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Spatial frequency selective reconstruction using Fourier transform holograms generated in functionalized mesogenic composites

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We have demonstrated spatial frequency selective reconstruction (SFSR) of two-dimensional optical images by using functionalized mesogenic composites possessing real-time holographic capability. The two-dimensional optical image was Fourier transformed by a lens and part of the spatial frequency was brought into interference with the reference beam in the Raman–Nath regime. The SFSR images were observed in the self-diffraction patterns and we calculated the expected reconstructed images which were in good agreement with the observed images.

1. Introduction

Recent advances in high performance liquid crystals possessing real-time holographic capability, together with low priced and high quality lasing devices, have renewed interest in the use of diffraction gratings in combination with organic materials [1–4]. Optical devices in which real-time holography plays an important role have already been demonstrated in various systems such as image amplification, spatial light modulation, optical computing and general two-dimensional optical image processing. In order to realize these applications, conventional holographic interferometry with two- or four wave mixing geometry is used [5, 6]. Photorefractive liquid crystals provide a candidate for real-time holographic media and show efficient optical nonlinearity for optical wave mixing and real-time capability [2]. The effect arises when charge carriers, photogenerated by a spatially modulated light intensity, separate by drift and diffusion processes and become trapped to produce a non-uniform space-charge field that modulates the refractive index to generate a phase grating. Thus refractive index modulation (holograms) can have read-write-erase capability.

Photorefractivity in liquid crystals is based mainly on orientational birefringence and the effects are named 'orientational photorefractive effects'. Since mesoegnic materials possess an abundance of useful materials characteristics, including large birefringence and easy fabrication over large areas, photorefractivity is highly sensitive and efficient. In recent years, we have reported that novel composites consisting of a functionalized copolymer, low-molar-mass liquid crystal and sensitizer show a high performance photorefractivity [7, 8]. Photorefractive mesogenic composites have the following advantages: operating voltage low enough for high diffraction efficiencies, large refractive index modulation, high resolution, and ease of fabrication of large area homeotropic alignments.

In the present paper, we exploit the optical nonlinearity inherent in the photosensitive mesogenic composite to demonstrate and explain the spatial frequency selective reconstruction (SFSR) of a two-dimensional optical image using Fourier transform holographic geometry. From the point of view of realization of photonics, although the material characteristics have been already investigated [7, 8], it is very important to demonstrate all-optical data processing with their use; photosensitive mesogenic composites emerge as promising elements for image processing applications such as the real-time image filtering described here.

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2. Experimental

2.1. *Samples*

The photosensitive mesogenic composites consisted of a mixture of low-molar-mass liquid crystal, functionalized copolymer and sensitizer; the chemical structures of all components are shown in figure 1. The functionalized copolymer was synthesized by free radical copolymerization of methacrylate monomers containing 4-cyanobenzoate and *N*-ethylcarbazoyl side groups. A small amount of 2,4,7-trinitro-9-fluorene (TNF) was also added, forming a charge-transfer complex with the carbazole units, to provide long wavelength photosensitization. The mesogenic composite was sandwiched between two indium tin oxide-coated glass slides with no treatment for liquid crystal alignment. The thickness of the mesogenic composite film was maintained with a 50 µm thick polyester film. Once the liquid crystals in the composite aligned homeotropically under the applied electric field, this homeotropic state was maintained under zero electric field, even at room temperature, due to polymer-stabilization effects. Figure 2 shows the absorption spectra of the photorefractive mesogenic composite. Due to the charge-transfer complexes, the light in the visible region was absorbed, which is advantageous for improving the sensitivity.

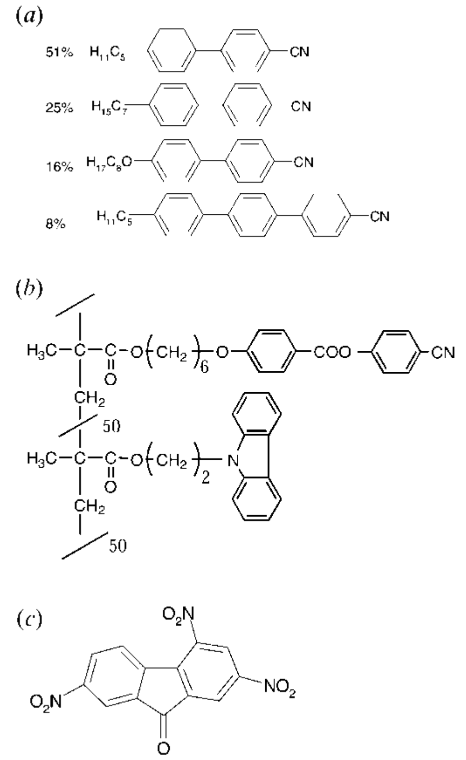

Figure 1. Chemical structures of components of the functionalized mesogenic composite. (*a*) Low-molar-mass nematic liquid crystal mixture (E7), (*b*) functionalized copolymer and (*c*) photoconductive sensitizer (TNF).

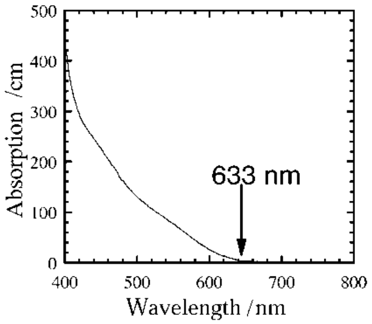

Figure 2. Absorption spectra of the mesogenic composite film.

2.2. *Experimental set-up for optical image processing*

Figure 3 illustrates the experimental set-up for SFSR of the two-dimensional optical image, combining a Fourier transform holographic operation and photosensitivities in the mesogenic composite. A c.w. He-Ne laser beam which emits at a wavelength of 633 nm was divided into two beams by a polarizing beam splitter (PBS); both writing beams were expanded, and images imprinted onto them by transparent objects (Mask1 in figure 3). The polarization direction of both beams was controlled to the *p*-polarized direction by a half-wave plate. As shown in figure 2, the electronic transition of the photorefractive mesogenic composite is off-resonant with a wavelength of 633 nm and the absorption loss was estimated to be less than $1.0\,\mathrm{cm}^{-1}$, which is preferable for high performance image processing. One of the images was Fourier-transformed by a lens (L2, signal beam), and the mesogenic composite film was placed in the Fourier plane. The other beam (reference beam) was superimposed on the same spot by another

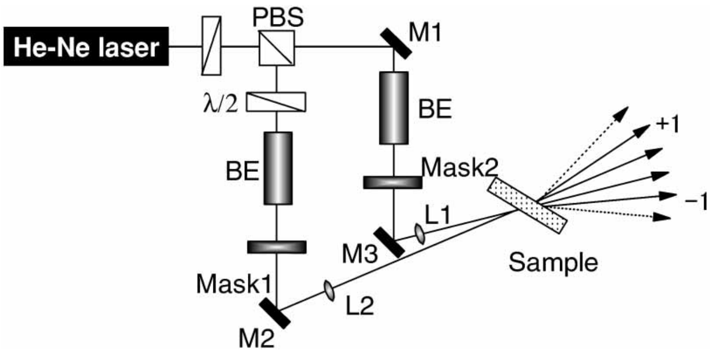

Figure 3. Schematic of the experimental set-up for SFSR. M1, M2 and M3: mirrors, L1 and L2: lens, $\lambda/2$: half-wave plate, and PBS: polarizing beam splitter.

lens (L1) and brought into interference with the signal beam. The intensity ratio between the signal and reference beams was controlled by the polarization direction of the incident laser beam to the PBS. The sample was tilted 45 degrees from the bisector of the two incident beams to provide a projection of the grating wave vector along the direction of the applied electric field. The applied electric field was 0.16 V μm^{-1}, and these choices of tilt angle and applied electric field maximized the signal to noise ratio.

It is necessary to determine whether the grating is a thin (Raman–Nath) or volume (Bragg) grating. For this purpose, the following well known parameter can be used [9].

$$Q = \frac{2\pi L\lambda}{\Lambda^2 n} \tag{1}$$

where λ is the wavelength of the light, n is the index of refraction, L is the thickness of the grating, and Λ is the grating constant. Under our experimental conditions, the crossing angle between the reference and signal beams was selected to be 0.8 degree, resulting in a grating spacing of about 45 μm and estimated Q value of about 0.07. Since the Q value was much smaller than unity, the grating was considered to be a plane grating (Raman–Nath type). For the Raman–Nath regime of optical diffraction, the angular spread of the grating vector is much larger than the Bragg diffraction angle, and multiple orders of diffraction are therefore allowed. Since the writing beams are self-diffracted in the Raman–Nath regime, the reconstructed image can be obtained without using another beam as a probe. In the present work, we investigated the SFSR properties by observing the positive first order self-diffracted beam.

3. Results and discussion

3.1. *Spatial frequency selective reconstruction (SFSR) of optical image*

Lenses play an important role in the optical signal processing described here, in particular, Fourier transformability is one of the most important properties of lenses in the present study. The input image may be represented by the function $u_s(x, y)$, and the distribution of light just behind the lens is

$$u_s(x, y)\exp\left(-ik\frac{x^2+y^2}{2f}\right) \tag{2}$$

where k is the wave number and f is the focal length. For the special case in which the screen is placed at the focal plane, the input image is transformed to [5]

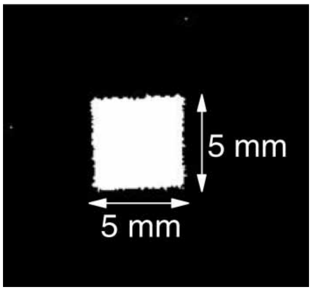

Figure 4. Photograph of test input image.

$$u'_s(x_f, y_f) = \left| \frac{1}{i\lambda f}\exp\left[ik\left(f + \frac{x_f^2+y_f^2}{2f}\right)\right] \iint u_s(x, y)\exp\left[-i\frac{2\pi}{\lambda f}(xx_f + yy_f)\right] dx\,dy \right|^2 \tag{3}$$

In the present work, in order to clarify quantitatively the mechanism of the SFSR, we consider the image plane when the object is a single square ($5 \times 5\,mm^2$) as shown in figure 4. Under our experimental conditions, the input image is Fourier-transformed by a lens as shown in figure 5 (*a*); the observed image was in good agreement with the theoretical image, figure 5 (*b*) calculated from equation (3). Fourier holography, by

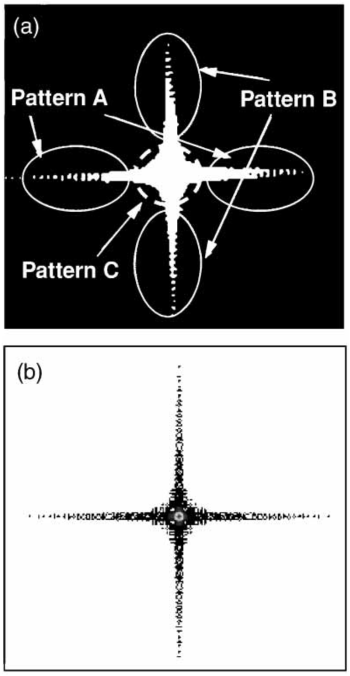

Figure 5. Fourier-transformed images generated by a lens L. The images were obtained from (*a*) experiment and (*b*) calculation. Three patterns A, B and C denote the three kinds of reference beam patterns used in this study.

using the Fourier-transformation properties of lenses, is one of the most general hologram techniques. These properties are essential to an understanding of the spatial filtering properties of optical image processing.

In the Raman–Nath thin grating regime, multiple diffraction orders are generated. Two-beam interference between the Fourier-transformed two-dimensional optical image and the reference beam provides holographic gratings. In the back focal plane of the imaging lens intensity distributions of the spatial frequencies of the optical image appear, as the Fourier spectrum and the reconstructed images depend on the intensity distribution of the reference beam. Thus the image with favoured spatial frequency can be reconstructed by controlling the intensity distribution of the reference beam, and these processes can be applied to optical two-dimensional image processing for SFSR.

3.2. *SFSR with varied reference beam patterns*

It is anticipated that the self-diffracted image reconstructed from the mesogenic composite may be controlled by the intensity distribution of the reference beam, according to the above-mentioned SFSR mechanism. In the present work, three kinds of reference beams with different intensity distributions, schematically described in figure 5 (*a*), are used for realization of the SFSR. If the complex amplitude of the reference beam is $u_R(x_f, y_f)$, the complex amplitude at the mesogenic sample composite located in the back focal plane of the lens is

$$u_{SFSR}(x_f, y_f) = u_R(x_f, y_f) \cdot u'_S(x_f, y_f) \qquad (4)$$

Reconstruction of the two-dimensional optical image by self-diffraction in the mesogenic composite is equivalent to an inverse Fourier transform and is described by

$$U_{SFSR}(x', y') \propto \left| F^{-1}[u_{SFSR}(x_f, y_f)] \right|^2 \qquad (5)$$

where $F^{-1}[\phi]$ is the inverse Fourier transform of a function ϕ.

In the present work, three kinds of reference beam with different intensity distribution patterns are used for the demonstration of SFSR; the intensity of the signal beam is almost equal to that of the reference beam at the focal plane. The reference beam with patterns A or B is superposed onto the Fourier-transformed image with high spatial frequencies in the horizontal and vertical directions of the input optical image, respectively. By using a the reference beam of pattern A or B, respectively, it is expected that a part of the input image with high frequency in the horizontal or vertical directions can be selectively reconstructed, while the reference beam of pattern C is overlapped with the signal image with low spatial frequencies.

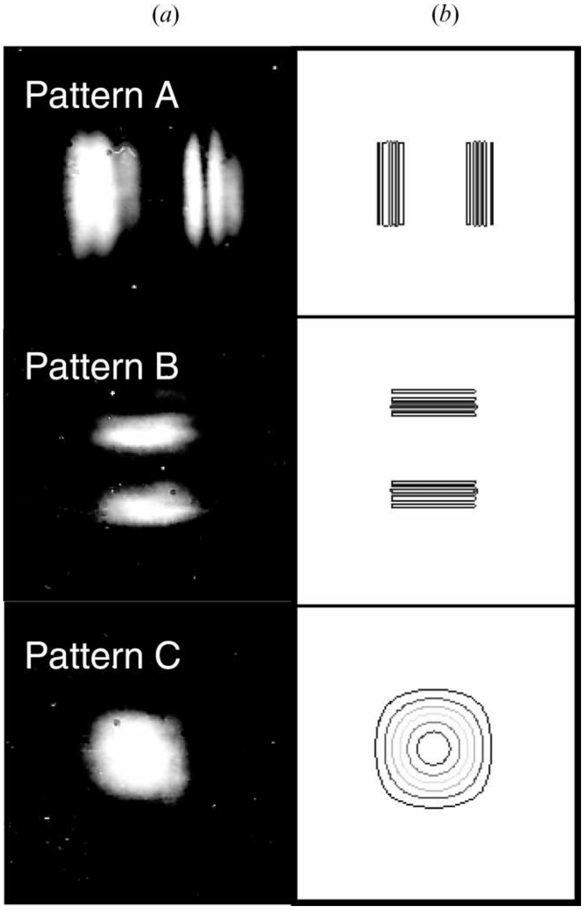

Figure 6. Comparison of (*a*) experimentally observed images and (*b*) numerical simulation results. Patterns A, B and C are in accordance with the images obtained from the three reference beam patterns described in figure 5 (*a*).

Figure 6 is a picture of the experimentally observed (*a*) and calculated (*b*) images with the object being a single square as shown in figure 4. The experimentally observed images were in good agreement with the calculated images, although a small discrepancy was observed in the case of pattern A. We attribute this discrepancy to our experimental geometry. Since the sample is tilted 45 degrees from the bisector of the two incident beams, to provide a projection of the grating wave vector along the direction of the applied electric field, the reconstructed image is refracted when it passes through the glass substrate. The refraction angle is dependent on the diffraction angle, and the experimentally observed image in the case of pattern A seems to stretch in the horizontal direction. In the case of pattern A, the reference beam is overlapped with the Fourier-transformed image with high spatial frequency in the horizontal direction, and the vertical edge of the input image is selectively reconstructed. On the other hand, in the case of pattern B, the horizontal edge of the input image is selectively reconstructed because the reference beam is overlapped with the Fourier-transformed image with high spatial frequency in the vertical direction. Since the reference beam in pattern C is superposed onto the central region of the Fourier-transformed image, the edge of the reconstructed image is blurred, although the reconstructed image is similar to the input image. Therefore the image with favoured spatial frequency can be selectively reconstructed by controlling the reference beam position.

3.3. *SFSR with varied intensity of the reference beam*

As another case of SFSR using the functionalized mesogenic composite, we have demonstrated SFSR by controlling the intensity of the reference beam. In this case, the diameter of the reference beam was much larger than that of the Fourier-transformed signal beam, and assumed to be large enough for the reference beam profile to be homogeneous in comparison with the signal beam profile. The diffraction efficiency is generally dependent on the modulation ratio of the interference pattern which can be written as:

$$m = \frac{2(I_R I_S)^{\frac{1}{2}}}{I_R + I_S} \qquad (6)$$

where I_S and I_R are the intensities of the signal and reference beam, respectively. Figure 7 shows the intensity ratio I_R/I_S versus the measured diffraction efficiencies, which are defined as the intensity ratio between the input signal and the first order Raman–Nath diffraction beams. The solid line in figure 7 represents the theoretical curve calculated from equation (6) by assuming that the diffraction efficiency is proportional to m (fringe modulation), and the theoretical curve is in good agreement with the experimental data. Thus the diffraction efficiency of our functionalized mesogenic composite is proportional to the fringe modulation generated by the signal and reference beams, and reconstruction of the two-dimensional optical image by self-diffraction in the mesogenic composite is described by

$$u_{SFSR}(x', y') \propto m(x_f, y_f) \cdot u'_S(x_f, y_f) \qquad (7)$$

where $m(x_f, y_f)$ denotes the spatial distribution of the fringe modulation at the focal plane.

Since a highly efficient grating is formed when the intensity of the signal eam is comparable to that of the reference beam, SFSR is expected to be achieved by simply controlling the reference beam intensity, although cylindrical symmetry is necessary for the spatial frequency of the reconstructed image. Figure 8 contains a two-dimensional plot of the experimentally observed and calculated images (with the object being a

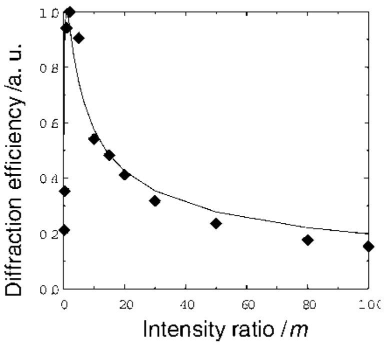

Figure 7. Raman–Nath diffraction efficiency of the photorefractive mesogenic composite versus the intensity ratio I_S/I_R between the signal and reference beams. Diffraction efficiency is defined as the intensity ratio between the input signal beam and the first order Raman–Nath diffraction beam.

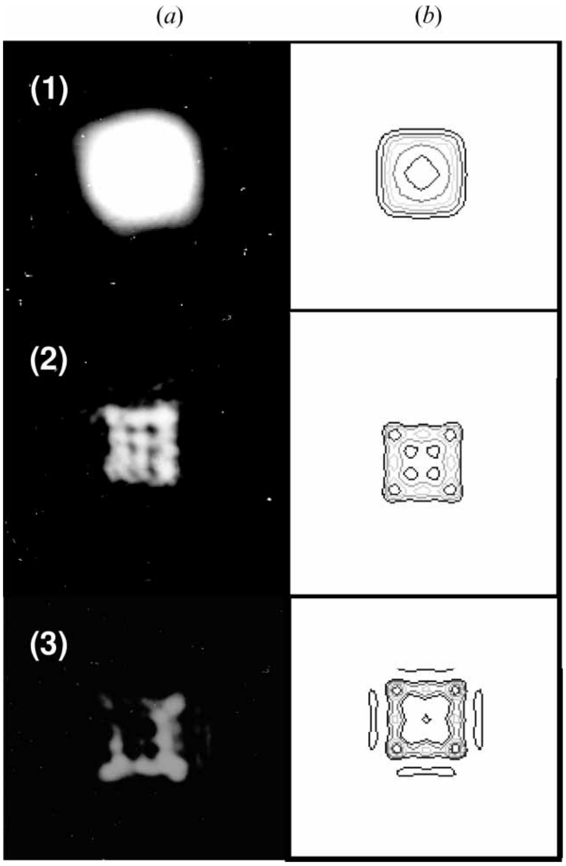

Figure 8. Comparison of (*a*) experimentally observed images and (*b*) numerical simulation results as a function of the intensity ratio between the signal and reference beams. The beam intensity ratio I_R/I_S was (1) 0.470, (2) 0.017, and (3) 0.003.

single square) on varying the ratio I_S/I_R. The observed images are in good agreement with the theoretical expectation. When the ratio I_S/I_R is large ($I_S/I_R = 0.470$), the edge of the reconstructed image is blurred, although the reconstructed image is similar to the input image. Since a highly efficient grating is formed near the central part of the Fourier transformed signal image, an image with low spatial frequency is selectively reconstructed. When the ratio I_S/I_R is small, the highly efficient grating is formed in the outside part of the Fourier transformed image, and the image with high spatial frequency is selectively reconstructed. Therefore the input image with higher spatial frequency is reconstructed by using a reference beam with lower intensity, and the enhancement of the edges of the two-dimensional optical images increases as the ratio I_S/I_R is increased.

In summary, in holographic recording, the reconstructed image is a faithful replica of the original image only if the intensity is less than the intensity of the reference beam. If this condition is violated, the input image with high spatial frequency is selectively reconstructed. Therefore SFSR can be achieved by simply controlling the reference beam intensity although cylindrical symmetry is necessary.

4. Conclusion

We have demonstrated spatial frequency selective reconstruction (SFSR) of two-dimensional optical images by using functionalized mesogenic composites possessing high performance orientational photorefractivities. The two-dimensional optical image was Fourier transformed by a lens, and a part of spatial frequency was brought into interference with the reference beam in the Raman–Nath regime. At a certain value of d.c. voltage applied to the mesogenic composite a self-diffraction process was strongly effective; as a result, diffraction spots appeared at a great distance from the sample. The self-diffraction beam contained the reconstructed image information, which was strongly dependent on the shape and intensity of the reference beam. The image with selected spatial frequency can be reconstructed by controlling the shape and/or intensity of the reference beam; we calculated the expected reconstructed images which were in good agreement with the observed images.

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