Optical Fourier processing using photoinduced dichroism in a bacteriorhodopsin film

Joby Joseph, F. J. Aranda, and D. V. G. L. N. Rao

Department of Physics, University of Massachusetts, Boston, Massachusetts 02125

J. A. Akkara and M. Nakashima

U.S. Army Natick Research, Development and Engineering Center, Natick, Massachusetts 01760

Received May 1, 1996

The photoinduced dichroism in bacteriorhodopsin films has been investigated in view of its application for optical Fourier processing. A simple optical system for Fourier processing is demonstrated that does not require precise alignment and vibration isolation. The basic principle of operation relies on the intensity dependence of photoinduced dichroism in a bacteriorhodopsin film. Experimental results with Fourier processing are shown for edge enhancement.

The optical Fourier transform is a powerful tool in optical computing and processing systems.[1,2] Use of nonlinear-optical materials for the implementation of Fourier-transform operations such as edge enhancement, bandpass filtering, noise removal, and pattern recognition[3,4] is well established. The parallel-processing nature of optics and the real-time characteristics of many nonlinear-optical materials contribute to the importance of optical Fourier processing with nonlinear materials. Photorefractive materials are currently popular as the nonlinear media for implementation of optical Fourier-transform systems.[3,5] Recently the biological molecule of bacteriorhodopsin has shown great promise as a nonlinear material for optical computing and processing.[6] Bacteriorhodopsin (bR) shows many intrinsic optical and physical properties for use as a real-time spatial light modulator[7,8] and also as an optical storage medium.[9] The useful optical properties include photochromism, third-order optical nonlinearity, and photoinduced anisotropy. These properties have been used by many researchers to implement applications such as pattern recognition, image subtraction and addition,[4,10] spatial filtering,[7] optical logic gates,[11] interferometry, holographic correlation, and image transmission with phase conjugation.[12] The spatial filtering performed by Thoma *et al.*[7] involves a control beam that precisely manipulates spatial frequencies at the Fourier plane. Imam *et al.*[13] recently demonstrated an incoherent-to-coherent converter, using the photoinduced anisotropic properties of bR thin films. The logarithmic transmission characteristics of bR films were used by Downie[14] to implement optical image processing. Recently Takei and Shimizu[15] used the photoinduced refractive-index change of bR for spatial light modulation.

We propose the use of photoinduced anisotropy in a bR film for achieving a real-time, self-adaptive spatial filtering system for optical Fourier processing, with the experimental demonstration of edge enhancement. The photoinduced anisotropy of bR films depends on the intensities of the illuminating beams. The incoherent-to-coherent converter scheme of Imam *et al.*[13] uses the photoinduced anisotropy that is due to an actinic beam. We have noticed that at an optimum constant actinic beam intensity the photoinduced dichroism and the resultant polarization rotation of a probe beam show a useful intensity dependence. The proposed system exploits the observed intensity dependence of photoanisotropy in a bR film for Fourier-processing applications. The advantages of this system are simplicity and ease of operation, with no requirement for precise alignment at the Fourier plane, vibration isolation, or coherent light. The conventional spatial-filtering technique[1] with selective masking of Fourier frequencies has the disadvantages of a lack of real-time operation because of the precise alignment needed for masking some spatial frequencies and the need for preparing masks in accordance with the input object information. Also, in many real-time Fourier-processing schemes that use the dynamic recording nature of photorefractive crystals and other nonlinear materials including bR,[7] precise alignment of control beams is required for spatial filtering.[5] In the present scheme the constraint of alignment at the Fourier plane is completely avoided. The filtering operation is accomplished through a process in which the input information has a single linear polarization but the output after the Fourier transformation automatically contains a range of linearly polarized light of various orientations that correspond to different spatial-frequency components of the object. This permits the use of an analyzer after an inverse Fourier transformation for polarization filtering, which in turn produces a spatial-filtering operation.

The utility of bR in optical image processing and related applications is based on the fact the absorption of light triggers a photochemical cycle in the bR molecule with a complex series of intermediate steps.[16] The initial B state of bR has an absorption peak at 570 nm, and the long-lived M state has an absorption peak at 412 nm. The lifetime of the M

0146-9592/96/181499-03$10.00/0

state can be altered by several orders of magnitude, milliseconds, by a reprotonation process. The most relevant states for our experiments in the bR photocycle are the B and M states. Illumination of bR film at a wavelength near 570 nm leads to the transition of molecules to the M state, reducing the absorption coefficient of the film at that wavelength, and these molecules are bleached. On illumination with a linearly polarized light (actinic beam), the film shows anisotropic properties of photoinduced dichroism and photoinduced birefringence.[17] The occurrence of photoinduced anisotropy in a bR film is an effect of the photosensitive bleaching of the bR molecules on light illumination. Because the actinic light is linearly polarized and the bR molecules in the film are randomly oriented, only those bR molecules oriented with their transition dipole moments for absorption in or near the electric field direction of the light are bleached.

When the wavelength of actinic light is ~570 nm, induced dichroism predominates overinduced birefringence. The presence of dichroism on actinic light illumination can produce a rotation of the plane of polarization of a probe beam passing through the dichroic parts of the film. This actinic-light-induced angular rotation of a probe beam's polarization and its dependence on probe beam intensity as explained below are the basic principles employed for the Fourier processing described here.

The bR film used in the present experiment was purchased from Wacker Chemical, Inc. It has a thickness of ~35 μm and an optical density of 0.47. All the experiments are performed at a 570-nm wavelength from an Ar–Kr laser (Coherent Innova 70 Spectrum). The dichroism in the bR film was induced by an actinic beam at the same wavelength as that of the probe beam. Both beams were derived from the same laser, and the difference in their path lengths was maintained at more than the coherence length of the laser. The plane of polarization of the actinic beam was oriented at 45° with respect to the probe beam. The actinic beam induces dichrosim in the bR film. The probe beam, as it passes through the now dichroic bR film, undergoes polarization rotation. The magnitude of rotation depends on the intensities of both actinic and probe beams. We measured this angular rotation by adjusting an analyzer. At first we measured the dependence of this induced angular rotation of probe beam polarization as a function of the intensity of the actinic light beam, using a weak probe beam so that it would not contribute to the photoinduced dichroism. The photoinduced angular rotation of the probe beam polarization reached a maximum for an optimum actinic beam intensity of ~10 mW/cm^2 and decreased with a further increase in the actinic beam intensity. Similar behavior was observed by Burykin *et al.*[17] for photoinduced dichroism, as expected. Then, keeping the actinic beam intensity near 10 mW/cm^2, where the angle of rotation and hence the corresponding dichroism is maximum, we gradually increased the intensity of the probe beam. Figure 1 shows the experimental data on the degree of rotation of probe beam polarization as a function of probe beam intensity under constant actinic beam intensity of 10 mW/cm^2. In our experiment the analyzer was mounted upon a rotation stage with a minimum detectable angular rotation of 0.1°. As the system is highly sensitive to changes in probe intensity, a more accurate rotation stage could be used. The effect of increasing the probe beam intensity is to decrease the degree of polarization rotation of the probe beam because high probe intensities reduce the anisotropy of the bR film. With high intensities of ~10 mW/cm^2 for the probe beam, the angular rotation experienced by the probe beam polarization is nearly zero. The result from Fig. 1 that increasing the probe beam's intensity reduces the angle of rotation of the probe beam passing through the BR under the influence of actinic light can be exploited effectively for optical Fourier processing.

Figure 2 is a schematic of the optical Fourier-processing system employing photoinduced dichroism in bR film. Lens L1 forms the Fourier transform of the object information (O) at the BR film (BR), and lens L2 forms the inverse Fourier transform at the CCD plane to yield the processed image. The actinic beam illuminates the bR film uniformly. Both the actinic beam and the probe beam that illuminates object O are derived from an Ar–Kr laser at 570-nm wavelength. The actinic beam is linearly polarized at 45° to the plane of polarizer P. Initially with no actinic beam present, polarizer P and analyzer A crossed each other. The probe beam illuminating the object produced an intensity of >10 mW/cm^2 at

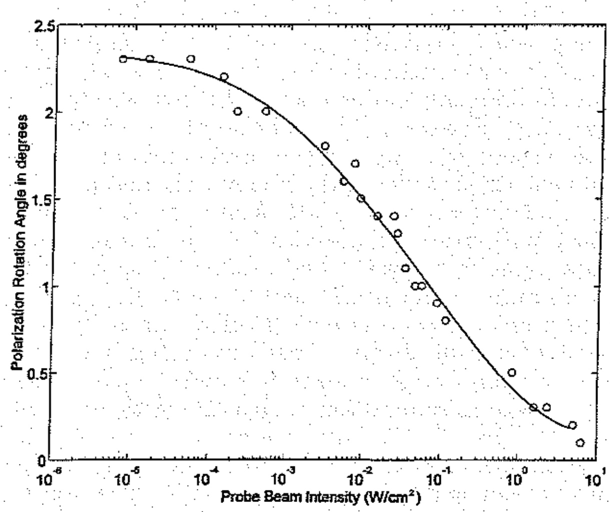

Fig. 1. Dependence of photoinduced polarization rotation on probe beam intensity with a constant actinic beam intensity of ~10 mW/cm^2. The solid curve is intended solely as a visual aid.

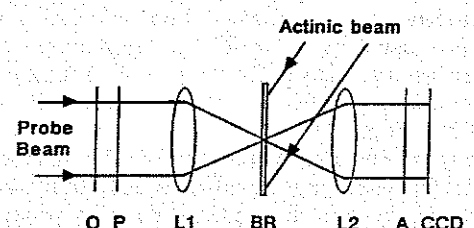

Fig. 2. Schematic experimental setup for optical Fourier processing using photoinduced dichroism in a bR film.

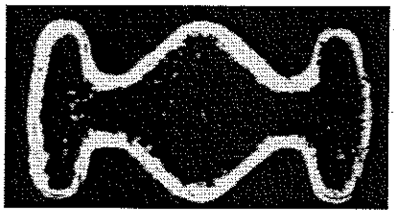

Fig. 3. Experimental result of edge enhancement with the inner portion of a razor blade as the object.

the center of the Fourier transform of O formed at the bR film plane. On illumination of the BR with an actinic beam of intensity ~10 mW/cm^2, only the edges of the object appear at the CCD, yielding high-frequency spatial filtering or edge enhancement. Figure 3 shows the result of edge enhancement; the inner portion of a razor blade was used as the object. This self-adaptive edge enhancement is explained as follows. The Fourier transform of an arbitrary object information formed at the bR plane has an intensity distribution with high intensities for low-frequency components and low intensities for high-frequency components. Figure 1 showed that at optimum actinic beam intensity the effect of increasing the probe beam's intensity is to decrease its degree of polarization rotation owing to photoinduced dichroism. This means that high-frequency components at the bR plane experience higher degrees of polarization rotation than the zero- and low-frequency components. Hence, if the input object information has a single linear polarization, after its passage through the bR under actinic light illumination it has a range of polarizations of different orientations. The Fourier processing is accomplished through the analyzer, which blocks specific polarization components, in turn blocking the corresponding spatial frequencies. When the analyzer is at a right angle to the input beam polarization, zero- and low-frequency components, which experience almost no polarization rotation because of their high intensities, are blocked by the analyzer. But the high-frequency components that correspond to the edges of the object experience polarization rotation, and hence pass through the analyzer to appear at the CCD camera to yield edge enhancement. Rotation of the analyzer can serve as a variable spatial filter for Fourier processing.

In conclusion, we have successfully demonstrated a self-adaptive optical Fourier-processing system that uses the photoinduced dichroic characteristics of a bacteriohodopsin film. The dependence of photoinduced dichroism on probe light intensity has effectively been used to imprint continuous polarization variations upon the different spatial-frequency components of an object information. Spatial filtering of desired frequencies is then performed by an analyzer. The simplicity of the present scheme is straightforward, with the processing requiring no alignment at the Fourier plane. No interference recordings are involved in this experiment; hence vibration isolation systems are not required. A coherent source is not a requirement for the experiment; a white-light source with an appropriate wavelength filter at ~570 nm can induce photoanisotropy in the bR film. The improved performance of the present system compared with that of other techniques is based on the advantage that a single optical setup can perform low-pass filtering, hand-pass filtering, and high-pass filtering operations with simple adjustments of the analyzer. One could also perform the same operations by varying the intensities of the beams. Detailed studies of a versatile image-processing system for applications such as noise filtering, flow visualization, waveletlike filtering, and beam shaping are in progress.

This research is supported by BAA contract DAAK 60-92-K-002 with the U.S. Army Natick Research, Development and Engineering Center.

References

1. J. W. Goodman, Opt. Photon. News **2**(2), 11 (1991).
2. H. M. Ozktas and D. A. B. Miller, Appl. Opt. **35,** 1212 (1996).
3. J. P. Huignard and J. P. Herriau, Appl. Opt. **17,** 2671 (1978).
4. D. Oesterhelt, C. Brauchle, and N. Hampp, Q. Rev. Biophys. **24,** 425 (1991).
5. T. Y. Chang, J. H. Hong, and P. Yeh, Opt. Lett. **15,** 743 (1990).
6. R. R. Birge, Sci. Am. **3,** 90 (1995).
7. R. Thoma, N. Hampp, C. Brauchle, and D. Oesterhelt, Opt. Lett. **16,** 651 (1991).
8. F. J. Aranda, R. Garimella, N. F. McCarthy, D. Narayana Rao, D. V. G. L. N. Rao, Z. Chen, J. A. Akkara, D. L. Kaplan, and J. A. Roach, Appl. Phys. Lett. **67,** 599 (1995).
9. R. B. Gross, K. Can Izgi, and R. R. Birge, A. A. Jamberdino, and W. Niblack, Proc. SPIE **1662,** 186 (1992).
10. V. Y. Bashenov, M. S. Soskin, V. B. Taranenko, and M. V. Vasnetsov, in *Optical Processing and Computing*, A. Arsenault, ed. (Academic, New York, 1989), p. 103.
11. D. V. G. L. N. Rao, F. J. Aranda, D. Narayan Rao, Z. Chen, J. A. Akkara, and M. Nakashima, Opt. Commun. **127,** 193 (1996).
12. J. D. Downie, Appl. Opt. **33,** 4353 (1994).
13. H. Imam, L. R. Lindvold, and P. S. Ramanujam, Opt. Lett. **20,** 225 (1995).
14. J. D. Downie, Appl. Opt. **34,** 5210 (1995).
15. H. Takei, and N. Shimizu, Appl. Opt. **35,** 1848 (1996).
16. R. R. Birge, Ann. Rev. Phys. Chem. **41,** 683 (1990).
17. N. M. Burykin, E. Ya. Korchemskaya, M. S. Soskin, V. B. Taranenko, T. V. Dukova, and N. N. Vsevolodov, Opt. Commun. **54,** 68 (1985).