Retardagraphy: A novel technique for optical recording of the retardance pattern of an optical anisotropic object on a polarization-sensitive film using a single beam

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A technique that employs a single laser beam is proposed for recording the retardance of an optical anisotropic object. The retardance pattern is converted into a polarization pattern using a quarter-wave plate and recorded on a polarization-sensitive medium. The recording medium is illuminated by homogeneous polarized light, and the light transmitted by the recording medium is analyzed to reconstruct the recorded retardance pattern.

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A novel optical recording technique, Retardagraphy, is proposed in this paper. In retardagraphy, the retardance pattern of an optical anisotropic object is recorded on a polarization-sensitive medium. The absolute values of the recorded information (retardance pattern) can be reconstructed using retardagraphy, whereas it is difficult to record and reconstruct the absolute values of the retardance pattern using other techniques like polarization holography[1, 2] or conventional holography. Retardagraphy is expected to be applicable to pattern matching between optical anisotropic objects. Furthermore, retardagraphy can be applied for optical data storage using a single laser beam when a variable optical anisotropic object such as a liquid crystal spatial light modulator (SLM) is used as the information source. In this study, the principle of retardagraphy and an experimental verification of the principle are reported.

In our recording technique, the retardance pattern is recorded on a polarization-sensitive medium as an optical anisotropy. Since retardance modulates the polarization state of the incident laser beam, the retardance pattern is transmitted as the phase difference between the two polarization components of the modulated laser beam as shown in fig. 1. In this study, the retardance pattern of a linear birefringent object is converted into a linear polarization pattern and recorded on a polarization-sensitive medium as the azimuth of the linear polarization.

The horizontal and vertical polarization states are composed of both signal and reference components. The phase of the signal component relative to that of the reference component is modulated by the linear birefringent object. The schematic for recording and reconstruction is shown in fig. 2. The relative amplitude and phase between the signal and reference components are set to 1 and Φ, respectively, using a half-wave plate and a variable retarder. Then, the Jones vector $\boldsymbol{J}_1$ of the recording polarization state is represented by

$$\boldsymbol{J}_1 = \frac{1}{\sqrt{2}} \begin{bmatrix} \exp\left[\mathrm{i}\left(\Phi + \Phi_0\right)\right] \\ 1 \end{bmatrix}, \tag{1}$$

where Φ_0 is an initial relative phase caused by the initial retardation of the recording laser beam. The polarization state of $\boldsymbol{J}_1$ is transformed into an elliptical polarization with an azimuth of 45° or −45°. Most polarization-sensitive media are sensitive to linear polarization. Therefore, it is convenient to transform the elliptical polarization state into a linear polarization state using a quarter-wave plate with a fast axis of 45°. This linear polarization, a transformation of the elliptical polarization, is expressed as follows:

$$\begin{aligned} \boldsymbol{J}_2 =& R\left(-\frac{\pi}{4}\right) \begin{bmatrix} 1 & 0 \\ 0 & -\mathrm{i} \end{bmatrix} R\left(\frac{\pi}{4}\right) \boldsymbol{J}_1 \\ =& \exp\left(\mathrm{i}\frac{\Phi + \Phi_0}{2}\right) R\left(\frac{\Phi + \Phi_0}{2} - \frac{\pi}{4}\right) \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \end{aligned} \tag{2}$$

where R is a rotator expressed as

$$R(\theta) = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}. \tag{3}$$

As shown in eq. (2), the azimuth of the linear polarization α becomes

$$\alpha = -\frac{\Phi + \Phi_0}{2} + \frac{\pi}{4}. \tag{4}$$

When the linearly polarized laser beam illuminates the polarization-sensitive medium, the

Jones matrix M of the birefringent medium is expressed as follows:

$$M(\Phi, \Delta\phi) = R(-\alpha) \begin{bmatrix} 1 & 0 \\ 0 & \exp(-\mathrm{i}\Delta\phi) \end{bmatrix} R(\alpha), \tag{5}$$

where $\Delta\phi$ is the retardance of the photoinduced birefringence, which is independent of the retardance pattern Φ. The principal axis α of the photoinduced birefringence corresponds to the retardance pattern. The recorded retardance pattern Φ is reconstructed by a left-circularly polarized laser beam. The reference component of the left-circularly polarized beam is same as the reference component of the recording beam. When the medium whose retardance is being recorded is illuminated by the reconstructed beam, the reconstructed beam is elliptically polarized by the photoinduced birefringence. The Jones vector $\boldsymbol{J}_3$ of the reconstructed beam from the medium is expressed as follows:

$$\begin{aligned} \boldsymbol{J}_3 =& M(\Phi, \Delta\phi) \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -\mathrm{i} \end{bmatrix} \\ =& \mathrm{i} \exp\left[-\mathrm{i}\left(\alpha + \frac{\Delta\phi}{2}\right)\right] R\left(-\alpha + \frac{\pi}{4}\right) \begin{bmatrix} \cos\epsilon \\ \mathrm{i}\sin\epsilon \end{bmatrix}, \end{aligned} \tag{6}$$

$$\epsilon = \frac{\Delta\phi}{2} - \frac{\pi}{4}. \tag{7}$$

The transformation of polarization from left-circular polarization into an elliptical polarization is equivalent to generating a right-circular polarization component, since a polarization state can be expressed by right- and left-circular polarization components. In order to separate the laser beam transmitted through the medium into signal and reference components, the two orthogonal circular polarization components are conveniently transformed to two orthogonal linear polarization components. The polarization state of the beam transmitted through the medium is transformed by a quarter-wave plate with a fast axis, in the following manner:

$$\begin{aligned}
\boldsymbol{J}_4 =& R(-\varphi)\begin{bmatrix} 1 & 0 \\ 0 & -\mathrm{i} \end{bmatrix} R(\varphi)\,\boldsymbol{J}_3 \\
=& R\left(-\varphi-\frac{\pi}{4}\right) A \begin{bmatrix} -B\exp\left[\mathrm{i}(\Phi+\Phi_0+2\varphi)\right] \\ 1 \end{bmatrix},
\end{aligned} \tag{8}$$

$$A = -\,\mathrm{i}\cos\left(\frac{\Delta\phi}{2}\right)\exp\left[-\mathrm{i}\left(\frac{\Delta\phi}{2}+\frac{\pi}{4}+\varphi\right)\right], \tag{9}$$

$$B = \tan\left(\frac{\Delta\phi}{2}\right). \tag{10}$$

If $\varphi = -\pi/2$, eq. (8) can be written as

$$\boldsymbol{J}_4 = R\left(\frac{\pi}{4}\right) A \begin{bmatrix} B\exp\left[\mathrm{i}(\Phi+\Phi_0)\right] \\ 1 \end{bmatrix}. \tag{11}$$

As shown in the above equation, the retardance pattern is reconstructed as a linear polarization component with an azimuth of $-45°$. When a linear polarizer with a transmission axis of $-45°$ is used, only the reconstructed signal component is extracted. However, the retardance pattern cannot be directly observed by ordinary photo-detection devices. The phase-shifting method is employed for effective extraction of the retardance pattern. The relative phase between the signal and reference components is shifted using a variable polarization retarder, and these components are superimposed using a polarizer with a transmission axis ϑ. As a result, the magnitude I of the Jones vector $\boldsymbol{J}_5$ can be derived from a photo-detection device as follows:

$$I(\vartheta) = |\boldsymbol{J}_5|^2 = \left| R(-\vartheta) \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} R(\vartheta) \boldsymbol{J}_4 \right|^2$$

$$= A^2 \left[\cos^2\vartheta' B^2 + \sin^2\vartheta' + 2B \sin\vartheta' \cos\vartheta' \cos\left(\Phi + \Phi_0 - \Delta\phi_\mathrm{s}\right)\right], \tag{12}$$

$$\vartheta' = \vartheta - \frac{\pi}{4}. \tag{13}$$

Finally, using the values of I that are calculated for $\Delta\phi_\mathrm{s} = 0$, $\pi/2$, π, and $3\pi/2$, the retardance pattern is extracted as follows:

$$\Phi = \tan^{-1}\left[\frac{I(\pi/2) - I(3\pi/2)}{I(0) - I(\pi)}\right] - \Phi_0. \tag{14}$$

Figure 3 shows the experimental setup used to verify the principle described above. An SLM (LCOS-SLM; Hamamatsu X10408-3) was used as the anisotropic object. The retardance of the SLM was recorded on a polarization-sensitive film made of azobenzene copolymer using a diode laser beam (407 nm). The polarization-sensitive material had been developed as part of our previous research.[3] The film thickness was approximately 800 nm. The polarization azimuth was adjusted using a half-wave plate so that the polarization state was elliptic with an azimuth of 45° or −45°. The elliptical polarization pattern was transformed into a linear polarization pattern with the azimuth corresponding to the retardance pattern of the SLM. The retardance pattern was projected on the azobenzene film in a reducing optical system. The recording beam intensity at the front of the film was ∼200 mW/cm^2. The irradiation time for information recording was set to 1 min.

The retardance pattern was reconstructed using a HeNe laser beam (632.8 nm). The reconstructed beam was left-circularly polarized using a half-wave plate and a quarter-wave plate. The reconstructed beam transmitted through the azobenzene film was analyzed by the phase-shifting method, and the retardance pattern was extracted. The extracted pattern was captured by a CCD (charge-coupled device) camera.

The recorded and the reconstructed retardance pattern are shown in fig. 4. The recorded pattern was expressed using 8 retardance value intervals in the range of 0-360°. The reconstructed retardance pattern is shown in fig. 4. It was observed that the reconstructed retardance pattern had some errors. Although the recording pattern was fully extracted, a few errors were detected in the reconstructed retardance pattern. These errors are not intrinsic to the procedure, but are caused by the general imprecision of the practical optical equipment.

In conclusion, a retardance recording technique, which we titled Retardagraphy, was proposed, and the principle underlying this technique was experimentally verified. In this paper, the retardance pattern between the horizontal and vertical polarization components was converted into the retardance pattern between the orthogonal and circular polarization components and recorded on a polarization-sensitive medium. In principle, an arbitrary combination of polarization components can be selected and suitably converted to match the properties of the polarization-sensitive medium. We are confident of the applications of retardagraphy in the analysis of optical anisotropic structures and recording of optical information.

References

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Figure captions

Fig. 1: Example of polarization modulation. (a) and (b) show the coordinates of polarization state and the modulated phase difference between horizontal and vertical polarization components of an elliptical polarization state, respectively.

Fig. 2: A schematic of (a) recording and (b) reconstruction. The direction propagation of the laser beams is defined as the z-axis; HWP, QWP, LBO, VR, P, and PD represent the half-wave plate, quarter-wave plate, linear birefringent object, variable retarder, polarizer, and photo-detector, respectively.

Fig. 3: Experimental setup for retardance recording. HWP, QWP, BM, M, DM, SCF, VR, P, and CCD are the half-wave plate, a quarter-wave plate, beam expander, a mirror, a dielectric mirror, lenses, sharp-cut filter, variable retarder, and CCD camera, respectively. A sharp-cup filter is used to block the recording laser (407 nm).

Fig. 4: Experimental results. (a) and (b) are two-dimensional retardance pattern on the LCOS-SLM and observed reconstructed retardance pattern, respectively.

Figures

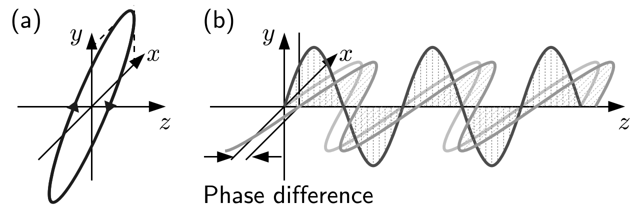

Fig. 1.

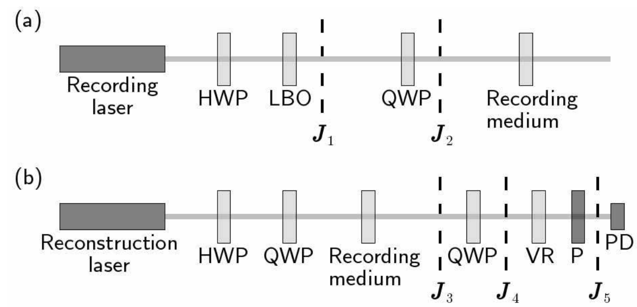
(a)
Recording laser
HWP
LBO
J_1
QWP
J_2
Recording medium
(b)
Reconstruction laser
HWP
QWP
Recording medium
J_3
QWP
J_4
VR
P
J_5
PD

Fig. 2.

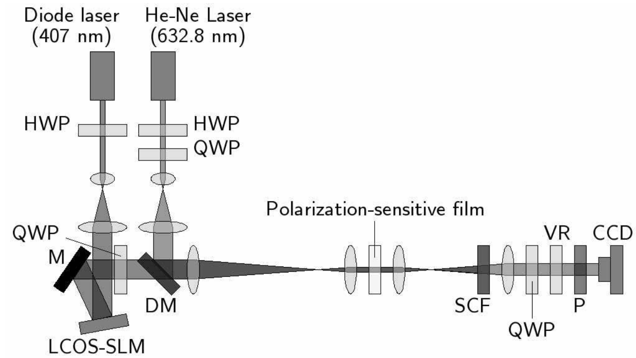
Diode laser
(407 nm)
He-Ne Laser
(632.8 nm)
HWP
HWP
QWP
Polarization-sensitive film
QWP
M
VR
CCD
DM
SCF
P
QWP
LCOS-SLM

Fig. 3.

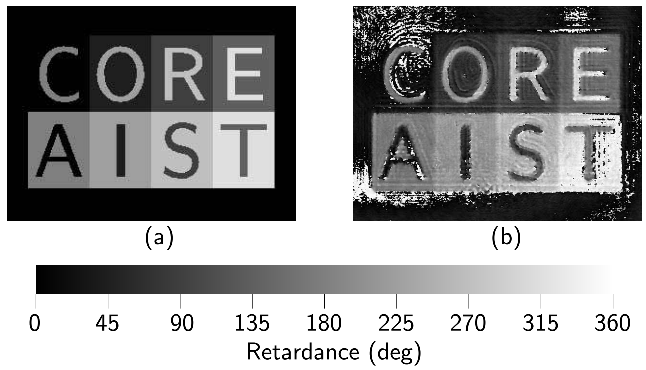
CORE
AIST
(a)
CORE
AIST
(b)
0
45
90
135
180
225
270
315
360
Retardance (deg)

Fig. 4.