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An incoherent optical correlator based on photoanisotropy

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Abstract. We describe theoretically the function of a nonlinear optical element based on photoanisotropy in azo-dye-doped polymers for optical correlation. This element allows the realization of a matched filter with two incoherent light beams. The described technique involves the insertion of a photoanisotropic polymer sample in the Fourier plane of the optical element. Due to the specific features of photoanisotropic materials the output is characterized by the convolution of the first wave with the autocorrelation function of the second wave.

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Optical information processing and storage is of increasing interest. For that the development of new optical methods is necessary. One important aspect is the use of incoherent light sources and light sources with a low degree of coherence. This allows a considerable simplification of experimental setups in comparison with techniques known from coherent optics. This attribute is of great importance especially in the field of optical correlation techniques which are of interest for instance for fingerprint detection, automatic inspection, or pattern recognition. These techniques base mainly on coherent optics. The original optical correlator proposed and demonstrated by Van der Lugt [1] contains a holographic filter in the Fourier plane. And the joint transform correlators [2–4] use the interference of the coherent Fourier transforms of the two objects under consideration. Due to the use of interference phenomena high stability requirements exist and the employment of coherent light sources is necessary.

For the reduction of these requirements the use of incoherent optics is of considerable interest. We describe a matched-filter technique based on a nonlinear optical element containing photoanisotropic polymers. Optically induced anisotropy in azo-dye-doped polymers depends on the intensity and the polarization state of a light wave. The process does not depend on the phase and therefore it is possible to use light sources with a low degree of coherence. The nature of this process is described in several papers [5–8].

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1 Theoretical description

For a theoretical description of such a nonlinear optical element it is convenient to consider a setup as shown in Fig. 1. A strong in x-direction linearly polarized wave $\boldsymbol{E}_1$ is passing through a transparency t_1, which is located in the front focal plane of lens L_1. After passing through the lens the Fourier transform T_1 of t_1 is performed in the back focal plane where the photoanisotropic polymer sample is situated.

$$\boldsymbol{t_1}(x, y) = \begin{pmatrix} t_1(x, y) \\ 0 \end{pmatrix}, \tag{1}$$

$$\mathcal{FT}\left[\boldsymbol{t_1}(x, y)\right] = \begin{pmatrix} \mathcal{FT}\left[t_1(x, y)\right] \\ 0 \end{pmatrix} = \begin{pmatrix} T_1(\xi, \eta) \\ 0 \end{pmatrix}. \tag{2}$$

The intensity (power density spectrum) is given by

$$I_{1,\mathrm{FT}} = \frac{\varepsilon_0 cn}{2} \mid T_1(\xi, \eta) \mid^2, \tag{3}$$

where ε_0 denotes the dielectric constant, c is the velocity of light, and n is the unperturbed index of refraction of the material. The influence of this electric field distribution leads to a change of the dielectric tensor of the medium. Due to the model developed by Kakichashvili [9–11] the initially isotropic polymer becomes anisotropic, which can be described by the following matrix:

$$\varepsilon = \begin{pmatrix} \varepsilon^0 + \kappa I_{1,\mathrm{FT}}(\xi, \eta) & 0 \\ 0 & \varepsilon^0 \end{pmatrix}. \tag{4}$$

ε^0 is the unperturbed dielectrical constant of the material and κ is a complex quantity describing the induced photoanisotropy parallel to the polarization direction of $\boldsymbol{E}_1$.

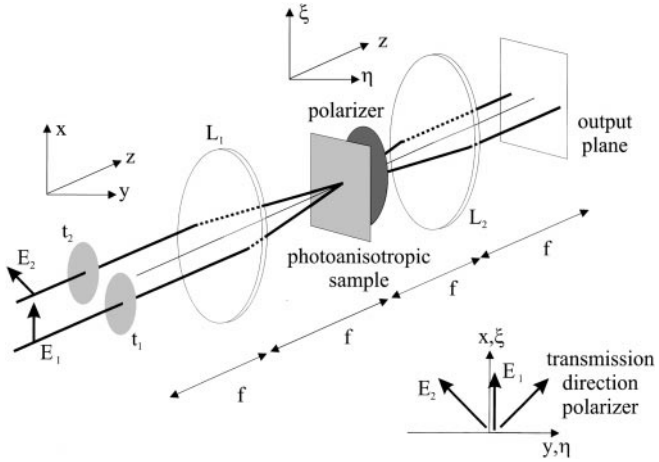

Fig. 1. Basic geometrical scheme. $\boldsymbol{E}_1$ and $\boldsymbol{E}_2$ denote the direction of the electrical field vector. The transmission direction of the polarizer is rotated by 90° with respect to $\boldsymbol{E}_2$

Therefore the Jones matrix of this element can be written as

$$\mathcal{J} = \begin{pmatrix} 1 & 0 \\ 0 & \mathrm{e}^{-\mathrm{i}\delta} \end{pmatrix} , \tag{5}$$

with

$$\delta = \frac{\sqrt{\mu\varepsilon_0}}{2\varepsilon_0}\kappa I_{1,\mathrm{FT}} kd = qI_{1,\mathrm{FT}} . \tag{6}$$

$k = 2\pi/\lambda$ is the wavenumber, d is the thickness of the polymer layer, and μ is the magnetic permeability of the material. $q = \left(\sqrt{\mu\varepsilon_0}/2\varepsilon_0\right)\kappa kd$ is a constant for a given sample. So the resulting birefringence is a function of the intensity of the Fourier transform of transparency t_1.

A second linear polarized wave is passing through transparency t_2 and through the lens. The polarization direction of this wave is rotated by 45° with respect to the polarization state of wave E_1. The intensity distribution of T_2 in the back focal plane of the lens has to be small in comparison to the intensity distribution of T_1

$$I_{T_2}(\xi, \eta) \ll I_{T_1}(\xi, \eta) . \tag{7}$$

So the influence of the second wave on the dielectric tensor of the sample is negligible. This wave is passing through the photoanisotropic sample which is acting as a pure retarder and goes through an polarizer which is situated immediately behind the sample. The transmission direction of this polarizer is rotated by 90° with respect to the polarization state of this second read-out beam $\boldsymbol{E}_2$.

The resulting field distribution O_{out} immediately behind the sample–polarizer combination can be calculated as

$$O_{\mathrm{out}} = K \begin{pmatrix} 0\,0 \\ 0\,1 \end{pmatrix} \mathcal{J}' \begin{pmatrix} T_2(\xi, \eta) \\ 0 \end{pmatrix} , \tag{8}$$

with

$$\mathcal{J}' = R\left(-\frac{\pi}{4}\right) \begin{pmatrix} 1 & 0 \\ 0 & \mathrm{e}^{-\mathrm{i}\delta} \end{pmatrix} R\left(\frac{\pi}{4}\right)$$

and

$$R\left(\frac{\pi}{4}\right) = \begin{pmatrix} \cos\frac{\pi}{4} & \sin\frac{\pi}{4} \\ -\sin\frac{\pi}{4} & \cos\frac{\pi}{4} \end{pmatrix} .$$

Here R denotes the the rotation matrix. Therefore O_{out} can be written as

$$O_{\mathrm{out}} = KT_2(\xi, \eta) \begin{pmatrix} 0 \\ 1 - \mathrm{e}^{-\mathrm{i}qI_{1,\mathrm{FT}}} \end{pmatrix} , \tag{9}$$

where $K = \mathrm{const.}$

Performing the back transformation yields

$$\mathcal{FT}\left[O_{\mathrm{out}}\right] = \mathcal{FT}\left[K \begin{pmatrix} 0 \\ 1 - \mathrm{e}^{-\mathrm{i}qI_{1,\mathrm{FT}}} \end{pmatrix} T_2\right] . \tag{10}$$

Under the assumption $q \ll 1$ which is valid due to the assumptions made by the Kakichashvili model the exponential function can be expanded into a Taylor series and yields

$$\mathrm{e}^{-\mathrm{i}qI_{1,\mathrm{FT}}(\xi,\eta)} \approx 1 - \mathrm{i}qI_{1,\mathrm{FT}}(\xi, \eta) . \tag{11}$$

Substitution into (10) yields

$$\mathcal{FT}\left[O_{out}\right] = \mathcal{FT}\left[K \begin{pmatrix} 0 \\ \mathrm{i}qI_{1,\mathrm{FT}}(\xi, \eta) \end{pmatrix} T_2(\xi, \eta)\right] . \tag{12}$$

The intensity in the focal plane is than given by

$$I_{\mathrm{out}} = K'^2 \left|\mathcal{FT}\left[I_{1,\mathrm{FT}}(\xi, \eta) T_2(\xi, \eta)\right]\right|^2 . \tag{13}$$

Due to the Wiener-Khinchin theorem and the convolution theorem this is equivalent to

$$I_{\mathrm{out}} = K'^2 \mid t_1 \otimes t_1 \star t_2 \mid^2 , \tag{14}$$

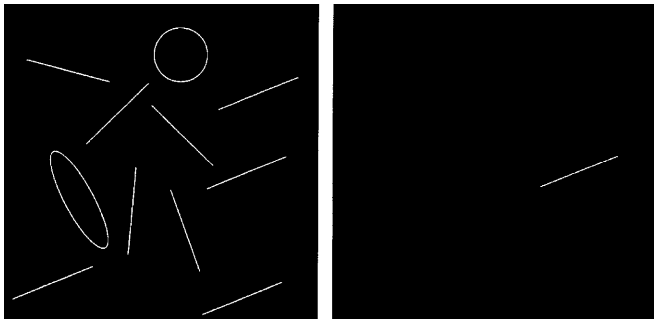

Fig. 2. Input transparencies t_1 (*left*) and t_2 (*right*)

Fig. 3. Calculated output $I_{\mathrm{out}} = K'^2|t_1 \otimes t_1 \star t_2|^2$

where $\otimes$ denotes the correlation and $\star$ denotes the convolution. This expression allows us to find out which structures are simultaneously present in the transparencies t_1 and t_2.

Numerical simulations show the capability of this method. Figure 2 shows the input transparencies t_1 and t_2. The calculated distribution in the output plane is shown in Fig. 3. In contrast to conventional techniques correlation peaks do not appear. The output delivers the object itself in the right position.

2 Conclusions

A theoretical description of a nonlinear optical element based on photoinduced anisotropy in azo-dye-doped polymers for information processing with mutually incoherent beams is given. This element is characterized by performing the convolution of an input transparency with the autocorrelation function of a second input transparency. So it is possible to find out which structures are simultaneously present in both transparencies. First experiments have shown that this method works in principle. A paper about experimental results is in preparation.

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