New Method for Obtaining Full-Stokes Parameters of High-Spectral Polarization Imaging System

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Abstract Taking into account of the slow measuring speed, low measuring accuracy and complex system structure of the existing Stokes parameters acquisition method, a new acquisition method of full-Stokes parameters in double Liquid Crystal Variable Retarder (LCVR) and Acousto-Optical Tunable Filter (AOTF) combining spectral polarization imaging system is established. Based on the working principle of AOTF and LCVR, this paper has explored the basic detection principles of the system before a new method for fast acquisition of full-Stokes parameters is proposed. According to polarization analysis, fixed control voltage is selected as the basis, in which four fixed voltages are selected as the control voltages of LCVR, and two identical LCVR are controlled at the same time to complete phase modulation of optical waves. The Stokes parameters can be obtained with four groups of phase delay which are plunging the same. Besides, a LCVR controller is designed to stabilize the output square wave whose root mean square is 0 to ±8.72 V. Then, its calibration is carried out in order to realize precise modulation of different optical waves. Finally, an experimental prototype is set up to test the target, with three polarizing plates P₁, P₂ and P₃ whose polarization directions being 0°, 90° and 45° respectively as the targets of polarization measurement. The full-Stokes parameter figures with a wavelength of 632 nm is obtained; paper painted with red, green and blue lines and the angle of 30 degrees are used as the target of spectral measurement, spectral imaging on 71 channels of 400~750 nm spectral range (spectral bandwidth of 5 nm), the spectrum curves of red, green, blue are acquired which accordant with their theoretical spectral graphs. The results show that not only all the Stokes parameters can be obtained quickly and accurately with the system, but also the structure of system is simplified and the imaging quality is improved.

Keywords High-spectral polarization imaging; Full-Stokes parameters; Double LCVR; AOTF; LCVR controller

Introduction

Spectral polarization imaging is an organic combination of spectral analysis technology, polarization measurement technology and space imaging technology, which can obtain the spectral information, polarization information and image information of the object simultaneously. Besides, being helpful to improve the detection and recognition ability of target effectively, it is widely used in medical imaging, environ-

Received, 2016-05-04; accepted, 2016-10-29

Foundation item: National Natural Science Foundation for Special of China(61127015), International Science and Technology Cooperative Project (2013DFR10150), Science and Technology Research Fund for Youth of Shanxi(2014021012)

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mental monitoring, military identification, deep space exploration and other fields. In terms of polarization imaging systems, the Stokes vector method does not limit the spectral range, and contains almost all the shapes of beams in nature\textsuperscript{[13-15]}, moreover, it can describe both full polarized light and partial polarized light as well as non-polarized light. Therefore, Stokes vector method is widely used as a macroscopic and measurable description method.

In recent years, the N. Gupta group of U. S. Army Research Laboratory proposed an acquisition method of Stokes parameters of high spectral polarization imaging system\textsuperscript{[16-19]}. This method requires constant replacement of the drive voltage to achieve the same phase delay at different wavelengths, which prolongs the measurement time, and reduces the measurement accuracy\textsuperscript{[16]}. In 2015, a method based on an Acousto-Optic Tunable Filter (AOTF) and a Liquid Crystal Variable Retarder (LCVR)\textsuperscript{[16-18]} is proposed. However, this method has the same problem as that of N. Gupta group. In fact, the use of two CCD for AOTF 1 diffraction imaging increases the complexity of system construction greatly\textsuperscript{[16]}.

Based on the previous studies, a fast acquisition method for all Stokes parameters of hyperspectral polarization imaging systems is proposed referring to two LCVR and one AOTF. Four driving voltage is chosen as reference to control two identical LCVR simultaneously, obtaining full-Stokes parameters through four sets of polarization image. Besides, a CCD camera is applied to detect the +1 diffraction light of AOTF, which can not only overcomes the existing defects of the system, but also improves the imaging quality further.

1 Basic Principle

1.1 The Principle of AOTF

AOTF is an electrically tunable filter based on the interaction of acoustic wave with light wave. When the incident light-wave and the ultrasonic wave are suitable for the momentum-matching, the incident light will be diffracted\textsuperscript{[19-20]}, and the corresponding length of the diffracted light wave \( \lambda_0 \) can be expressed as

\[
\lambda_0 = \frac{V_c}{f_s} \sqrt{n_i^2 + n_s^2 - 2n_in_s \cos(\theta_0 - \theta_s) - n_s^2}
\]

in which, \( V_c \) is the speed of sound, \( f_s \) is frequency of sound wave, \( \theta_0 \) and \( \theta_s \) are the polar angles of incident light and diffracted light, respectively, \( n_i \) and \( n_s \) are the refractive index of incident light and diffracted light, respectively.

1.2 The Principle of LCVR

LCVR is an optical phase retarder based on the electrically controlled birefringence of liquid crystal. The refractive index of liquid crystal molecules is controlled by changing the voltage that is loaded on both ends of the liquid crystal, then the phase delay of the incident light is adjusted continuously, and finally different polarization states can be detected. The relationship between the voltage applied to the liquid crystal electrode and the tilt angle of the liquid crystal molecule is\textsuperscript{[21-22]}

\[
\theta = \begin{cases} \frac{\pi}{2} - 2\arctan \left( \frac{U - U_0}{U_0} \right) & (U \leq U_0) \\ \pi - \frac{\pi}{2} - 2\arctan \left( \frac{U - U_0}{U_0} \right) & (U > U_0) \end{cases}
\]

in which, \( U_0 \) is the threshold voltage, \( U \) is the corresponding voltage of a liquid crystal molecule to a specific angle. We can know that, when the applied voltage is less than or equal to the threshold voltage, the tilt angle of the liquid crystal molecules is \( \theta_0 \), when the applied voltage is greater than the threshold voltage, the tilt angle of the liquid crystal molecules is \( \theta \), the specific function relationship between deflection angle and the applied voltage is given in\textsuperscript{[16]}

When the light passed through a phase retarder with a thickness of \( d \), the phase delay is

\[
\delta = \frac{2\pi(n_e \sin \theta - n_i) d}{\lambda} = \frac{2\pi(n_e - n_i) d}{\lambda} \cos^2 \theta
\]

\( n_i \) and \( n_e \) is the reflection rate of 0 light and \( e \) light, respectively, and \( \lambda \) is wavelength.

According to equation (3), it is found that the phase delay \( \delta \) is related to the deflection angle \( \theta \), and equation (2) shows that the deflection angle \( \theta \) is related to the voltage \( U \) applied to the LCVR. In conclusion, the phase-modulation of the incident light wave can be realized by changing the voltage that is loaded on the LCVR.

2 Hyperspectral Polarization Imaging System

2.1 Fundamentals of System Detection

The principle of hyperspectral polarization imaging system based on dual-LCVRs and AOTF is shown in figure 1. The polarization direction of the polarizer \( P_1 \) is the reference direction of 0°, the fast axis direction of LCVR1 and LCVR2 are 90° and -45°, respectively, the polarization direction of the polarizer \( P_2 \) and \( P_3 \) placed on the both sides of AOTF are perpendicular to each other, which can effectively eliminate the influence of grade 0 and grade -1 diffraction light. The target light passed through the pre-optical system, LCVR1, LCVR2 and AOTF, and then imaged on the CCD camera. During the operation of the whole system, we used personal computer to control the light of dual-LCVRs and AOTF, and finally achieved the polarization imaging of the target.
2.2 Acquisition Method of Full-Stokes Parameters

According to the Stokes parameter representation method referred in [17], combining with the detection principle of the above system, the corresponding Stokes parameter $\mathbf{S}'$ of measured target light ejected by dual-LCVRs and AOTF is

$$
\mathbf{S}'(\lambda) = \begin{bmatrix}
S'_x(\lambda) \\
S'_y(\lambda) \\
S'_z(\lambda)
\end{bmatrix} = 
\begin{bmatrix}
1 \cos\delta_2 \sin\theta_2 \sin\omega_2 - \sin\delta_2 \cos\omega_2 \\
1 \cos\delta_2 \sin\theta_2 \sin\omega_2 + \sin\delta_2 \cos\omega_2 \\
0 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
S_0(\lambda) \\
S_1(\lambda) \\
S_2(\lambda) \\
S_3(\lambda)
\end{bmatrix}
$$

In the experiment, two identical full-wave LCVR are used, according to the conclusion of (2) and (3), it is found that when the voltage is the same, the theoretical value of the phase delay produced by the dual-LCVRs is also the same, so whenever the dual-LCVRs loads a driving voltages, we can get two phase delay of the same kind. During the experiment, four sets of same phase delay $\delta_i (i=1, 2, 3, 4)$ can be obtained by changing the driving voltage of the dual-LCVRs, so (4) can be expressed as

$$
\begin{bmatrix}
S_0(\lambda) \\
S_1(\lambda) \\
S_2(\lambda) \\
S_3(\lambda)
\end{bmatrix} = 
\begin{bmatrix}
1 \cos\delta_i \sin\theta_2 \sin\omega_2 - \sin\delta_2 \cos\omega_2 \\
1 \cos\delta_i \sin\theta_2 \sin\omega_2 + \sin\delta_2 \cos\omega_2 \\
0 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
S_0(\lambda) \\
S_1(\lambda) \\
S_2(\lambda) \\
S_3(\lambda)
\end{bmatrix}
$$

$$
\delta_i (i=1, 2, 3, 4) \text{ is phase delay, subscript } i \text{ is the number of drive voltage groups, } I_i \sim I_4 \text{ are the intensity of the collected images, respectively, according to (5) the following can be obtained}
$$

$$
\mathbf{S} = \mathbf{M}^{-1} \mathbf{I}
$$

where

$$
\eta_i = (\cos\delta_i - \cos\delta_0) \sin\theta \sin\omega_0 + \cos\delta_0 \sin\theta_0 \sin\omega_0 + (\cos\delta_i - \cos\delta_0) \sin\theta \cos\omega_0 + (\cos\delta_0 \sin\theta \cos\omega_0)
$$

$$
\eta = (\cos\delta - \cos\delta_0) \sin\theta \sin\omega_0 + \cos\delta_0 \sin\theta_0 \sin\omega_0 + (\cos\delta - \cos\delta_0) \sin\theta \cos\omega_0 + (\cos\delta_0 \sin\theta \cos\omega_0)
$$

$$
\eta_i = (\cos\delta_i - \cos\delta_0) \sin\theta \sin\omega_0 + \cos\delta_0 \sin\theta_0 \sin\omega_0 + (\cos\delta_i - \cos\delta_0) \sin\theta \cos\omega_0 + (\cos\delta_0 \sin\theta \cos\omega_0)
$$

$$
\eta = (\cos\delta - \cos\delta_0) \sin\theta \sin\omega_0 + \cos\delta_0 \sin\theta_0 \sin\omega_0 + (\cos\delta - \cos\delta_0) \sin\theta \cos\omega_0 + (\cos\delta_0 \sin\theta \cos\omega_0)
$$

2.3 LCVR Controller

In order to achieve the continuous adjustment of LCVR phase delay, a LCVR controller is designed as shown in figure 2, the MCU is used as the core processing unit, the serial devices is used to achieve the communication of host computer and slave computer. LabVIEW sent the voltage signal to the MCU, then the MCU read the digital signal transferred from
the host computer, and transmitted the signal to the bipolar output module of DAC, the operational amplifier voltage are output to dual-LCVRs, and realized the accurate phase delay finally.

![Fig. 2 Structure of LCVR control power](image)

The DAC applied is AD7541 which has 12 data bits, with the resolution of $1/2^{12} - 1 = 2.44 \times 10^{-1}$ and an accuracy of 0.02 for LCVR. Above all it can meet the design requirements of high precision. Through experimental debugging, the controller can achieve continuous and adjustable DC output, and the amplitude range is from 0 to +8.72 V. When the driving voltage of LCVR is greater than 6 V, the phase delay changes slowly and converges to a non-zero minimum, so that the controller can meet the control voltage requirement of LCVR.

3 Experiments and Analysis

3.1 Calibration Experiment of LCVR

In order to improve the accuracy of the experiment, the LCVR scaling experiment has been carried out. LCVR is LCC1221-A produced with THORLABS company (wavelength range from 550 to 700 nm), the experiment platform is shown in figure 3.

![Fig. 3 LCVR calibration device platform](image)

By using the light-intensity method, 0.5 V as the step size of control voltage, the corresponding curve of the phase delay $\delta$ and the control voltage $U$ is shown in figure 4 (a).

After wards, the control voltage is set to 1, 2, 3 and 4 V, and the phase delay of different wavelengths under the same voltage is obtained. Finally, the relation curves of different wavelengths and phase delay under different voltages are obtained, as shown in figure 4 (b).

3.2 Spectroscopic polarization imaging experiment

The experimental prototype of spectral polarization imaging experiments were performed according to figure 1. LCVR1 and LCVR2 are the same two LCC113-A LCD full wave retarder. AOTF is LGDN-3Z filter developed by 26th Research Institute of Electronic Science and Technology. CCD is DH-HV 035051 developed by Daheng Imaging, polarizer is LPVISE100-A from Thorlabs.

![Fig. 4 Calibration curve](image)

(a), Phase delay-voltage relationship curve; (b), Phase delay-wavelength relationship curve

The target to be measured is shown in the figure 5(a), three polarizing plates $P_1$, $P_2$ and $P_3$ whose polarization directions are respectively $0^\circ$, $90^\circ$ and $45^\circ$ are used as the targets of polarization measurement, paper painted with red, green and blue lines and the angle between which are $30^\circ$ are used as the target of spectral measurement, so that we can obtain the polarization information and the spectral information simultaneously. The diffraction wavelength of AOTF is $\lambda = 632$ nm, and four different driving voltages are successively loaded at both ends of the LCVR1 and LCVR2, and the Stokes parameter maps of the target are obtained, as shown in figure 5 (b-c).

Since $S_i$ is the total light intensity of the target, all the regions in figure 5(b) are brighter and the brightness is uniform. $S_i$ indicates the intensity difference between the polarization components of the light in the $0^\circ$ and $90^\circ$ directions, so that $P_1$ is the brightest in figure 5 (c), and $P_2$ is the darkest.
$S_i$ is the intensity difference between the polarization components of the light in the 45° and −45° directions, so $P_i$ is the brightest in figure 5 (d), and the rest of the region is dark. $S_i$ indicates the circularly polarized component of light, and because the experiment only tests the linear polarizer, so all regions in figure 5 (e) are dark. Besides, because the diffraction wavelength of AOTF is 632 nm, which is closest to the wavelength range of red light, the red line is the brightest.

![Fig. 5 Figures of different parameters](image)

(a): The measured target; (b)–(e): Stokes parameter map obtained when $\lambda$ = 632 nm

Spectral imaging experiments were performed on the system with spectrum range from 400 to 750 nm, scanning interval of AOTF is 5nm. The four regions red A, green B, blue C and background D marked in figure 5 (a) are the average imaging targets, and the spectral diagram is shown in figure 6. In order to eliminate the influence of local spots of light and dark of CCD imaging, spectral curve is taken as regional average results. From the figure, in the wavelength range of 450 to 490 nm, the strength of blue (area C) is the strongest; in the wavelength range of 500 to 580 nm, the strength of green (area B) is the strongest; at wavelengths greater than 600 nm, the strength of red (area A) is the strongest, which is consistent with the analytical spectrum of red, green, and blue. It is proved that the system can realize the spectral imaging of different bands.

![Fig. 6 Spectral curve of partial band](image)

4 Conclusion

In this paper, a new method is proposed to obtain full-Stokes parameter of high spectral polarization imaging system with dual-LCVRs and AOTF. Meanwhile, the system structure is introduced and the mechanism of the method is explored. What’s more, a phase modulation controller is designed to control the LCVR, building a prototype of the spectral polarization imaging system. With the accurate calibration of LCVR controller, the full-Stokes parameter figure is obtained, getting spectral imaging with spectral range from 400 to 750 nm (spectral bandwidth is 5 nm). The results show that this kind of full-Stokes parameter acquisition method with simple structure and high imaging resolution can provide new theoretical and experimental reference for hyperspectral polarization imaging technology.

References

高光谱偏振成像全 Stokes 参量获取新方法

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摘要 考虑到现有 Stokes 参量获取方法测量速度慢、测量精度低、系统结构复杂等特点，提出了一种基于双液晶可调相位延迟器(liquid crystal variable retarder，LCVR)和声光可调滤波器(acousto-optic tunable filter，AOTF)的光谱偏振成像系统中全 Stokes 参量的新获取方法。从 AOTF 和 LCVR 的工作原理出发，介绍了系统的基本探测原理；根据偏振分析提出了快速获取全 Stokes 参量的新方法——该方法选取四个固定的 LCVR 控制电压，同时控制两个相同的 LCVR 对光波进行相同调制，得到四组(八个)两两相同的相位延迟即可求得 Stokes 参量。此外，设计了能够稳定输出均匀为 $0 \pm 8.72 \text{ V}$ 连续可调方波的 LCVR 控制器，并对其进行定标，实现了不同波长下的精确调制。搭建实验样机，以偏振方向分别为 $0^\circ$, $90^\circ$ 和 $45^\circ$ 的三个偏振片 $P_1, P_2, P_3$ 作为偏振测量目标。测得了波长为 $632 \text{ nm}$ 时的全 Stokes 参量图；以画有夹角为 $30^\circ$ 的红色、绿色、蓝色三色线条的实验板作为光谱测量目标，对 $400 \sim 750 \text{ nm}$ 光谱范围的 71 个通道(光谱带宽为 $5 \text{ nm}$)进行光谱成像，得到了与红色、绿色和蓝色的分析谱段范围相一致的光谱曲线。结果表明，该系统不仅可以快速准确地获取全部 Stokes 参量，而且系统结构简单、成像质量良好。

关键词 高光谱偏振成像；全 Stokes 参量；双 LCVR；AOTF；LCVR 控制器

（收稿日期：2016-05-04，修订日期：2016-10-29）

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