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Integrated spectral phase delay calibration technique for a liquid crystal variable retarder used in wide-bandwidth working channel

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ABSTRACT

Laser sources with limited wavelengths are commonly used to calibrate the phase delays of liquid crystal variable retarders (LCVRs). However, the parameters describing the phase delays obtained in this manner in certain bands do not match the parameters in the wide-bandwidth working channel employed in polarized imaging detection systems based on LCVRs, which results in deviations in the detection precision. In this paper, we propose an integrated calibration method based on both a multi-band light source and a laser source. The method uses the calibration data obtained by the laser source to correct the calibration data obtained by the light source. The parameters of the phase delays in various spectral channels can be used to precisely measure the LCVR phase delays in the bands of the light source. We conducted experiments to obtain and compare the measured and fitted results for a light source in the 568 nm band. Then, the parameters were used in the instrument matrix calibration of our LCVR based polarized imaging system. The results show that the detection precision of the polarization degree improved more than 0.3% for linear polarized incident light, and more than 0.6% for elliptically polarized light, when our calibration method was applied. These improvements will prove useful in polarizer research, and to improve polarized imaging systems based on LCVRs.

1. Introduction

Polarized imaging detection systems are widely used to obtain information about ground targets, ocean and atmosphere [1–8]. These systems are based on different structures, including liquid crystal variable retarders (LCVRs) [9–12]. The birefringence of a LCVR changes when an appropriate voltage is applied, which results in a specific phase delay, and systems based on LCVRs can modulate the polarization states of incident light [13,14]. In polarized imaging detection systems based on LCVRs, four pairs of voltages are used to drive two LCVRs in each band to produce four pairs of different phase delays, and the generated intensity maps can be used to obtain the polarization information of the incident light in each band using the instrument matrix. Here, the precision depends on the phase delay of the LCVR and the calibration accuracy of the instrument matrix [15–18]. For accurate results, it is necessary to calibrate the relationship between the phase delay of the LVCR and the corresponding drive voltage in each band. Many researchers are now working to accomplish this. For example, Xiao et al. [19] measured the phase delay of an LCVR using the Mueller matrix, and discussed the effects of the incidence angle and drive voltage on the phase delay of the LVCR. Xiao et al. [20] proposed a theoretical mathematical model based on the Jones-matrix to research LCVRs, Gladish and Duncan et al. [21,22] obtained a curve describing the relationship between the phase delay and the drive voltage using semiconductor laser source, while Terrier et al. [23] used a horizontally linear polarized laser source. López-Téllez et al. [24] proposed a method of calculating the phase delay of an LCVR based on the Stokes vector and Muller matrix, and measured the phase delay in the 633 nm band. Research into several other polarization parameters is ongoing.

To the best of our knowledge, all current research has employed lasers as ideal incident light sources to calibrate LCVRs because lasers are monochrome and straight. However, for imaging polarization detection systems based on LCVRs, since the phase delays are directly related to the wavelength of the incident light and the bandwidths are much wider than that of the laser source in every spectral channel, using a laser source for calibration without considering the effect of the practical bandwidth will certainly affect the detection precision of the system. In some cases, the specifics of the phase delays obtained by the laser source in certain bands do not agree with the parameters of the working bands in polarized imaging detection systems based on LCVRs. Thus, in this

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paper, we propose an integrated calibration method using the accurately obtained drive voltage parameters of the laser source to correct the calibration data of a multi-band light source. This method is based on the fact that the drive voltage parameters of the phase delay of the LCVR do not depend on the bandwidth or wavelength of the incident light. This will enable the precise calibration of the phase delay of the LCVR using a multi-band light source. Our method also solves the problem of the laser source wavelength being limited in terms of the phase delay parameters in the working bands of polarized imaging detection systems based on LCVRs.

2. Analyzing the effect of the light source bandwidth on the phase delay calibration of the LCVR

In order to determine the phase delay of an LCVR, we first need to characterize the relationship between the phase delay and corresponding drive voltage at a particular wavelength. Here, calibration by the light intensity calculation formula of the phase delay of the LVCR was carried out using Stokes vectors and the Muller matrix. A tunable argon ion laser (Melles Griot 43 series ion laser) was modulated to output light with 10 different central wavelengths in the visible light band. The output light was suitably monochrome, and the principle of calibration is shown in Fig. 1. Both the polarizer P1 and analyzer P2 are Glen-Taylor prisms (Eachwave MGTYS20) with an extinction ratio of 1:10^5 and a transmitted axis angle of 90°. The LCVR used here is the Meadowlark LRC-200, which is a liquid crystal variable retarder with attached compensator that ensures the phase delay of the LCVR can reach $\leq 0°$. The LCVR was placed between P1 and P2 with a fast axis angle of 45°. The driver, which was controlled by the computer, provided a voltage bar signal of 0–10 V at 2 kHz. The intensity of output light in the band from 400 nm to 1100 nm was acquired by an optical power meter (Newport Power Meter Model 1936-R and Newport 918D-SL-OD3R Silicon Photo detector), and the experimental data was simultaneously acquired and processed using a computer.

While the drive voltage of the LCVR was increased from 0 to 10 V in 0.1 V steps, the corresponding output light intensity was measured. The maximum intensity value is denoted I_{max}. In practice, it is common to use a voltage interval of 0.02 V when acquiring I_{max} because the maximum light intensity may eliminate the errors caused by ambiguity in I_{max}. The phase delay δ corresponding to the different drive voltages can be determined using Eq. (1) once different light intensities I have been obtained.

$$\delta = 2N\pi \pm \arccos\left(\frac{2I}{I_{max}} - 1\right), \quad N = 0, 1, 2, \ldots \tag{1}$$

Since the wavelengths and drive voltages used in the experiment were limited, the phase delay corresponding to all the wavelengths and drive voltages of the LCVR working bands were obtained based on the phase delay characteristics of the measured data at a particular wavelength of the working bands.

The least-square based curve fitting method was employed, and the fitting function was derived from the characteristics of the LCVR and its compensator. The derivation process is described in detail below.

In terms of the voltage, the tilt angle β of the liquid crystal is a function of the voltage, which can be expressed as [19,26]:

$$\beta(V) = \begin{cases} 0, & V \leqslant V_C \\ \frac{\pi}{2} - 2\tan^{-1}\exp\left\{-\left(\frac{V-V_c}{V_0}\right)^M\right\}, & V > V_C \end{cases} \tag{2}$$

where V is the voltage applied to the LCVR, V_C is the threshold voltage under which the molecular axis of the liquid crystal begins to rotate, which can be obtained by experiment, V_0 is a constant, and M is an empirical value. The phase delay of the LCVR can be described by [19]:

$$\delta_L = \frac{B_0 t_0 \sin^2\alpha}{\lambda}, \quad \alpha = \frac{\pi}{2} - \beta \tag{3}$$

where B_0 is the birefringence of the liquid crystal when no voltage is applied, t_0 is the thickness of the liquid crystal, and λ is the wavelength. For a particular wavelength, $B_0 t_0/\lambda$ is constant, and α is the angle between the incident light and the molecular axis of the liquid crystal. According to Eqs. (2) and (3), the final phase delay of the LCVR can be obtained as follows:

$$\delta_L = \frac{B_0 t_0}{\lambda} \times \frac{4}{\left[\exp\left\{-\left(\frac{V-V_c}{V_0}\right)^M\right\} + \frac{1}{\exp\left\{-\left(\frac{V-V_c}{V_0}\right)^M\right\}}\right]^2} \tag{4}$$

Since an LCVR with compensator is studied in this paper, the phase delay of the compensator must also be considered. An expression that describes the phase delay of the compensator is shown in Eq. (5), where B_C and t_C are the birefringence and thickness of the compensator, respectively.

$$\delta_C = \frac{B_C t_C}{\lambda} \tag{5}$$

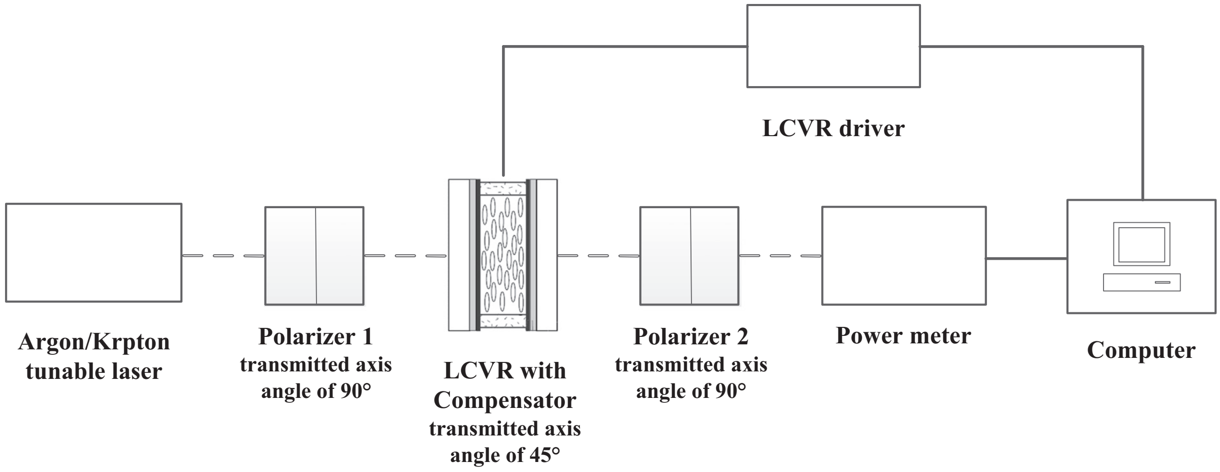

Fig. 1. The principle of calibration.