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# Risley Prisms Scanning Optical Imaging System Using Liquid Crystal Spatial Light Modulator

**Dalin Song[1,2], Jun Chang[1]*, Yifei Zhao[2], and Qing Zhao[3]**

[1]*School of Optics and Photonics, Beijing Institute of Technology, Beijing 100081, China*
[2]*The First Research Institute of the Ministry of Public Security, Beijing 100048, China*
[3]*Beijing Institute of Control and Electronic Technology, Beijing 100038, China*

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Chromatic aberrations induced by Risley prisms made of a single material can be substantially compensated using a liquid crystal spatial light modulator while still keeping the prism pairs compact, simple and lightweight. A ±10° optical scanning imaging system with ±2° instantaneous field based on LC-SLM correction is designed as an example. The ultimate simulation results show that this kind of scheme is an effective way of improving imaging performance dynamically across the full field of scanning.

*Keywords* : Optical design, Risley prisms, Achromatic aberration, Liquid crystal spatial light modulator
*OCIS codes* : (080.3620) Lens system design; (220.1000) Aberration compensation

## I. INTRODUCTION

With limitations to its lens focal length and to the resolution of array detectors, an optical system usually has difficulty in meeting the requirements of large field and high resolution simultaneously. Risley prisms are one kind of optical structure consisting of two wedge prisms. As a light beam passes through each prism, it bends toward a new angle due to refraction. When the two prisms rotate by certain angles, the optic axis of the following lens scans through the space. And consequently, a large field of regard with high imaging resolution can be achieved. Compared to other scanning devices like double mirrors which usually need complex mechanisms and a relay optical system, the Risley prism scanning structure provides numerous advantages including compactness, small size, high speed, robustness and easy implementation. Risley prisms have been widely used in the fields of search and rescue and for ophthalmologists' imaging [1, 2].

Due to prism dispersion, the large amount of chromatic aberration induced by Risley prisms degrades imaging performance. A feasible solution is using a combination of different materials instead of a single prism to satisfy the achromatic condition. The achromatic Risley prisms can correct lateral chromatic aberration substantially [3]. However, the achromatic prism containing at least two opposite angle wedges brings large volume and weight, and thus puts pressure on the driving motor.

In order to maintain the advantages of compact structure of the single material Risley prisms, an alternative optical scheme using a Liquid Crystal Spatial Light Modulator (LC-SLM) to correct dynamic prism achromatic aberration is proposed. An example system is proposed subsequently which maintains acceptable image quality, and the simulation results show it is an effective method of prism scanning.

## II. LC-SLM DISPERSION CHARACTERISTIC ANALYSIS

LC-SLM is a kind of compact and low-cost device which can be used to correct optical wavefront error dynamically and to improve performances of scanning optical imaging systems [4]. LC-SLM contains a number of thin cells of birefringent liquid crystal material sandwiched between two parallel glass plates with high birefringence

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*Corresponding author: optics_chang@126.com, ORCID 0000-0001-8048-1956

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nematic liquid crystal [5]. It can bring user-controlled, spatially varying phase retardance to the light wavefront. This kind of compensation can be controlled at each pixel on the LC-SLM surface by applying a small voltage (grayscale) to the pixel. Even if the maximum wavefront error needed is greater than the dynamic phase retardance changing range of the LC-SLM, correction can still be done modulo [2π] [6].

Phase modulation characteristics are the most important property of LC-SLM. Phase retardation for different wavelengths is discrepant. A Twyman-Green interferometer can be used here to measure the response to a voltage signal applied on the LC-SLM [7]. By loading 0-255 grayscale on the LC-SLM (Model: PLUTO-VIS), the phase modulation for three wavelengths of light can be measured separately as shown in Fig. 1 [8].

Modulation for short wavelengths is deeper than for long wavelengths. New curves in Fig. 2 are drawn with green light phase modulation as abscissa and red/blue light phase modulation as ordinate. Near-linear dependency can be found among different wavelength light modulation curves. We suppose

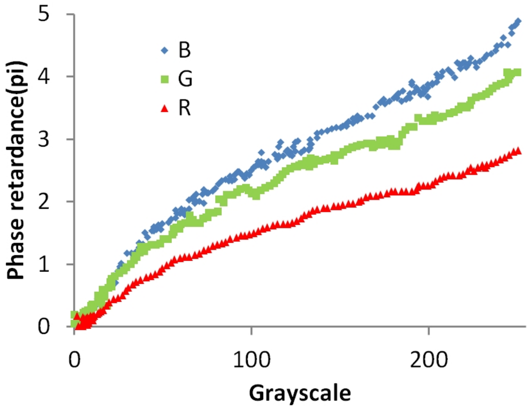


FIG. 1. Phase modulation graph for R (670 nm), G (532 nm) and B (473 nm) light.

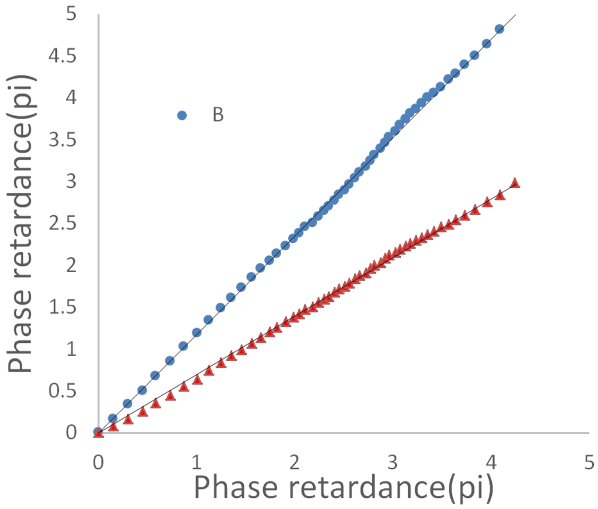


FIG. 2. Relationship curve among R/G/B light phase modulation.

$$\begin{aligned}\phi_B &= b\phi_G \\ \phi_R &= r\phi_G\end{aligned} \tag{1}$$

where $\phi_B$, $\phi_G$, $\phi_R$ are the phase retardance for blue (473 nm), green (532 nm) and red (670 nm) light separately. The fitting coefficients calculated for PLUTO-VIS are $b = 1.1763$ (fitting error $R^2 = 0.9992$), $r = 0.6991$ (fitting error $R^2 = 0.9983$) separately.

In order to compensate the lateral chromatic aberration induced by the prism, we suppose the phase retardance distribution to be

$$\phi(t) = A(t)y \tag{2}$$

where $A(t)$ is the phase distribution coefficient changing with time, and y is the normalized coordinate on the LC-SLM surface. The direction of the y axis is always in parallel with field scanning. The corresponding optical path is $\lambda\phi(t)$. The deflection angle for different wavelength rays after LC-SLM is

$$\begin{aligned}\delta_B(t) &= \arctan[bA(t)\lambda_B] \\ \delta_G(t) &= \arctan[A(t)\lambda_G] \\ \delta_R(t) &= \arctan[rA(t)\lambda_R]\end{aligned} \tag{3}$$

So, the chromatic aberration induced by LC-SLM between blue and red light is

$$\delta_{B-R\_SLM}(t) = \arctan[bA(t)\lambda_B] - \arctan[rA(t)\lambda_R] \tag{4}$$

## III. THEORIES OF DYNAMIC CHROMATIC ABERRATION CORRECTION USING LC-SLM

The chromatic aberration induced by Risley prism pairs can be described as

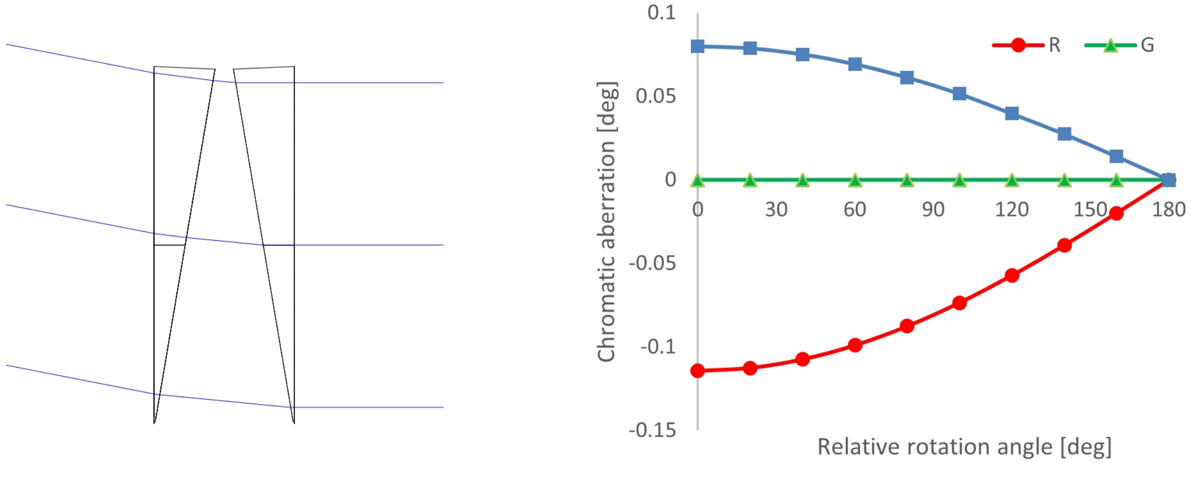
$$\delta_{B-R\_prism\ pairs}(t) = 2(n_B - n_R)\alpha \cdot \cos\frac{\omega(t)}{2} \tag{5}$$

where $n_B$ is the refractive index of the prism material for blue light, $n_R$ is the refractive index of the prism material for red light, $\alpha$ is the prism corner angle and $\omega(t)$ is the relative rotation angle between the two prisms.

Figure 3 shows the layout of the Risley prism (BK7, $\alpha = 10°$) and its chromatic aberration with $\omega(t)$ changing.

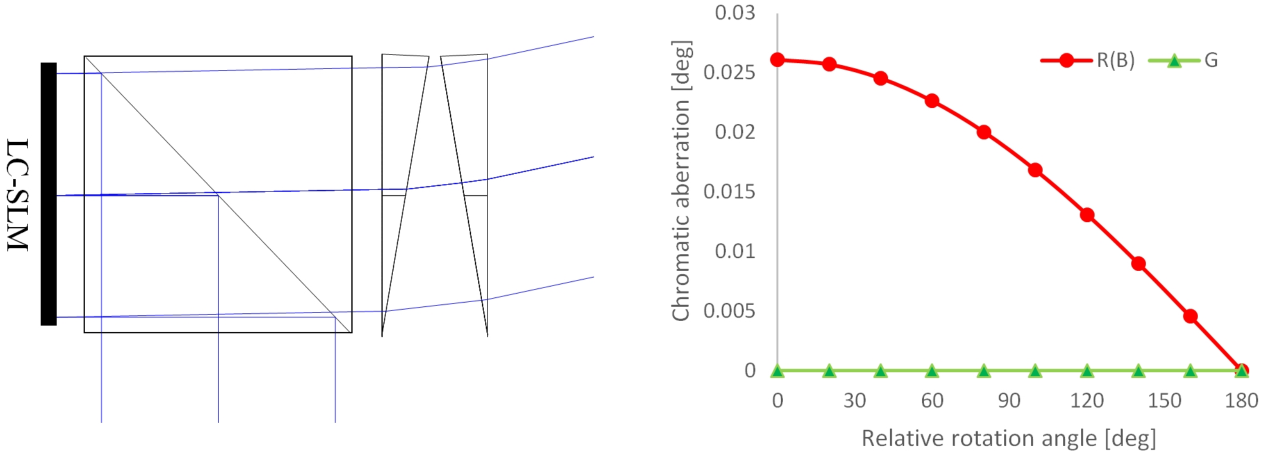
To correct the large amount of chromatic aberration induced by Risley prisms, the phase distribution on the LC-SLM surface should meet the relationship as

$$\delta_{B-R\_SLM}(t) + \delta_{B-R\_prism\ pairs}(t) = 0 \tag{6}$$



(a) (b)

FIG. 3. Layout of Risley prism (a) and chromatic aberration (b).



(a) (b)

FIG. 4. LC-SLM to compensate chromatic aberration (a) and residual chromatic aberration relative to green light (b).

Figure 4 shows the LC-SLM adopted to compensate the chromatic aberration, and the chromatic aberration is about 13% of that of the prisms without LC-SLM. Figure 5 shows the phase delay on the LC-SLM surface at the maximum scanning angle ($\omega(t) = 0°$). Chromatic aberration can be compensated dynamically by continually altering the phase delay distribution during the scanning process by applying the appropriate grayscale to each pixel on the LC-SLM surface. Because the aberrations at each different scanning position can be calculated in advance, the required grayscale value for each pixel at a given field angle can be preprogrammed into the LC-SLM controller.

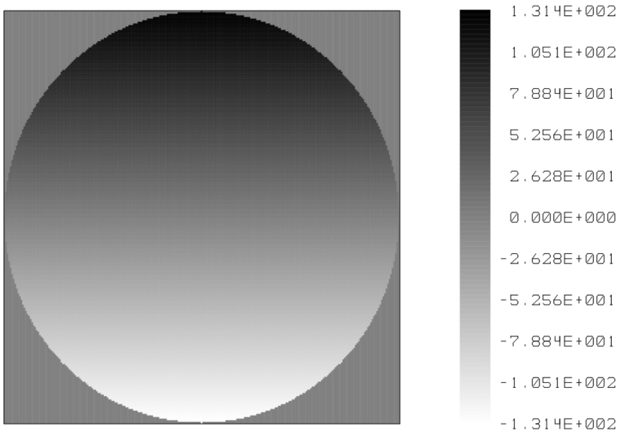


FIG. 5. Phase delay map of LC-SLM surface (periods of 2 pi radians, $\omega(t) = 0°$).

## IV. UTILIZATION OF LC-SLM AS CHROMATIC CORRECTOR IN A SCANNING OPTICAL SYSTEM

We designed a F/5 scanning imaging system with ± 2° instantaneous field of view covering scanning angle of ±10°. Table 1 lists the design specifications. Layout of the complete imaging system is shown in Fig. 6, which shows the result of the stepwise design process. The Risley prism pairs and LC-SLM are used to meet the requirement of field scanning and chromatic aberration compensation function as analyzed in section 3. The optical axis is folded by a beam splitter placed in front of the reflected LC-SLM. Figure 7 shows the phase delay on the LC-SLM surface for 0°, 5° and 10° scanning field.

The RMS spot radius vs. instantaneous field for 0°, 5° and 10° scanning field of the optical system with and without LC-SLM are shown in Figs. 8(a) and 8(b) respectively. Figure 9 plots the RMS spot radius of the central instantaneous field across the large field of scanning, which reflects that the aberrations of the whole imaging system with LC-SLM is about 1/5 of the one without LC-SLM. The results show that the aberration of the system has been compensated substantially.

TABLE 1. Relevant specifications for the design of a scanning optical system

| | |
|---|---|
| Design wavelength | 473 nm 532 nm 670 nm |
| F/# | 5.0 |
| Focal length | 50 mm |
| Prism corner angle | 10.7° |
| Field of scanning | ±10° |
| Instantaneous field of view | ±2° |

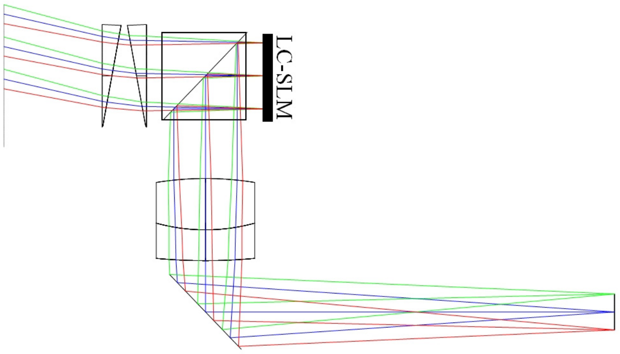


FIG. 6. Complete scanning optical system layout.

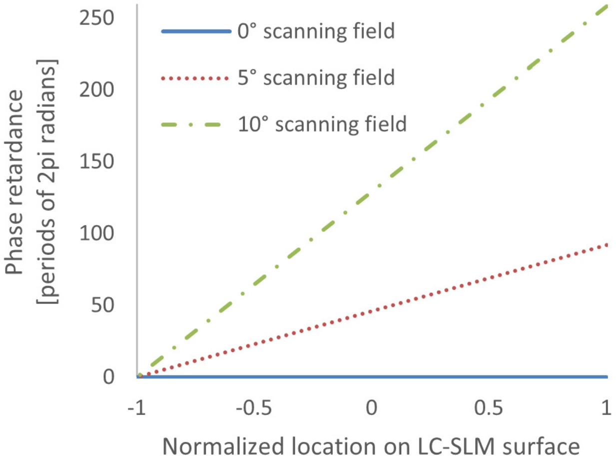
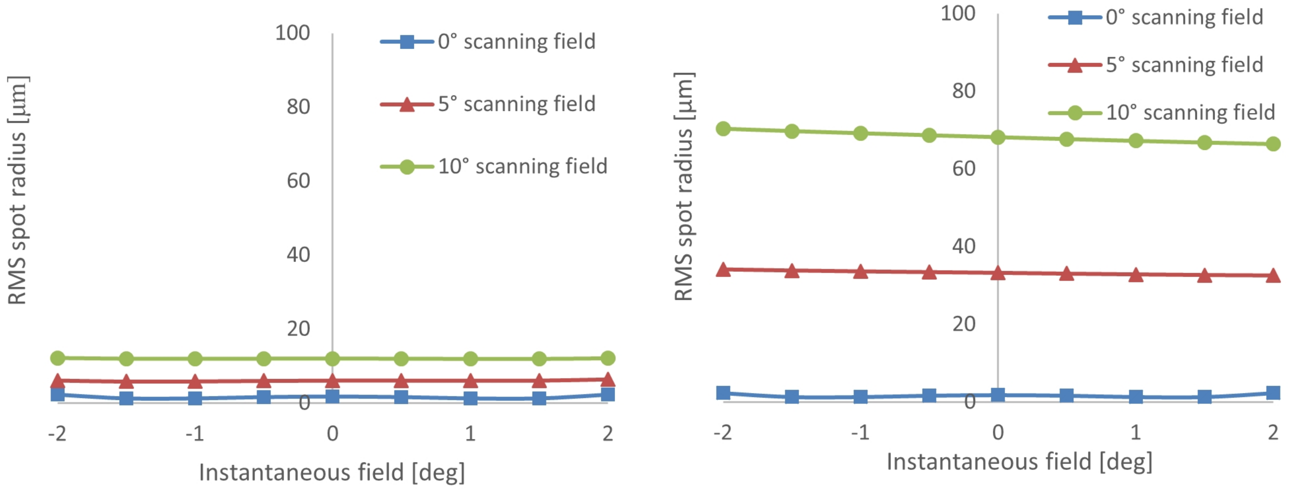


FIG. 7. Phase retardance distribution on LC-SLM surface along the direction in concern with scanning angle.



(a) (b)

FIG. 8. RMS spot radius plots with (a) and without LC-SLM (b).

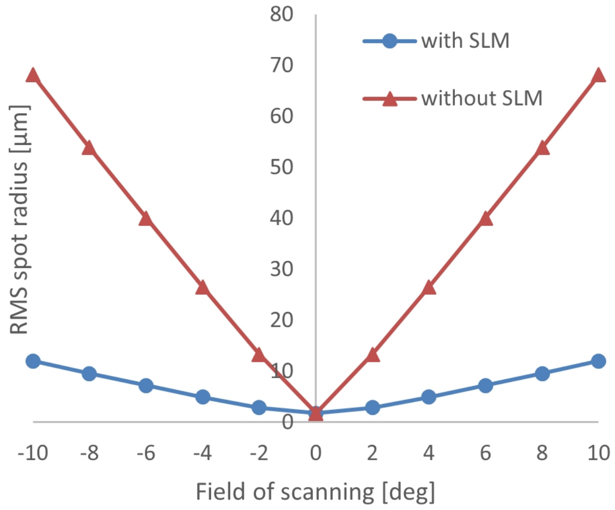


FIG. 9. RMS spot radius across the large field of scanning with and without LC-SLM.

## V. CONCLUSION

This paper has analyzed and shown the design of the Risley prism pairs scanning optical imaging system using LC-SLM scheme. The simulation results show that it is an effective way to compensate the chromatic aberration induced by the compact single material Risley prisms. However, improvements are also need. One disadvantage is LC-SLM can only manipulate linearly polarized light, and thus the utility rate of luminous energy will be reduced by half. This problem can be circumvented by some methods such as the construction of an LC-SLM with two orthogonal LC layers [9]. More research work needs to be done.

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