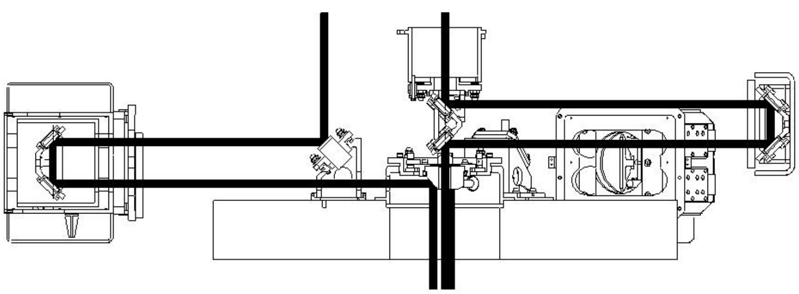

Figure 2. The diagrammatic sketch of delayed optical paths.

3. FILM COATING-INDUCED POLARIZATION

The polarization effect caused by the film coating is weak polarization, but it is still a key factor to consider in sophisticated instruments such as optical interferometric telescopes. Figure 3 shows the polarization variation of the four metal coatings at the same reflection angle. After simulation analysis, the polarization induced by Ag and Al is modest, but the polarization states of Al_2O_3 and MgF_2 have changed a lot. When building precision instruments, coating material should be chosen more carefully.

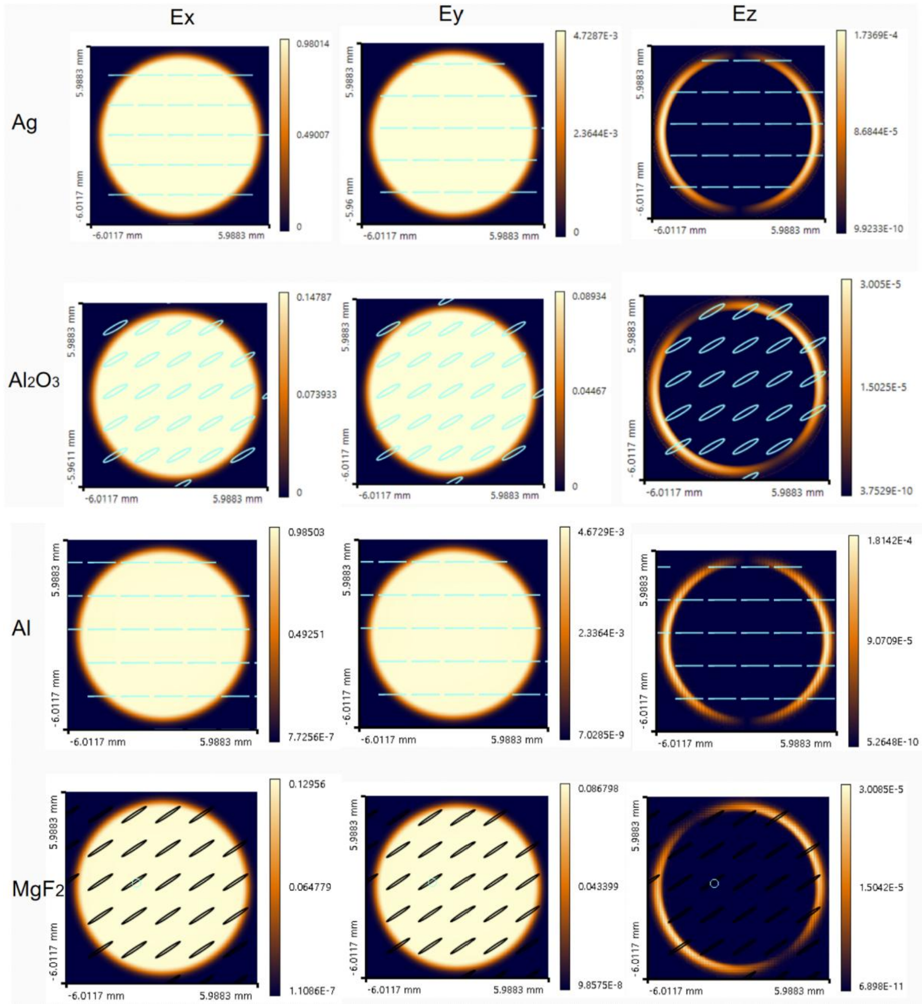

Figure 3. Polarization effects induced by the four different coating materials(Ag, Al_2O_3,Al,MgF_2).

4. CONTRAST DEGRADE BY POLARIZATION DIFFERENCE

Starting from the theory of vector wave superposition, it can be known that in the area where two (or more) light waves overlap, some vibration will strengthen, and some vibration will weaken. The combined vibration generated by two (or more) light waves at the encounter point is the vector sum of the vibration generated by each wave at this point.

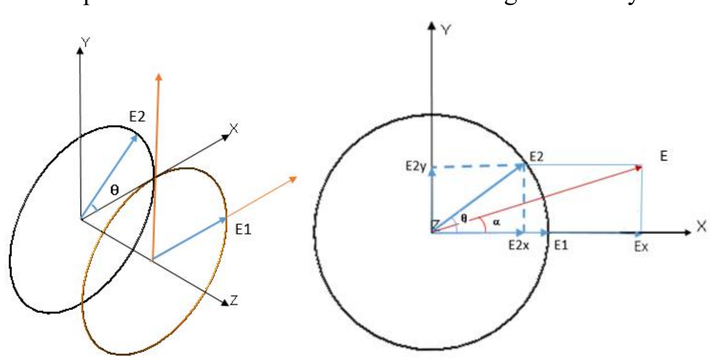

Figure 4. (Left)Two beams with polarization difference; (Right)Decomposition and synthesis of optical vectors.

Two monochromatic plane waves $\overrightarrow{\boldsymbol{E_1}}$, $\overrightarrow{\boldsymbol{E_2}}$, with the same frequency, same amplitude but the vibration direction of difference, varying by θ degrees, propagate along the Z direction, as shown in Figure 4.

If $\overrightarrow{\boldsymbol{E_1}}$and $\overrightarrow{\boldsymbol{E_2}}$ meet at any point P in the direction of Z, the combined vibration $\vec{E}$ of the light wave at the point P can be expressed as:

$$\begin{aligned}\vec{E}(\mathrm{P}) = \overrightarrow{E_1}(\mathrm{P}) + \overrightarrow{E_2}(\mathrm{P}) &= \left[\overrightarrow{E_{1\mathrm{x}}}(\mathrm{P}) + \overrightarrow{E_{1y}}(\mathrm{P})\right] + \left[\overrightarrow{E_{2x}}(\mathrm{P}) + \overrightarrow{E_{2y}}(\mathrm{P})\right] \\ &= \left[\overrightarrow{E_{1\mathrm{x}}}(\mathrm{P}) + \overrightarrow{E_{2x}}(\mathrm{P})\right] + \left[\overrightarrow{E_{1y}}(\mathrm{P}) + \overrightarrow{E_{2y}}(\mathrm{P})\right] \\ &= \overrightarrow{E_x}(\mathrm{P}) + \overrightarrow{E_y}(\mathrm{P})\end{aligned} \quad (1)$$

Using **α** to represent the vector length (amplitude) of two monochromatic plane light waves $\overrightarrow{\boldsymbol{E_1}}$ and $\overrightarrow{\boldsymbol{E_2}}$, the amplitude A of the combined light wave can be expressed as:

$$\boldsymbol{A^2 = (a + a\,cos\theta)^2 + (a\,sin\theta)^2 \;\; = 2a^2 + 2a^2cos\theta} \quad (2)$$

The angle α between the combined vibration $\vec{E}$ and the X axis can be expressed as:

$$\tan\alpha = \frac{a\,sin\theta}{\boldsymbol{a + a\,cos\theta}} \;\; = \frac{sin\theta}{1 + cos\theta} \quad (3)$$

If two plane waves with different vibration direction map to the focal plane, the interference fringe contrast will be reduced. Figure 5 shows the changes of the interference fringes under different polarization angles, from the initial interference being the strongest to the interference vanishing as the angle increases.

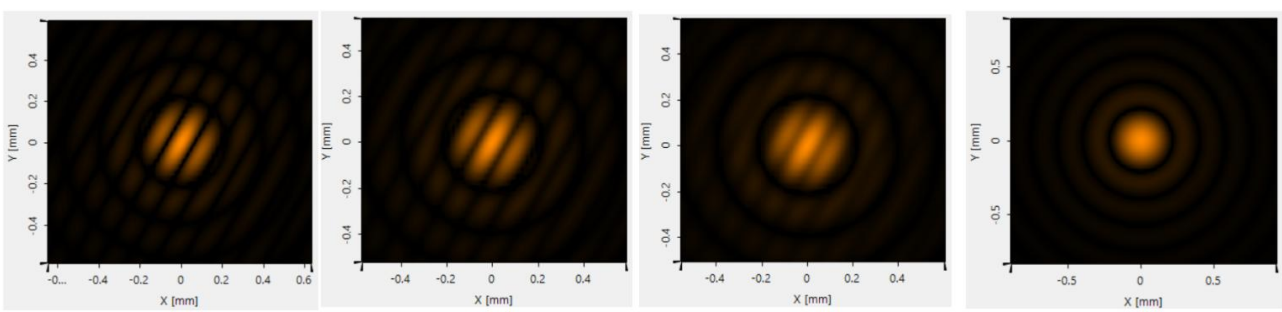

Figure 5. The changes of the interference fringes under different polarization angle difference (0°, 30°, 60°, 90°)

As shown in formula (4), the cosine modulation term $|cos\theta|$ plays a decisive role in the contrast of interference fringes, which is in line with the concept of "directional cosine" pointed out by Traub in reference[2]. In this paper, the simplest way to ensure no polarization difference between the two lights is to ensure that all corresponding reflections have the same directional cosine.

$$\mathrm{K} = \frac{A^2{}_{max} - A^2{}_{min}}{A^2{}_{max} + A^2{}_{min}} = \frac{(2a^2 + 2a^2|cos\theta|) - (2a^2 - 2a^2|cos\theta|)}{(2a^2 + 2a^2|cos\theta|) + (2a^2 - 2a^2|cos\theta|)} = |cos\theta| \quad (4)$$

5. K-MIRROR FOR REDUCE POLARIZATION DIFFERENCES

Unlike the three-piece K-mirror unit, the K-mirror unit we developed is composed of two parts, namely a prism coated with reflective film on the outer surface. The top angle of the prism can be accurately controlled by the manufacture. The other mirror lies above the reflective prism and constitutes the three-reflection system, see Figure 6.

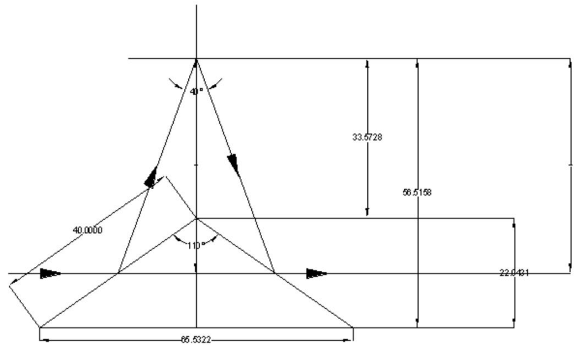

Figure 6. Design diagram of K mirror unit.

The trajectory of the spot during the K-mirror rotation was monitored using a CCD camera with 4.4um/pixel. The difficulty of alignment is the consistency between the optical axis of the K-mirror and the mechanical rotation axis. Thus the micro-collimation telescope is used to coincide the optical axis with the rotation axis, see Figure 7.

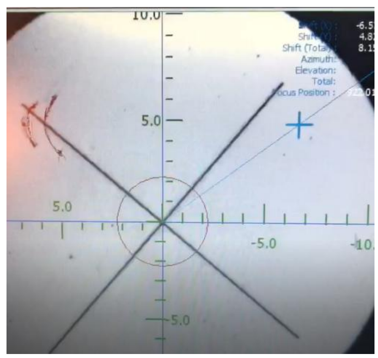

Figure 7. Alignment with micro-collimation telescope.

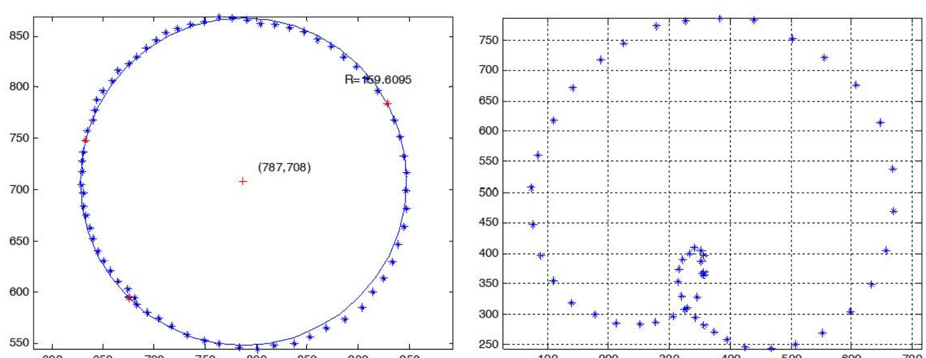

Figure 8. Trajectory of the spot during the K-mirror rotation:(Left)After alignment; (Right) Before alignment.

As shown in Figure 8, after alignment, the motion trajectory of the spots has improved, but there is still a problem of large radius of rotation compared with using the commercial linear polarizer, see Figure 9. It also indicates that even commercial products cannot fully achieve the trajectory radius of 0. More efficient alignment strategies are needed to reduce the radius of motion trajectory in the future.

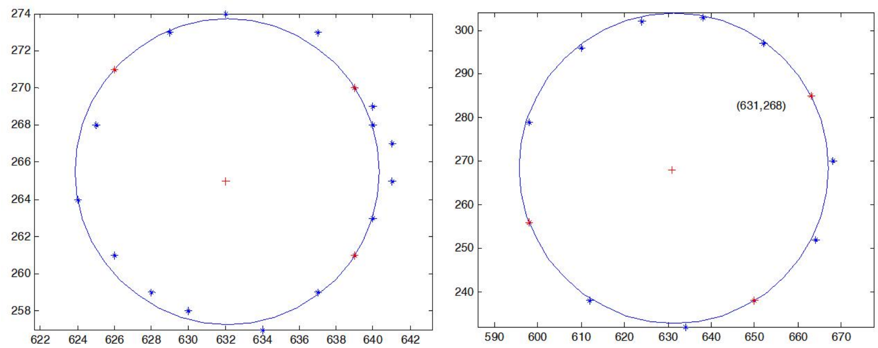

Figure 9. Trajectory of the spot using the commercial linear polarizer from two different companies.

6. CONCLUSION

Astronomy applications require high accuracy, high contrast, and diffraction-limit performance. Polarization effect is one of the very important factors for optical designers to consider during building huge optical interference telescope. One point to be considered is to reduce the polarization differences between delayed optical paths, especially in devices that rely on interference fringe detection. Another consideration is that you should also be very careful when choosing the coating, by choosing the coating material with the least impact on the polarization. As for K-mirror, we also need to find more effective ways to align the internal and external light paths. In short, we still have a lot of works to do to make it better developed.

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