Optical implementation of phase extraction pattern recognition

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Phase extraction pattern recognition is implemented on a coherent electro-optical system. The results of the experimental investigation are very interesting and indicate several advantages of this new approach over traditional ones.

In some recent publications, Ersoy [1,2] et al. proposed a new approach for pattern recognition, namely, nonlinear matched filtering. One of the proposals was to extract the phase distribution of the Fourier Transform (FT) of the input function and multiply it by the phase distribution of the filter. The product is then inverse FT (IFT) to yield the output correlation plane. This is shown block diagrammatically in fig. 1. N_l is a point nonlinearity, operating on the function $R(u, v)$, defined by

$$N_l\{R(u, v)\} = \exp[i\varphi(u, v)] , \quad (1)$$

where

$$R(u, v) = |R(u, v)| \exp[i\varphi(u, v)] . \quad (2)$$

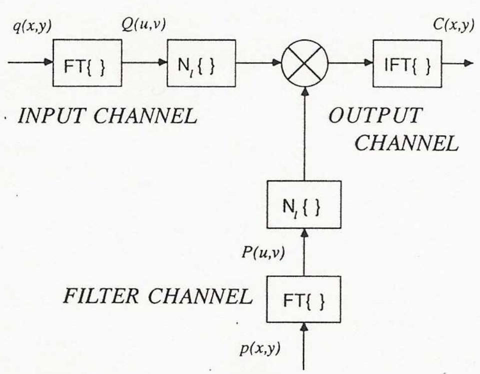

Fig. 1. Block diagram of the NL filtering (correlation) system. $p(x, y)$, $q(x, y)$ and $C(x, y)$ denote the filter, input and output correlation functions, respectively, and N_l is a point nonlinearity, operating on the function $R(u, v)$.

This system offers various advantages including the ability to achieve very sharp correlation peaks [1,2] (Dirac δ functions, theoretically) with high optical efficiency [3] as indicated by computer simulations. In this letter we propose a hybrid electro-

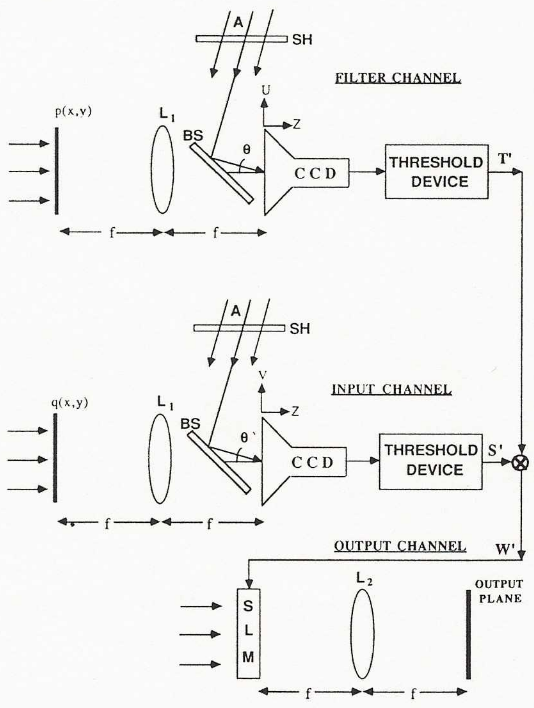

Fig. 2. Electro-optical implementation of the process. The FT of the inputs (performed by lenses L) is superposed by plane waves in beam splitters, BS, and recorded by CCD cameras.

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optical implementation of a phase extraction pattern recognition system as shown schematically in fig. 2. The FTs are performed optically while the phase extraction is performed by the computer with an appropriate interface between the optical and electronic components.

The sequence of operations is as follows. Initially a transparency containing the filter function $p(x, y)$ is placed at the input plane in the upper channel of fig. 2. The FT of the input, obtained by lens L_1 having a focal length f, is superposed on a reference plane wave of amplitude A and recorded by the CCD camera. The reference wave is incident at an angle θ set such that the wave vector is parallel to the uz plane. The intensity distribution recorded by the camera is given by

$$T(u, v) = |A|^2 + |P(u, v)|^2 + 2|A|\,|P(u, v)| \cos[2\pi\alpha u + \Phi_P(u, v)]\,, \tag{3}$$

where

$$\alpha = (\sin\theta)/\lambda\,, \tag{4}$$

$$P(u, v) = \mathscr{F}\{p(x, y)\}\,, \tag{5}$$

$$\Phi_P(u, v) = \arg\{P(u, v)\}\,, \tag{6}$$

with $\mathscr{F}$ denoting the FT. The intensity distribution of $P(u, v)$ is recorded separately by closing the shutter SH. This distribution is used, subsequently for the thresholding operation,

$$T'(u, v) = 0, \quad \text{if } T(u, v) < |A|^2 + |P(u, v)|^2\,, \qquad = 1, \quad \text{otherwise}\,, \tag{7}$$

which can be written in the form

$$T'(u, v) = \frac{1 + \mathrm{sgn}\{\cos[2\pi\alpha u + \Phi_P(u, v)]\}}{2}\,. \tag{8}$$

This relation can be also expressed as a Fourier series expansion,

$$T'(u, v) = \tfrac{1}{2}\left(1 + \sum_{n=-\infty, n\,\mathrm{odd}}^{\infty} \frac{2}{n\pi} \times (-1)^{(n-1)/2} \exp\{in[2\pi\alpha u + \Phi_P(u, v)]\}\right). \tag{9}$$

The FT of $T'(u, v)$ yields an infinite number of diffraction orders along the x axis. The first orders, centered at $(\pm\lambda f\alpha, 0)$, corresponds to the FT of $\exp[\pm i\Phi_P(u, v)]$, respectively.

The foregoing procedure is repeated for the input function $q(x, y)$ (the lower channel of fig. 2) except for the fact that the angle of the plane wave is altered such that the wave vector is now parallel to the vz plane. That is, the new plane of incidence is perpendicular to the one used to generate the filter. After a thresholding operation as before we obtain,

$$S'(u, v) = \frac{1 + \mathrm{sgn}\{\cos[2\pi\alpha v + \Phi_Q(u, v)]\}}{2} \tag{10}$$

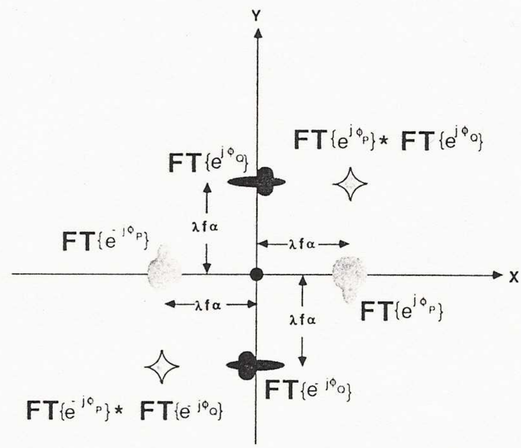

Fig. 3. FT of $W''(u, v)$ – the output correlation plane. The desired correlation regions are marked by ◇.

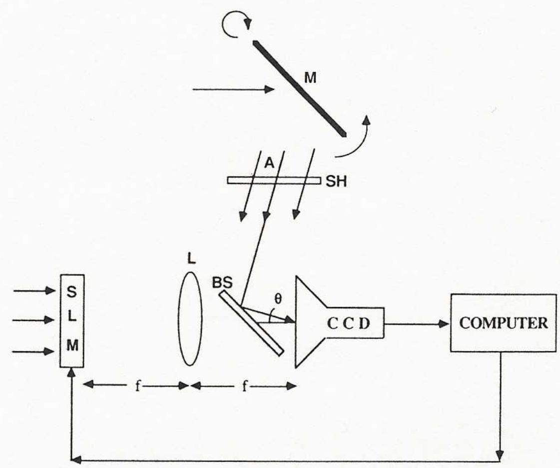

Fig. 4. The 2f laboratory setup executing the process of fig. 2, in three cycles.

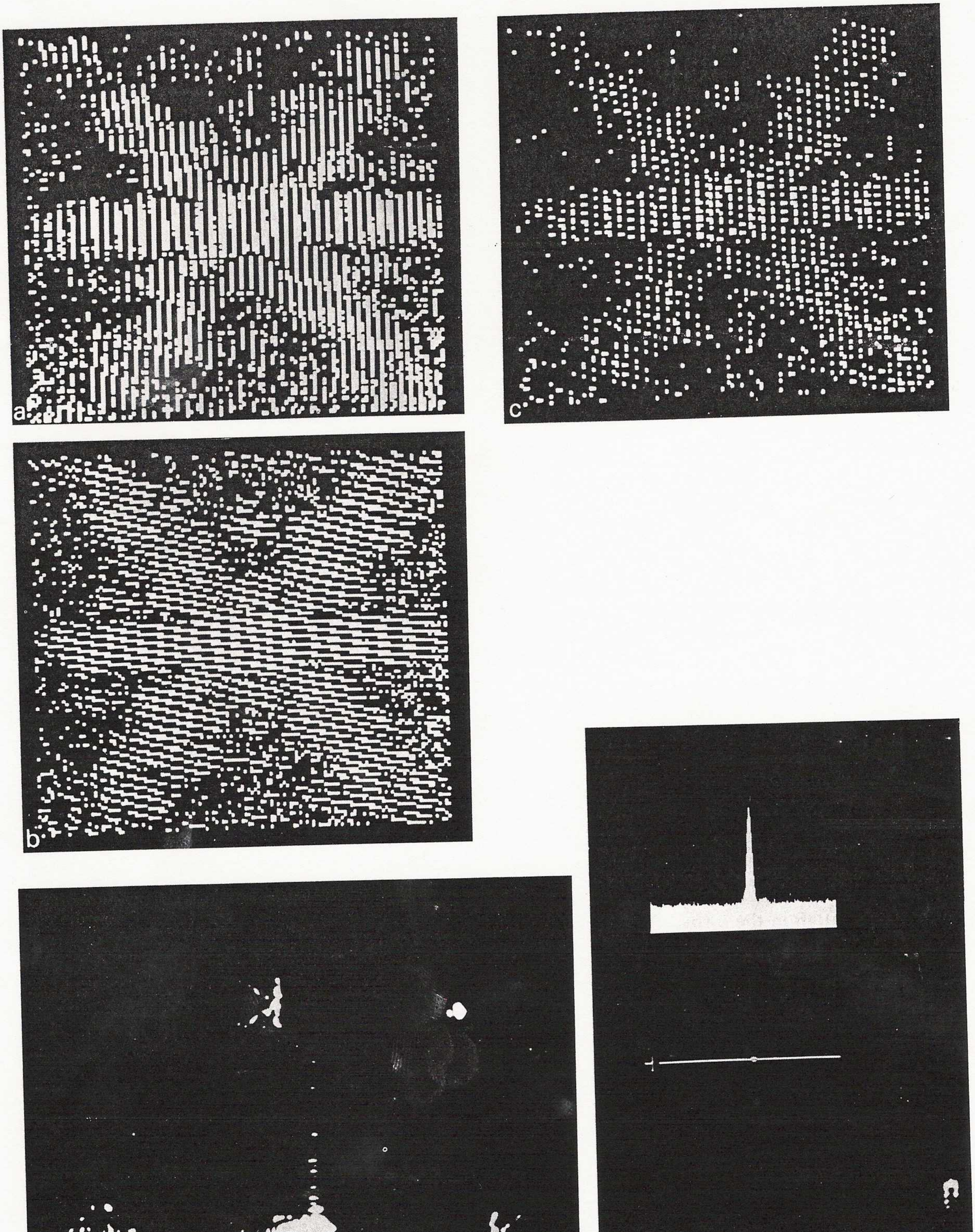

Fig. 5. (a) The binarized interference pattern of the filter-matched to the letter 'K'. (b) The binarized interference pattern of the input – the letter 'K'. (c) W' – the product of S' and T'. (d) The FT of W'. (e) Intensity cross section of (d).

or,

$$S'(u,v)=\tfrac{1}{2}\left(1+\sum_{n=-\infty,n\mathrm{odd}}^{\infty}\frac{2}{n\pi}\right.$$

$$\left.\times(-1)^{(n-1)/2}\exp\{\mathrm{i}n[2\pi\alpha v+\Phi_Q(u,v)]\}\right). \quad (11)$$

The FT of $S'(u,v)$ yields an infinite number of diffraction orders along the y axis. The first orders, centered at $(0, \pm\lambda f\alpha)$, correspond to the FT of $\exp[\pm\mathrm{i}\Phi_Q(u,v)]$, respectively.

Performing a FT on the product

$$W'(u,v)=S'(u,v)\,T'(u,v) \quad (12)$$

displayed on the SLM leads, at the order (1, 1) or (−1, −1), to the desired cross-correlation. The relevant terms of $W'(u,v)$,

$$(1/\pi^2)\exp\{\pm\mathrm{i}[2\pi\alpha u+2\pi\alpha v$$

$$+\Phi_P(u,v)+\Phi_Q(u,v)]\}$$

yield the required correlation terms after a FT as illustrated in fig. 3.

In the laboratory we performed the whole process in a single optical channel (fig. 4) in three time cycles. The two different wave vectors of the plane wave were obtained by properly tilting the mirror, M.

The reference input for one set of experiments was the letter 'K'. The binarized filter, $T'(u,v)$ (eq. (9)) is shown in fig. 5a. For the same input, the binarized interference pattern corresponding to $S'(u,v)$ (eq. (11)) is shown in fig. 5b. Note that the fringes in fig. 5a are perpendicular to those of fig. 5b, as expected. $W'(u,v)$, the product of $S'(u,v)$ and $T'(u,v)$, is shown in fig. 5c and its FT, in fig. 5d. The cross-cor-

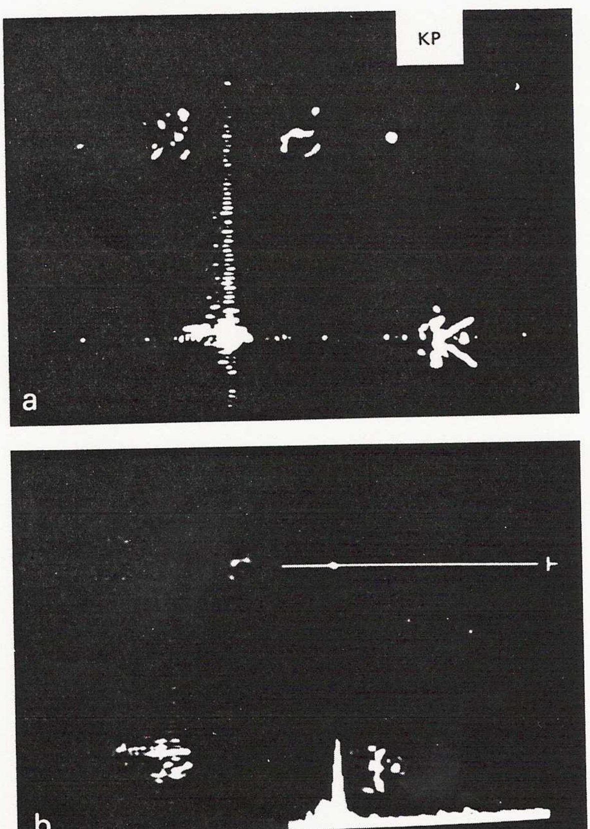

Fig. 6. (a) The FT of W', when the letters 'P' and 'K' are the input, 'K' the filter. (b) Cross section of (a).

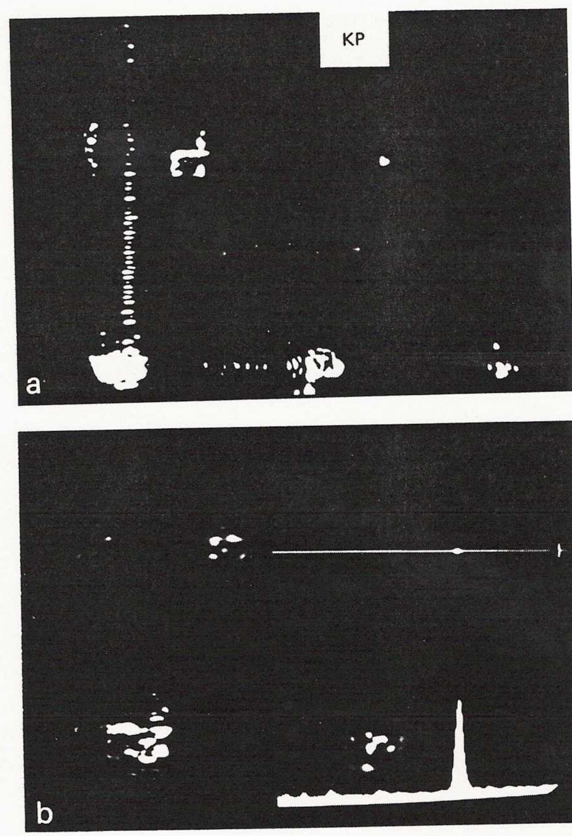

Fig. 7. (a) FT of W' obtained when the letters 'P' and 'K' are the input, 'P' the filter. (b) Cross section of (a).

relation signal at position (1, 1) is displayed in fig. 5e.

Using the same filter, an input composed of the letters ‘P’ and ‘K’ (one next to the other) was displayed on the SLM. Multiplying the binarized interference pattern of the input by the binarized interference pattern of the filter resulted in W', whose FT is shown in fig. 6a. A strong peak at the position of the correlation with the letter ‘K’ is clearly observed whilst the letter ‘P’ is not detected. This is made even clearer in fig. 6b where a cross section of the relevant correlation peak is shown.

Finally, using the same input as for fig. 6, we generated $W'(u, v)$, this time however with the filter matched to ‘P’. The FT of W' is shown in fig. 7a and the cross section of the cross correlation peak is shown in fig. 7b. We observe a strong peak at the position corresponding to the ‘P’, as expected.

In summary we demonstrated an optical phase extraction pattern recognition system. The main attributes of this procedure are extremely narrow correlation peaks, like an inverse filter, but with very high light efficiency (much higher than any linear system can achieve). Thus an exceptionally high discrimination is obtained. Also, as both the input and filter are processed in the same optical system, optical distortions are automatically accounted for.

References

[1] O.K. Ersoy and M. Zeng, J. Opt. Soc. Am. A 6 (1989) 636.

[2] O.K. Ersoy, Y. Yoon, N. Keshava and D. Zimmerman, Opt. Eng. 29 (1990) 1002.

[3] T. Kotzer, J. Rosen and J. Shamir, Phase extraction pattern recognition, OSA Annual meeting, Boston Mass, November 1990.