9-14-1998

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Recommended Citation

Joseph, Joby; Aranda, F. J.; Rao, D.V.G.L.N.; DeCristofano, B. S.; Kimball, B. R.; and Nakashima, M., "Optical implementation of the wavelet transform by using a bacteriorhodopsin film as an optically addressed spatial light modulator" (1998). *Physics Faculty Publications.* Paper 29.
http://scholarworks.umb.edu/physics_faculty_pubs/29

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AIP | Applied Physics Letters

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Citation: Appl. Phys. Lett. **73**, 1484 (1998); doi: 10.1063/1.122180

View online: http://dx.doi.org/10.1063/1.122180

View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v73/i11

Published by the American Institute of Physics.

APPLIED PHYSICS LETTERS VOLUME 73, NUMBER 11 14 SEPTEMBER 1998

Optical implementation of the wavelet transform by using a bacteriorhodopsin film as an optically addressed spatial light modulator

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(Received 30 January 1998; accepted for publication 16 July 1998)

An optical system utilizing the photoinduced dichroism in a bacteriorhodopsin film has been demonstrated for the optical implementation of wavelet transforms. The dichroism, induced by the image of a wavelet filter on a bacteriorhodopsin film leads to polarization rotation of the Fourier components of an image. The polarization-rotated Fourier components of an input scene are analyzed with a polarizer to give the wavelet transform components. The dichroism is induced with beams whose profiles are determined by wavelet filters in order to perform the optical wavelet transform. © *1998 American Institute of Physics.* [S0003-6951(98)03637-7]

Wavelets are functions that allow the representation of data by slicing it into different frequency components and subsequently studying each component with a resolution matched to its scale. They have advantages over traditional Fourier methods in analyzing physical situations where the signal contains discontinuities and sharp spikes.[1] The wavelet transform (WT) represents a signal or a two-dimensional scene in terms of a family of functions that are derived from a single basic function or wavelet by dilation and translation operations.[2,3] The wavelet transform has shown promising applications in the fields of image compression, multiresolution image analysis, transient signal, and image processing.[4,5] Optics with its inherent advantages of speed and ease of parallel processing has been utilized by many researchers for the implementation of wavelet transforms. Many optical schemes have been developed for one-dimensional as well as two-dimensional wavelet transformation.[6–11]

Optical implementation of two-dimensional wavelet transformation is most commonly obtained as correlation of the Fourier transform (FT) of the input image with different scaled versions of the wavelet filters. These wavelet filters (FT of wavelets) are generated as band pass filters. The scaling operation for the WT can be implemented in an optical system with a combination of lenses.[3] The scaling operation can also be performed using a computer, in which case an interface between the computer and the optical system is needed. We describe an optical system for the implementation of the WT in which a bacteriorhodopsin (bR) film can be used as interface between the computer display and the optical system. The optically induced anisotropy in a bR film makes it work as an optically addressed spatial light modulator in this application.[12,13]

Recently, bR has been used to demonstrate a real-time spatial light modulator[14] and an optical storage device.[15] Researchers have implemented applications such as pattern recognition, optical logic gates,[16] spatial filtering,[14,17] interferometry, phase conjugation,[18] incoherent-to-coherent conversion, and spatial light modulation.[12,13] In this letter, we demonstrate the use of the photoinduced dichroism exhibited by bR films, for the optical implementation of the wavelet transform. The bR is employed as an optically addressed spatial light modulator, in which a computer-generated wavelet filter can be imaged on the bR film. The bR film is kept at the Fourier plane in a 4f imaging system. Dichroism induced by this image leads to polarization rotation for wavelet filter selected Fourier components of an input scene. The polarization-rotated Fourier components are analyzed with an analyzer in order to obtain the wavelet transform components of the input scene.

The Fourier transform represents an input signal in terms of sinusoidal functions, whereas the wavelet transform represents the signal in terms of nonsinusoidal functions called

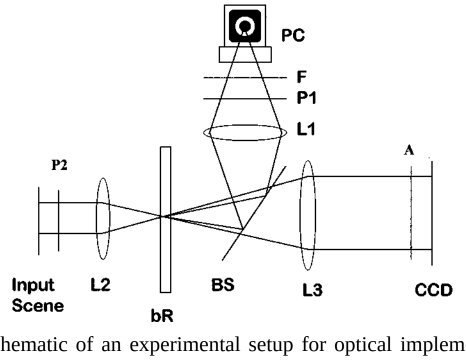

FIG. 1. Schematic of an experimental setup for optical implementation of the WT using a bR film.

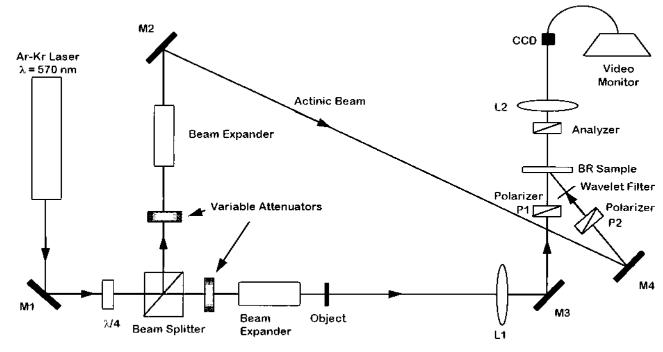

FIG. 2. Experimental arrangement (M)- mirror, (L)- lens, (P)-polarizer, (CCD)-camera, (λ/4)-quarter wave plate.

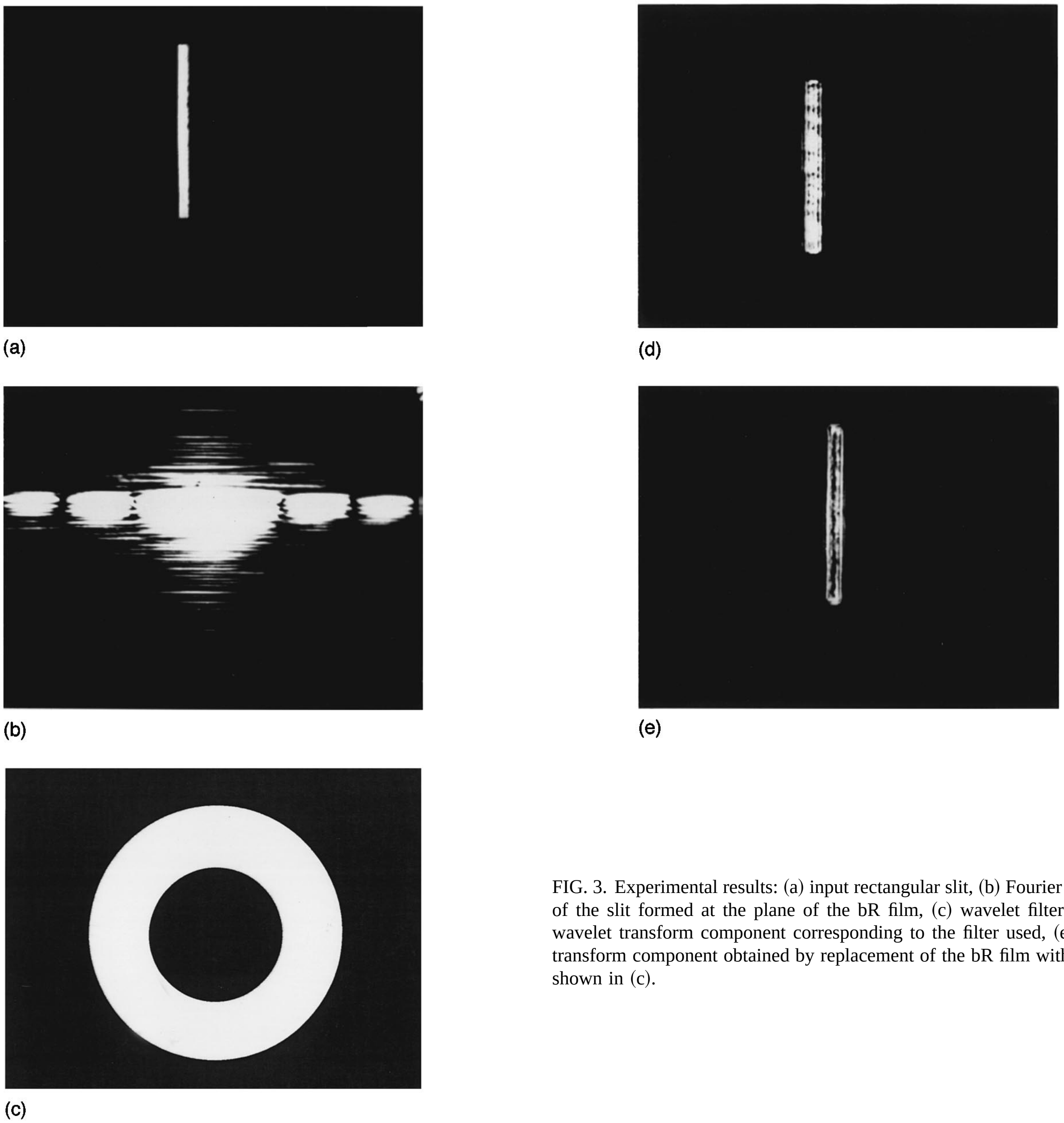

FIG. 3. Experimental results: (a) input rectangular slit, (b) Fourier transform of the slit formed at the plane of the bR film, (c) wavelet filter used, (d) wavelet transform component corresponding to the filter used, (e) wavelet transform component obtained by replacement of the bR film with the filter shown in (c).

wavelets.[1] In the two-dimensional case, the WT of a signal $s(x,y)$ is given by[7,19]

$$W(a_x,a_y,b_x,b_y)=\int\int s(x,y)h^*_{a,b}(x,y)dx\,dy, \tag{1}$$

where $h_{a,b}(x,y)$ represents the wavelets that are derived from a fundamental wavelet $h(x,y)$ (called a mother wavelet). In the Fourier domain, a WT can be expressed as

$$\begin{aligned}W(u,v)&=\mathrm{FT}[W(a_x,a_y,b_x,b_y)]\\&=\frac{1}{(a_x,a_y)^{1/2}}S(u,v)H^*_a(u,v),\end{aligned} \tag{2}$$

where $S(u,v)$ is the FT of $s(x,y)$ and $H_a(u,v)$ is the FT of the scaled function $h[(x/a_x),(y/a_y)]$.

The optical implementation of a WT is based on Eq. (2) which shows the WT as the product of the FT of an input signal and the FT of the wavelets, in which $H_a(u,v)$ are bandpass filters (wavelet filters). A basic 4f optical system of a VanderLugt type correlator can be employed for the product of the FT of the signal with the wavelet filters (WFs).[9]

The use of bR in optical image processing and related applications is based on the fact that absorption of light triggers the photocycle of the bR molecule with a complex series of intermediate steps.[20–22] When the wavelength of actinic light is ~570 nm, induced dichroism predominates over induced birefringence as expected form the Kramers-Kronig dispersion relation. The presence of dichroism produces a rotation of the plane of polarization of a probe beam passing through the dichroic parts of the film.[17,22,23]

A schematic of an experimental setup for optical implementation of the WT using a bR film is shown in Fig. 1. Wavelet filters generated on a computer are displayed on its display device. A wavelength filter F filters 570 nm at which bR exhibits maximum photoinduced dichroism. $P1$ is a polarizer and lens $L1$ images the displayed wavelet filter onto a bR film after reflection from a beam splitter (BS). Lens $L2$ forms the FT of a coherent input scene at ~570 nm onto the bR film. $P2$ is a polarizer aligned at 45° to polarizer $P1$. Lens $L3$ forms an image of the input scene on a charge coupled device (CCD) camera. An analyzer, A, is kept crossed to the polarizer $P2$. The polarization of the probe beam is rotated when it passes through a dichroic medium. The image of the wavelet filter formed on the bR film induces dichroism, and the Fourier components of the input image which pass through these dichroic parts have their polarization rotated. These polarization-rotated components pass through the analyzer and are detected by the CCD camera. The output of the analyzer is equivalent to a correlation between the FT of the input image and the wavelet filter, hence as per Eq. (2), the image captured by the CCD camera will be the WT component of the input scene, corresponding to the wavelet filter formed on the bR film.

The bR film used in the experiment, a wild-type bR film purchased from Wacker Chemical Inc. (USA), had a thickness of 35 μm, and was sandwiched between glass plates. Studies of the photoinduced dichroic characteristics of the film showed that the dichroism reached a maximum for an illuminating beam of intensity of $\sim$10 mW/cm^2. Figure 2 shows the experimental setup used for the demonstration of optical implementation of wavelet transform. In this experiment, the beam carrying the wavelet filter image as well as the beam bearing the input scene are derived from an Ar–Kr laser operating at a wavelength of 570 nm. The linearly polarized output from the laser was made circularly polarized using a $\lambda/4$ plate and a 50/50 BS divided the beam into two parts. The transmitted part, after passing through a variable attenuator and a beam expander, illuminated the input scene. A lens of focal length 64 cm was used to form the FT of the scene onto the bR film. Lens $L2$ of focal length 10 cm forms an image of the scene onto a CCD camera. The polarizer $P1$ is aligned for maximum vertical transmission and the analyzer is kept crossed to the polarizer $P1$. The reflected part from the BS, after beam expansion, illuminates a WF prepared on a transparency sheet. Polarizer $P2$ is aligned at 45° with respect to polarizer $P1$. The wavelet filter transparency is kept at a distance of 2 cm before the bR film, to form an image of the wavelet filter on the bR film.

Since the analyzer is kept crossed to the polarizer $P1$, when the WF bearing beam is cut off, there is no light to be collected by the CCD camera. Under the illumination of the bR film with the WF image, the bR film becomes dichroic according to the profile of the WF. The Fourier components of the input scene, passing through the dichroic parts of the film, undergo polarization rotation. A band of the polarization-rotated Fourier components is passed through the analyzer to be collected by the CCD camera. Hence, the image formed at the CCD plane, in the presence of a WF image on the bR film, is a wavelet transform component of the input scene.

Figure 3 shows the experimental results of optical wavelet transformation. The input scene used was a rectangular slit of width 1 mm [Fig. 3(a)], with an average intensity of 0.1 mW/cm^2. Figure 3(b) shows a portion of the Fourier transform of the slit formed at the plane of bR film and Fig. 3(c) shows the wavelet filter used. The wavelet filter used had an outer diameter of 1.425 mm and inner diameter of 0.75 mm, with an average intensity of 10 mW/cm^2. Figure 3(d) shows the wavelet transform component captured by the CCD camera corresponding to the wavelet filter used. Further components of the WT can be obtained by scaling the wavelet filter. For comparison, Fig. 3(e) shows the WT component obtained when the bR film is replaced with the wavelet filter of Fig. 3(c).

An experimental system has been demonstrated for the optical implementation of the wavelet transform using the photoinduced anisotropy of a bR film as an optically addressed spatial light modulator. Even though laser light is used in our system for the wavelet filter image with the availability of bR films with low light sensitivity, it may be possible to implement the optical wavelet transform as shown in Fig. 1. The results shown in Fig. 3 clearly establish the use of a bR film and photoinduced dichroism for optical implementation of the wavelet transform.

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