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Phase encoded binary phase-only filter recorded in the Epson liquid crystal screen

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A phase encoded binary phase-only filter (BPOF) recorded on commercially available liquid crystal screen from Epson video projector is proposed. Optical results of recognition are presented and compared with the results obtained by using the BPOF with enhanced light efficiency recorded by silver halide sensitized gelatin (SHSG) technique.

1. Introduction

The development of the high technology in optoelectronics has led to low cost electrically addressed crystal liquid spatial light modulators (SLM) with significantly improved contrast ratio and optical phase quality [1], [2], [3]. These active matrix cells consisting of twisted nematic liquid crystal can work in amplitude-dominant or phase-dominant regime depending on applied configuration and controlled drive voltage [4].

The phase-dominant regime of SLM is very attractive for applications in optical processors, in particular, in optical correlators which usually suffer from low light efficiency. The SLM introduced in the filter plane of the optical correlator displays the filter distribution controlled by computer. With the SLM working in the amplitude regime, the filter distribution should always be encoded by using encoding methods typical of digital holography (for example, detour-phase methods) [5]. In the case of the SLM working in the phase-dominant regime, there are two possibilities of recording. Firstly, the encoding of the light distribution can be done by detour-phase method or other related methods such as Damman's gratings [6], which code the phase information in lateral positions of the binary apertures, similarly to the amplitude case. The second possibility, very useful for phase-only filtering, is the direct recording of the kinoform distribution [7], [8].

Both approaches, encoding methods application or direct kinoform recording, have advantages and disadvantages. It is well known [5] that in general phase recording of a hologram introduces some distortions which cause deformation of the reconstructed object. It means that the phase-recorded matched filters have distorted impulse response, which results in their limited application in correlation methods [9]. Good recognition results are obtained only if the parameters of the phase -recorded filter are properly chosen and controlled [10]. However, in the case of binary encoding, the impulse response of the binary phase-recorded filter is disturbed no more than the impulse response of the amplitude version [11]. Therefore, the recognition capability of the optical correlator is not degraded [12], [13]. But the encoding method needs usually more than one cell to record one pixel value of the light distribution and the number of cells of SLM is recently rather limited. As a result, the space-bandwidth product of the optical processor is very low. Direct kinoform recording optimizes the space-bandwidth product of the system by using only one cell for one pixel value, but if the range of the phase changes of the SLM is smaller than 2π, the deformation of the impulse response of the filter is introduced by imperfect phase matching [14], [15].

In this paper, a real-time version of computer-generated binary phase-only filters (BPOF) with enhanced light efficiency is proposed. Filters encoded by Burckhardt's method [16] are recorded in computer-controlled liquid crystal screen working in phase-dominant regime. The optical results of recognition are presented.

The quality of the filters and the results of recognition have been compared with the results obtained by using computer generated binary phase-only filters encoded by the same Burckhardt's coding scheme and recorded in silver halide (sensitized) gelatin [13].

2. Phase-recorded binary phase-only filter (BPOF) encoded by Burckhardt's method

2.1. Binary phase-only filters

Let the reference target $g(x,y)$ have the Fourier transform $G(u,v) = A(u,v) \exp[i\Phi(u,v)]$, where $A(u,v)$ and $\Phi(u,v)$ are the amplitude and the phase of the Fourier transform of the target, respectively. According to Horner's definition [17], the phase-only filter $H_{\mathrm{POF}}(u,v)$ has the form

$$H_{\mathrm{POF}}(u,v) = \exp[-i\Phi(u,v)]. \tag{1}$$

The binary version $H_{\mathrm{BPOF}}(u,v)$ of the phase-only filter defined by the formula [18]

$$H_{\mathrm{BPOF}} = \begin{cases} +1 & \text{for } \mathrm{Re}\{H_{\mathrm{POF}}(u,v)\} > 0, \\ -1 & \text{otherwise} \end{cases} \tag{2}$$

yields a binarized version of a cosine filter [19]. It means that the impulse response consists of the target and its inverted version. Therefore, the output signal in the correlation plane is the result of correlation of the input object with the target and an inverted version of the target.

2.2. Burckhardt's method of encoding

The BPOF's are encoded digitally using Burckhardt's method. Burckhardt's coding scheme for producing computer-generated holograms belongs to the family of detour phase encoding methods [11] and is based on the decomposition of a complex value into three complex numbers with positive amplitude and phases equal to 0, $2/3\pi$ and $4/3\pi$. This means that the complex transmittance $A\exp(i\Phi)$ of each pixel of the filter is replaced by the superposition of three complex numbers [16]:

$$A\exp(i\Phi) = A_0 + A_1\exp(i2/3\pi) + A_2\exp(i4/3\pi) \tag{3}$$

where A_0, A_1 and A_2 are real and positive. The decomposition of Eq. (3) is not the only one. Usually, to obtain experimental results the decomposition suggested by Burckhardt is applied: the minor component A_0, A_1, or A_2 becomes equal to zero in each pixel [20].

Each pixel of the filter is represented in the hologram by a cell with three subapertures with transmissions A_0, A_1 and A_2. By illumination of the filter with an inclined beam in such a way that the phase variation between the two sides of a cell is equal to 2π, the complex amplitude $A\exp(i\Phi)$ is obtained.

The binary phase-only filter defined by Eq. (2) has amplitude A uniform and equal to one [17], and the phase Φ takes only two values, 0 or π. Thus, the transmittance $\exp(i\Phi)$ which represents only real values (binary cosine filter) can be obtained by superposition of only two terms

$$\exp(i\Phi) = A_0^b + A_1^b\exp(i\pi). \tag{4}$$

In the case of the amplitude recording the coefficients A^b take only two values, 0 or 1, which means that each pixel of the filter is represented by a cell which has two apertures with transmittance 0 or 1. Thus we obtain a binary mask.

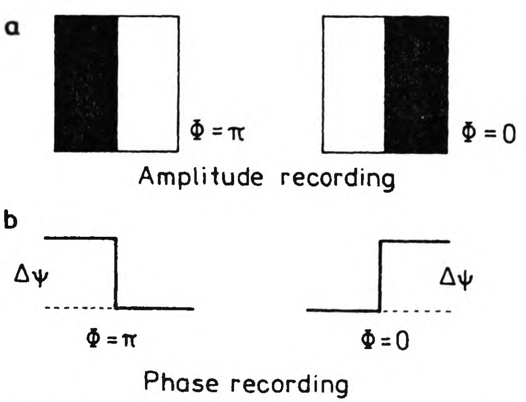


Fig. 1. Cell structure with two components encoding two phase values in the case of amplitude recording (a) and in the case of phase recording (b)

Figure 1a shows the cell structure with two components encoding two phase values 0 or π in the case of amplitude recording. The transmittance $C_{j,k}(u,v)$ of the cell corresponding to the j,k pixel of the BPOF filter is described by [11]

$$C_{j,k}(u,v) = \sum_{p=0}^{1} a_{j,k}(p)\mathrm{rect}\left(\frac{u}{\delta u/2}-p\right)\mathrm{rect}(v/\delta v) \tag{5}$$

where u, v and δu, δv are the coordinates in the filter plane and the cell dimensions, respectively, and p is the index of the subaperture of the cell. In the case of amplitude recording, the coefficients $a_{j,k}(p)$ are real and positive and represent the transmission of proper subapertures of the cell.

2.3. Phase recording of BPOF

It is not necessary that the coefficients $a_{j,k}(p)$ of the corresponding subaperture of the cell have only real and positive values. In the case of the phase recording (for example, by using the bleaching procedure) which introduces phase modulation, the coefficients $a_{j,k}(p)$ are complex and take the form [11]

$$a_{j,k}(p) = \exp[i\psi_{j,k}(p)] \tag{6}$$

where $\psi_{j,k}(p)$ is the phase value resulting from the phase recording.

The transmission of both subapertures of the encoded cell is 100% and only the phase shift $\Delta\psi_{j,k}$ between them is observed (see Fig. 1b) as a result of the phase modulation equal to

$$\Delta\psi_{j,k} = \psi_{j,k}(0)-\psi_{j,k}(1). \tag{7}$$

The value of $\Delta\psi_{j,k}$ of the phase shift can be arbitrary, but to achieve the maximum light efficiency of the filter it is necessary to get $\Delta\psi_{j,k} = \pi$ [11]. Thus, one of the best choices for coefficients $a_{j,k}(p)$ in the case of the phase recording regarding the light efficiency is: $a_{j,k}(0) = \exp(i\psi_0+\pi)$ and $a_{j,k}(1) = \exp i(\psi_0)$ for $\Phi = \pi$, whereas $a_{j,k}(0) = \exp i(\psi_0)$ and $a_{j,k}(1) = \exp(i\psi_0+\pi)$ for $\Phi = 0$. The constant ψ_0 is the initial value of the recording phase material.

The transmittance of the BPOF which has the form of binary phase mask with $M\times N$ cells is [11]

$$T(\mu,v) = \sum_{j=-M/2}^{M/2-1}\sum_{k=-N/2}^{N/2-1} C_{j,k}(\mu-j\delta\mu, v-k\delta v). \tag{8}$$

The corresponding impulse response $\bar{T}(x,y)$ of the filter takes the form [11]

$$\bar{T}(x,y) = \sum_{j=-M/2}^{M/2-1}\sum_{k=-N/2}^{N/2-1} \overline{C_{j,k}}(x,y)\exp\{2\pi i[x(j\delta u)+y(k\delta v)]\} \tag{9}$$

where $\overline{C_{j,k}}(x,y)$ is the Fourier transform of the transmittance of the cell described by Eq. (5) which causes the "sinc" modulation.

2.4. Correlation plane of the optical correlator with the low space-bandwidth-product

The "sinc" modulation of the impulse response related to the finite size of the pixel can be neglected only for high resolution recording such as the electron beam litography [21]. In digital holography this influence is usually eliminated by the precompensating of the recorded object [11]. Recent spatial light modulators

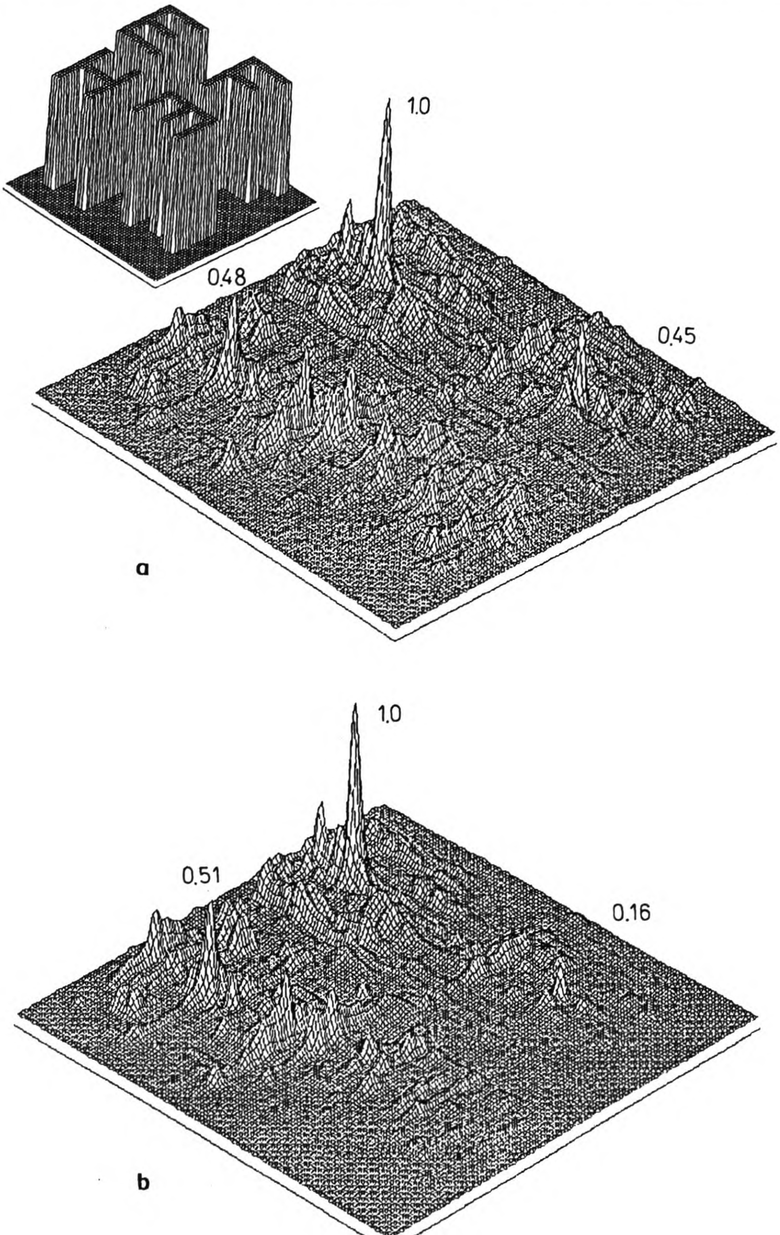


Fig. 2. Correlation plane without (a) and with (b) the influence of the "sinc" modulation

controlled by computer assure only low resolution with limited number of pixels. In such a situation, the influence of the "sinc" modulation changes remarkably the impulse response $\bar{T}(x,y)$ of the filter [11], and as a consequence, modifies also the light distribution in the correlation plane [22].

As an example, Figure 2 shows the correlation plane obtained digitally for the input scene containing 4 characters ("E", "E" rotated, "F" and "H"). BPOF is matched to the character "E". The dimension of the input matrix is 128×128. Figures **2a** and **2b** present the intensity distribution in two cases: without (Fig. 2a) and with (Fig. 2b) the influence of "sinc" modulation [22]. We see that the "sinc" modulation changes significantly the correlation peak values. This can create misunderstanding during classification.

3. Experimental results

3.2. Optical set-up

The real-time optical correlator with the commercially available liquid crystal screen (LCTV) from Epson video projector (VP-100PS) located in the filter plane has been applied for recognition procedure (Fig. 3). The pixel count of the screen is 320×220. Each pixel measures 55×60 μm with a centre-to-centre spacing of 80×90 μm. The total transmission efficiency of the device is about 38% in the case of the helium-neon laser light. The "brightness" and "contrast" potentiometers of Epson video projector have been used for direct control of the transformation of gray level to applied voltage [1], [2], [7].

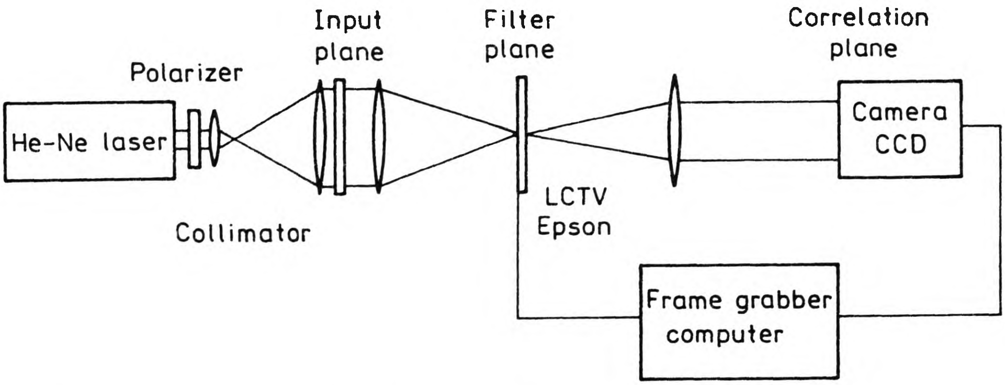
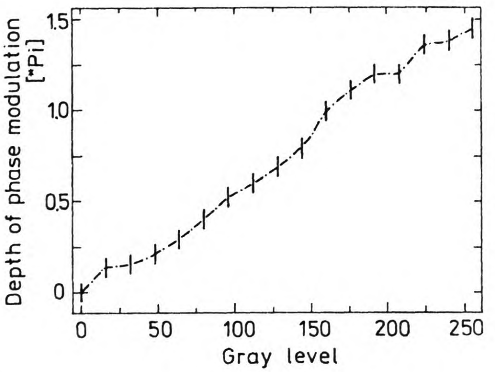
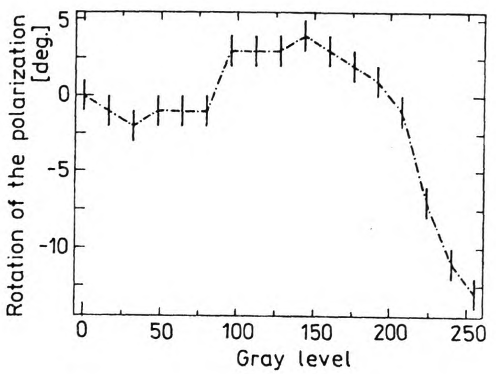


Fig. 3. Optical correlator with the LCTV in the filter plane

The modulation properties of the LCTV depend on the brightness bias voltage [4]. Binary phase-only filters have been recorded in liquid crystal screen working in phase-dominant regime corresponding to a very low level of bias. The phase modulation has been obtained with the brightness control turned to minimum, but the bias voltage has been still above the optical threshold giving only the phase-dominant instead of phase regime. The "contrast" value has been chosen experimentally to be equal to six, taking into consideration dynamic region and linearity of the liquid crystal screen.

The phase modulation depth of the liquid crystal screen as a function of the gray levels (Fig. 4) has been measured in Michelson interferometer. The measurement





▲

Fig. 4. Phase modulation as a function of the gray level in the LCTV. The brightness control voltage has been turned to minimum. The contrast control voltage has been turned to 6

Fig. 5. Angle of rotation of polarization as a function of the gray level in the LCTV. The brightness control voltage has been turned to minimum. The contrast voltage has been turned to 6

error is about 5%. Experimental parameters chosen by us have assured acceptable linearity and distinguishing of 16 gray levels. We have achieved the maximum phase shift of about 270 degrees for the gray level equal to 255. The dominance of the phase regime has been analyzed by the measurement of the rotation angle of polarization which accompanies the phase modulation. The values of the rotation angle of polarization as a function of the gray levels are presented in Fig. 5. By analyzing Figs. 4 and 5, we see that experimental parameters of the optical set-up assure the phase-dominant regime because the phenomenon of rotation of polarization is really neglected.

When the LCTV is controlled by a standard frame-grabber the squared image is displayed as a rectangle. It would be a serious problem for matched filtering because the filter displayed in LCTV screen has impulse response deformed [23]. For compensating the deformation a computer program that performs two-dimensional scaling with independent scaling factors in the horizontal and vertical directions has been applied.

The light distribution in the correlation plane has been recorded by a CCD camera.

3.2. Filter recording

The binary phase-only filter has been matched to the "butterfly 1" (see the top of Fig. 6). The dimensions of the input matrix are 128 × 128 pixels. Each pixel value has been encoded by the Burckhardt's method for phase recording. The resulting matrix

(256 × 256 pixels) has been displayed on liquid crystal screen located in the Fourier plane of the optical correlator.

Figure 7 shows the diffraction efficiency of the phase-recorded BPOF as a function of the phase modulation depth which corresponds to the phase shift $\Delta\psi_{j,k}$. Grey and black bars represent the light intensity obtained experimentally for zero and first diffraction order, respectively. For comparison, corresponding digital results are marked by the lines with full or empty squares. All results are normalized to the total transmitted energy. The maximum of the light efficiency in the first order of

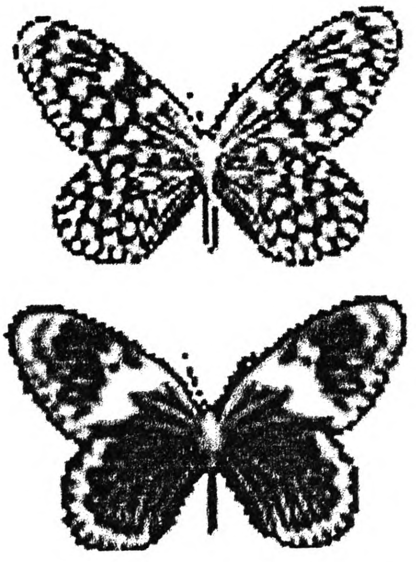


Fig. 6. Input scene. The BPOF is matched to the upper object

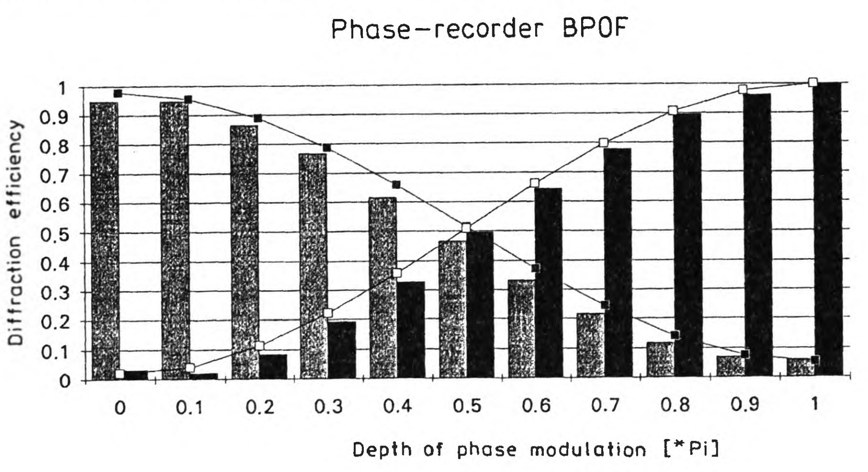


Fig. 7. Diffraction efficiency of the phase-recorded BPOF as a function of the phase modulation depth. Digital results: lines with full or empty squares correspond to the zero and first order of diffraction, respectively. Optical results: gray and black bars

diffraction corresponding to $\Delta\psi_{j,k} = \pi$ has been achieved for the gray level equal to 170. This case has been chosen for filter recording in the Epson liquid crystal screen.

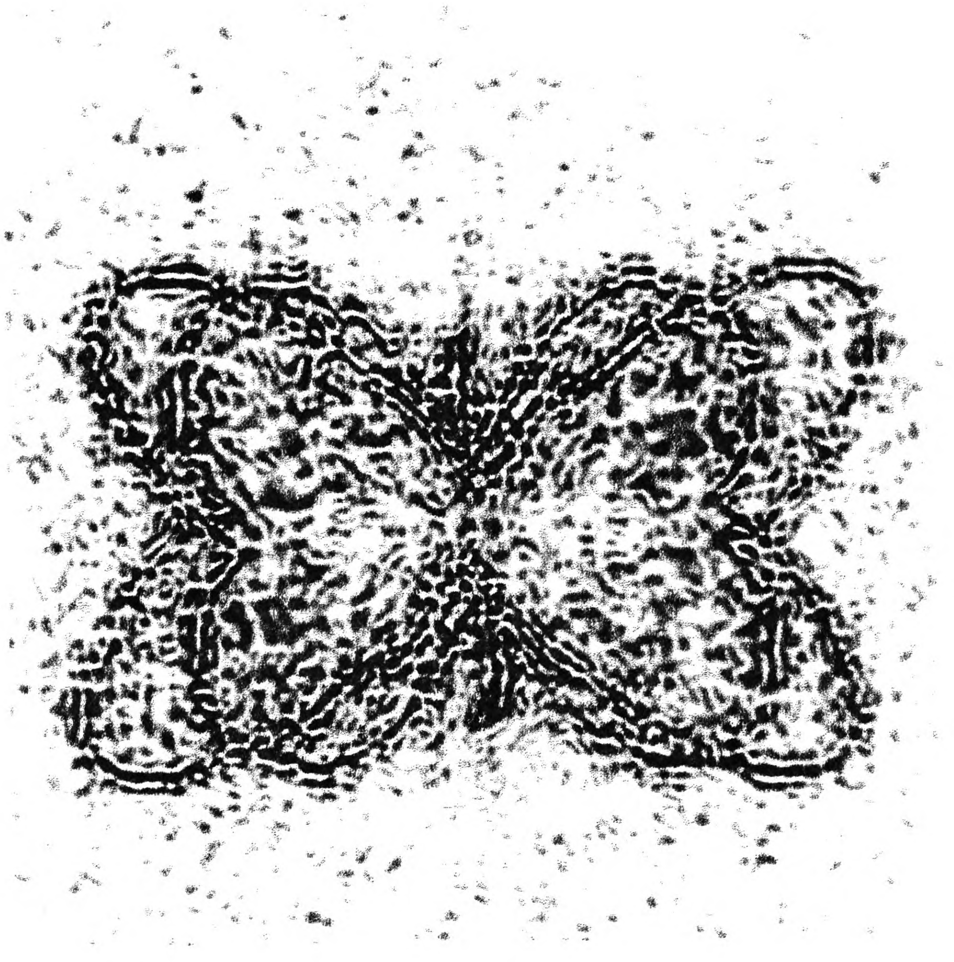


Fig. 8. Impulse response of BPOF obtained optically

The impulse response of the filter obtained optically for the case of the maximum light efficiency is presented in Fig. 8. We see that the impulse response consists of the target and its inverted version. The edge enhancement, typical of the phase-only filter is observed.

3.3. Optical pattern recognition

The input scene and the recognition results obtained optically are shown in Fig. 6 and Fig. 9**a**, respectively. For comparison, Fig. 9**b** presents the recognition results obtained by using BPOF recorded on the same LCTV as the binary kinoform.

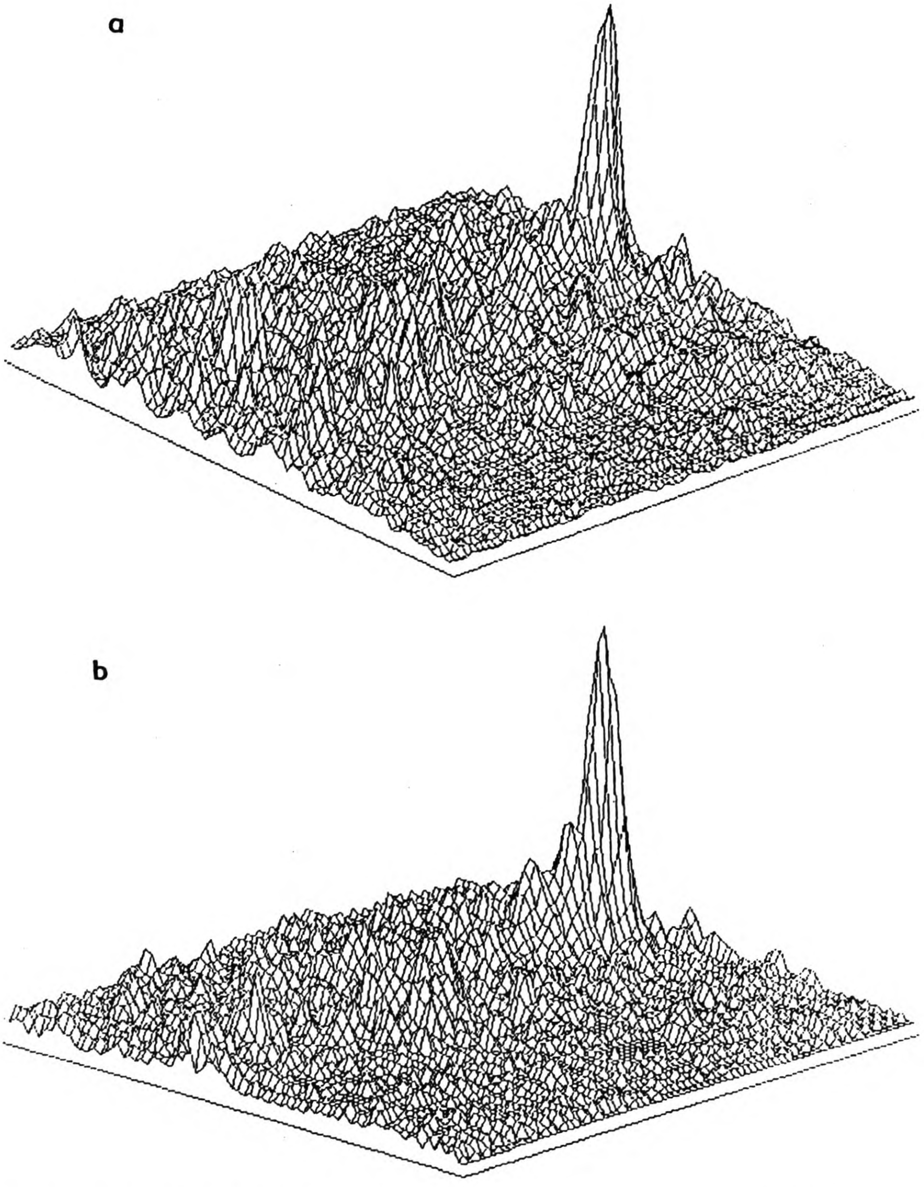


Fig. 9. Optical results of recognition. Correlation plane: **a** — for phase encoded BPOF, **b** — for binary kinoform

The results of the recognition are satisfactory. The level of noise in the correlation plane estimated by the peak-to-root mean square ratio (PRMSR) is equal to 14, and the ratio of the autocorrelation signal to the cross-correlation is equal to 2.4.

The filter quality and the results of recognition have been compared with the results obtained by using computer-generated binary phase-only filters with enhanced light efficiency recorded in silver halide (sensitized) gelatin [13].

The comparison has been drawn in the table, taking into account:

– Measured values of the transmission of the filters, defined as the ratio of the total transmitted energy I_t to the total incident energy I_i.

– Level of noise in the correlation plane estimated by the peak-to-root mean square ratio (PRMSR) defined as [24]

$$\mathrm{PRMSR} = \frac{C_{(0)}^2}{y_{\mathrm{RMS}}^2} \tag{10}$$

where $C_{(0)}$ is the correlation peak energy, and y_{RMS} is defined according to

$$y_{\mathrm{RMS}} = \left[\frac{1}{N_\Omega}\sum_{i\in\Omega} y(i)^2\right]^{1/2}, \tag{11}$$

Ω denotes the set of output pixels for which the output values are below 50% of the peak value and N_Ω denotes the number of pixels in this set.

– The ratio D of the autocorrelation signal to the cross-correlation, describing the discrimination quality of the processor.

– The diffraction efficiency of the filter. The diffraction efficiency is defined in this case as the ratio of the sum of measured energy of the first orders of diffraction to the total transmitted energy. The phase modulation depth achieved by the SHSG technique is equal to $\pi/2$ and does not correspond to the case of the maximum light efficiency.

Table. Phase-recorded BPOF. Transmission, diffraction efficiency, PRMSR, and the ratio D in the case of SHSG method and in LCTV recording

	SHSG	LCTV
Transmission	82%	38%
Diffraction efficiency	48%	71%
$\Delta\psi$*	$\pi/2$	π
D	5.7	2.4 (3.6)
PRMSR	35.6	13.9 (15.6)

* Phase modulation depth applied during the filter generation.

For comparison, in brackets we give PRMSR and D values obtained for the BPOF recorded as the binary kinoform and displayed on the same LCTV working in the same regime.

4. Conclusions

We have used a commercially available LCTV working in phase-dominant regime for encoding BPOF. From the family of detour-phase methods the Burckhardt's coding scheme has been chosen. We have shown that real-time version of computer-generated BPOF with enhanced light efficiency (phase-encoded) obtained in this way gives satisfactory results of recognition. This method can also be useful for reconfigurable computer generated holographic interconnections [25], [26] in optical computing or neurocomputing.

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