Quantum Electronics **48** (11) 1048–1054 (2018)

OPTICAL PROCESSING OF INFORMATION

https://doi.org/10.1070/QEL16751

Experimental study of a joint-transform correlator

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***Abstract.* Results of an experimental study are presented for a working model of a joint-transform correlator with a liquid-crystal spatial light modulator at the input. Correlator operation with amplitude and phase modulation and various methods for joint power spectrum processing is compared to investigation results of the modelling partially performed earlier. A simple method is suggested for nonlinear processing of a joint spectrum, namely, limitation of its intensity by a photodetector.**

Keywords: *joint-transform correlator, nonlinear processing of a joint spectrum.*

1. Introduction

A joint-transform correlator (JTC) is a promising device for optical information processing in image identification systems [1–4]. A scheme of the device suggested in [5] was later repeatedly discussed. The correlation function in such a correlator is obtained, first, by using a lens for performing a direct Fourier transformation of input and reference signals (images), which are disposed closely in the input plane of the correlator, and the spatial distribution of their joint power spectrum is recorded (in the back focal plane of the lens). Then, with the same or other lens, the inverse Fourier transform of this distribution is made. At the JTC output, along with spurious optical signals (at a centre of the detection plane), the light intensity distributions are formed (far from the optical axis), which are proportional to the correlation signals.

The JTC properties have been actively studied since the 1970s. Some correlator modifications were suggested for improving such characteristics as a signal/noise ratio, localisation of the correlation maxima, and ability to recognise various kinds of signals and images. Improvements were mainly obtained due to processing of a spatial distribution of the joint power spectrum prior to performing the inverse Fourier transform. The following methods were suggested for affecting the joint spectrum: binarisation, threshold limitation, special amplitude modulation, blocking a constant component and so on [6–10]. The main aim of these methods is to enhance high-frequency components of the spectrum, which are responsible for an image fine structure and to reduce zero-order amplitudes in the correlation plane for reducing optical background. Other methods for improving a JTC were also considered, for example, the purely phase input for removing noise in recognising images against a bright background [9]. All the investigations mentioned were mainly realised with methods of mathematical modelling; there are few publications on the corresponding experimental study.

As a next step towards JTC practical employment we have performed experiments with a JTC operational model and a real-time input unit based on a liquid-crystal (LC) array taken from a video projector [11]. The model comprised a Fourier-processor with a LC spatial light modulator (SLM) at the input and a web-camera at the output. This processor was used both for forming the joint spectrum and for the inverse Fourier transform while obtaining the correlation function at the system output. A computer was used to input the signal to the LC SLM, to process the joint spectrum (with certain algorithms) and to display information from the JTC. The model employed a LC SLM with the number of elements 1024 × 768. A high optical quality of the LC array provided negligible parasitic phase modulation at the processor input.

2. Joint spectrum limitation by a photodetector for improving the JTC signal quality

For obtaining correlation with the JTC model discussed we used nonlinearity of a photodetector characteristic. Operation in a nonlinear range of signal amplitudes (close to photodetector saturation) provided a relatively low noise of the detection unit and made it possible to experimentally realise some methods of nonlinear processing, which have been studied previously by mathematical modelling. The level of joint spectrum limitation by the photodetector, which is equivalent to the threshold processing [7], was easily regulated by changing a radiation power of the laser used for spectrum recording. The employment of such a limiting hardware method does not require extra time for computer processing of the spectrum, in contrast to previously suggested methods (binarisation and others) or the employment of additional elements for optical modulation [10].

Experimental output JTC signals obtained in cases of autocorrelation and cross-correlation for input and reference images in the linear and nonlinear modes of joint spectrum detection are presented in Figs 1 and 2. Here, an amplitude modulation was used in LC SLM.

Autocorrelation signals at the JTC output (for the input and reference signals in the form of letter A) are shown in

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Received 18 June 2018; revision received 27 August 2018
Kvantovaya Elektronika **48** (11) 1048–1054 (2018)
Translated by N.A. Raspopov

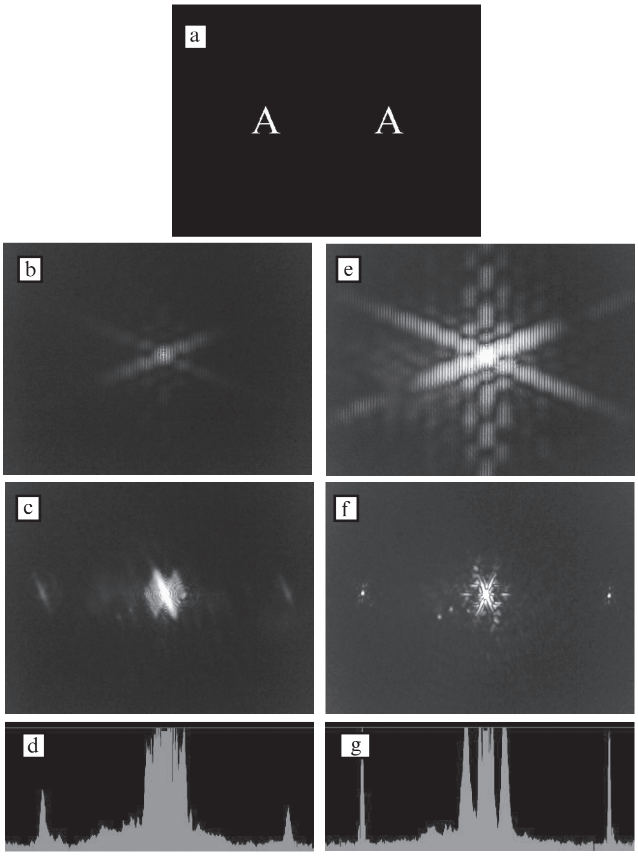

Figure 1. (a) JTC signals in (b, c, d) linear and (e, f, g) nonlinear modes of joint spectrum intensity detection for equal input and reference JTC signals: (b, e) joint spectra, (c, f) output JTC signals, and (d, g) cross sections of output signals.

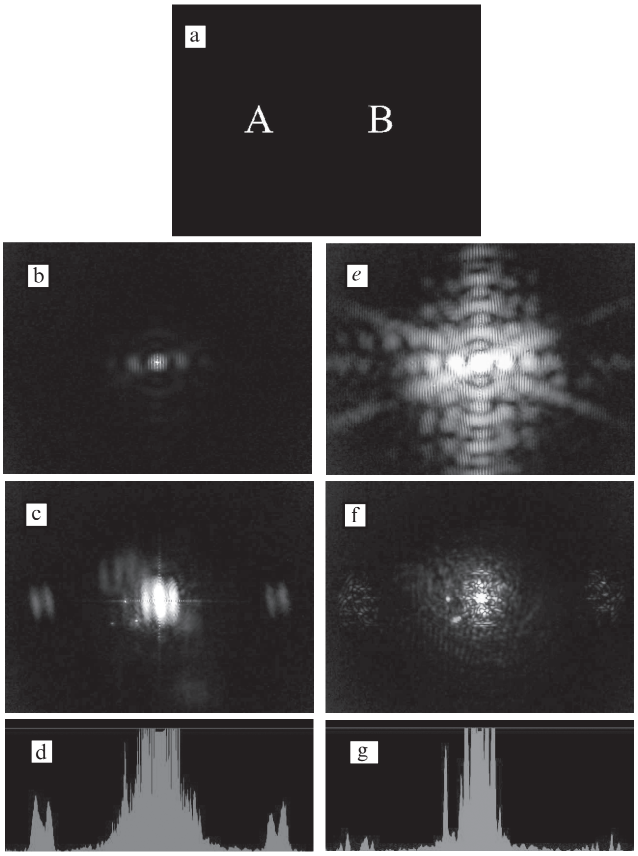

Figure 2. (a) JTC signals of different input and reference signals for (b, c, d) linear and (e, f, g) nonlinear modes of joint spectrum detection.

Fig. 1. One can see that in the nonlinear detection mode (Fig. 1e) the joint spectrum is saturated, autocorrelation maxima (to the left and right from the central peak in Figs 1f and 1g) are narrow and have a substantially greater amplitude than in the linear mode (signal in Fig. 1g is attenuated by an absorbing filter by a factor of 100 as compared to the signal in Fig. 1d). These effects are related to a substantial increase in the amplitude of a joint spectrum in the case of nonlinear detection and to the limitation of its low-frequency component by a photodetector.

Cross-correlation signals at the JTC output are shown in Fig. 2 for the input and reference signals in the form of letters A and B. Taking into account JTC output signal attenuation by filers, the ratios of autocorrelation (Fig. 1) to cross-correlation (Fig. 2) signal power were in the nonlinear mode approximately six times greater than in the linear mode. This is related to the contouring effect in the nonlinear mode of the images participating in correlation due to a lower gain of the low-frequency joint spectrum part as compared to the high-frequency part.

3. Comparison of the binarisation method and limitation by a photodetector. Estimates of the dynamic range and signal-to-noise ratio

JTC signals obtained under computer binarisation of a joint spectrum prior to the inverse Fourier transform and in the case of signal intensity limited by a photodetector are shown in Fig. 3. The results are given for various intensities of the detected joint spectrum for A letters. The binarisation threshold was optimal in each case for obtaining the maximal signal-to-noise ratio near the autocorrelation peak.

From these data follows that processing results are very close. The output autocorrelation signals increase in amplitude and become narrower as the amplitude of the joint spectrum raises in detection and its low-frequency part is limited. One can see that at a high increase in the joint spectrum amplitude, the amplitudes of the side lobes of the correlation maxima also increase especially in the case of binarisation. When the joint spectrum is limited by a photodetector, the amplitudes of the side lobes of the correlation maximum grow slower, which can be explained by a graduate fall of the amplitudes in the high-frequency part of the detected joint spectrum (apodization), which partially persists in this case.

For estimating the influence of the limitation level of a joint spectrum on the signal-to-noise ratio at the JTC output we detected this spectrum at various radiation powers of the laser source and measured a signal and noise at the JTC output. The joint spectra detected by a photodetector are show in Fig. 4 along with the corresponding output signals, in the case of the input signal presented by two input and one reference images (letters A). Resulting measured signal-to-noise ratios at the JTC output are shown in Fig. 5 as functions of the exposure in detecting the joint spectrum intensity. One can see that this ratio increases at a greater limitation level of the joint spectrum and remains great in the exposure range of about 10 dB; then it falls. A sufficiently wide range of the

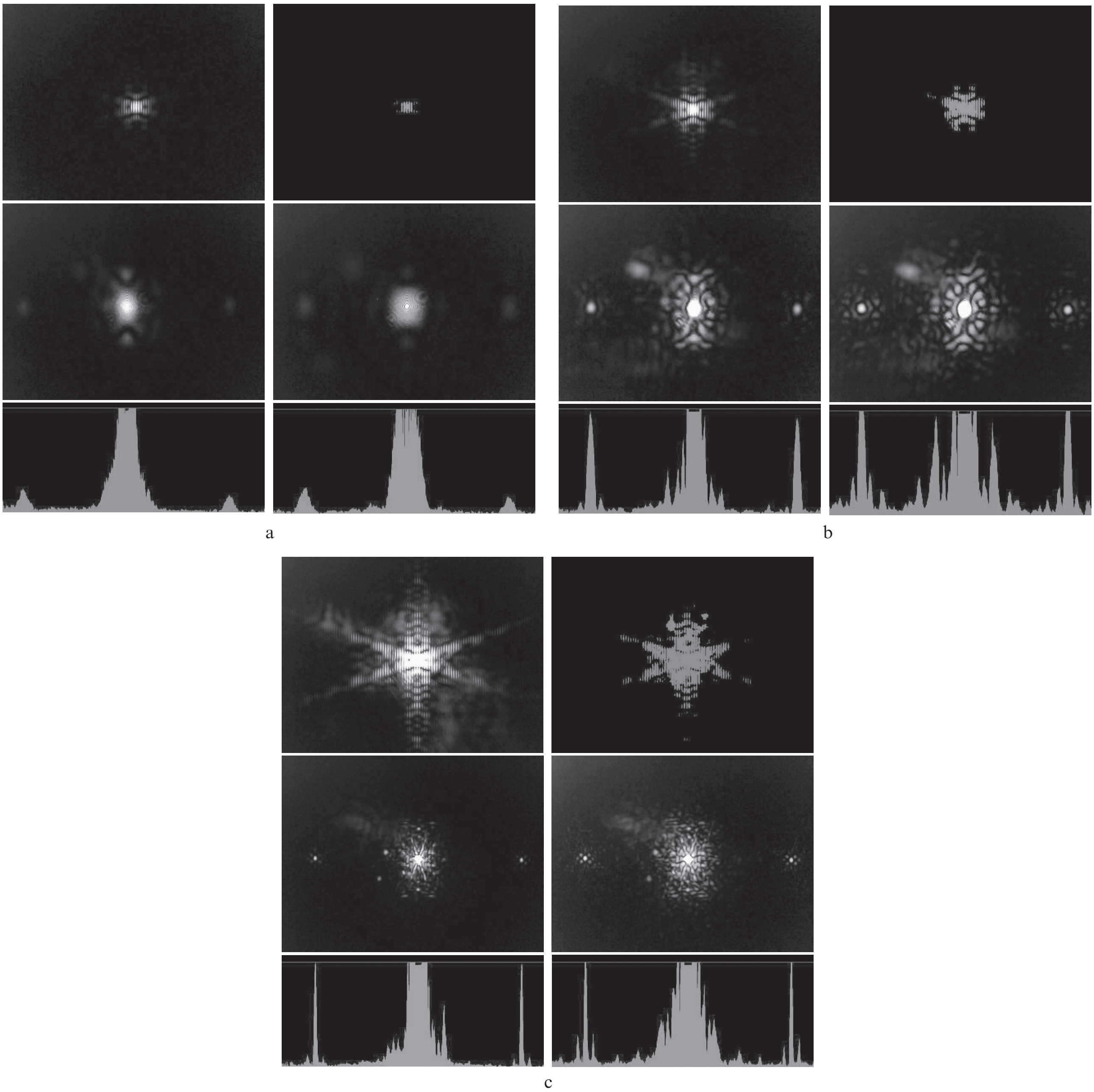

Figure 3. JTC signals for joint spectrum processing by the methods of binarisation (right) and limitation by the photodetector (left) in cases of (a) low, (b) average and (c) high joint spectrum intensities.

optimal exposures makes it possible to avoid JTC tuning under a substantial amplitude variation of input signals.

The possibility of noise reduction at the correlator output was studied by performing experiments on blocking the joint spectrum in a low spatial frequency range. In these experiments, the JTC input signal comprised (vertically distant) one reference and one input images (letters A). In Fig. 6 one can see dependence of the ratio signal-to-noise in the correlation domain as a function of the blocked domain size of the zero-order joint spectrum. The noise level (Fig. 6c) and amplitudes of the correlation maxima (Fig. 6d) depend on the size of the blocked domain (Fig. 6a). In these experiments, the signal-to-noise ratio was 4×10^3 without blocking filter (circle), 5.8×10^3 with a small circle, and 4.5×10^3 with a large circle. Thus, for obtaining the maximal signal-to-noise ratio at the JTC output it is necessary to choose the size of the zero-order blocked domain of joint spectrum. In this case, the blocking has a small advantage (Fig. 6) in the signal-to-noise ratio under the condition of necessary special computer processing of the joint spectrum, which requires additional time, or if a particular filtering device is used, which complicates the system.

We also investigated dependences of the correlator dynamic range on the number of simultaneously processed similar input signals. Due to the nonlinearity of joint spectrum detection in the case of several signals, false cross-modulation maxima arise in the correlation domain (to the left and right from the autocorrelation maximum, as shown in Fig. 4g). One can show that their values sharply fall with a reduction of input signal amplitudes (faster than the value of autocorrelation maxima). The dynamic range of input signal variation corresponding to the interval from the correlation maxima appearance from noise to appearance of false max-

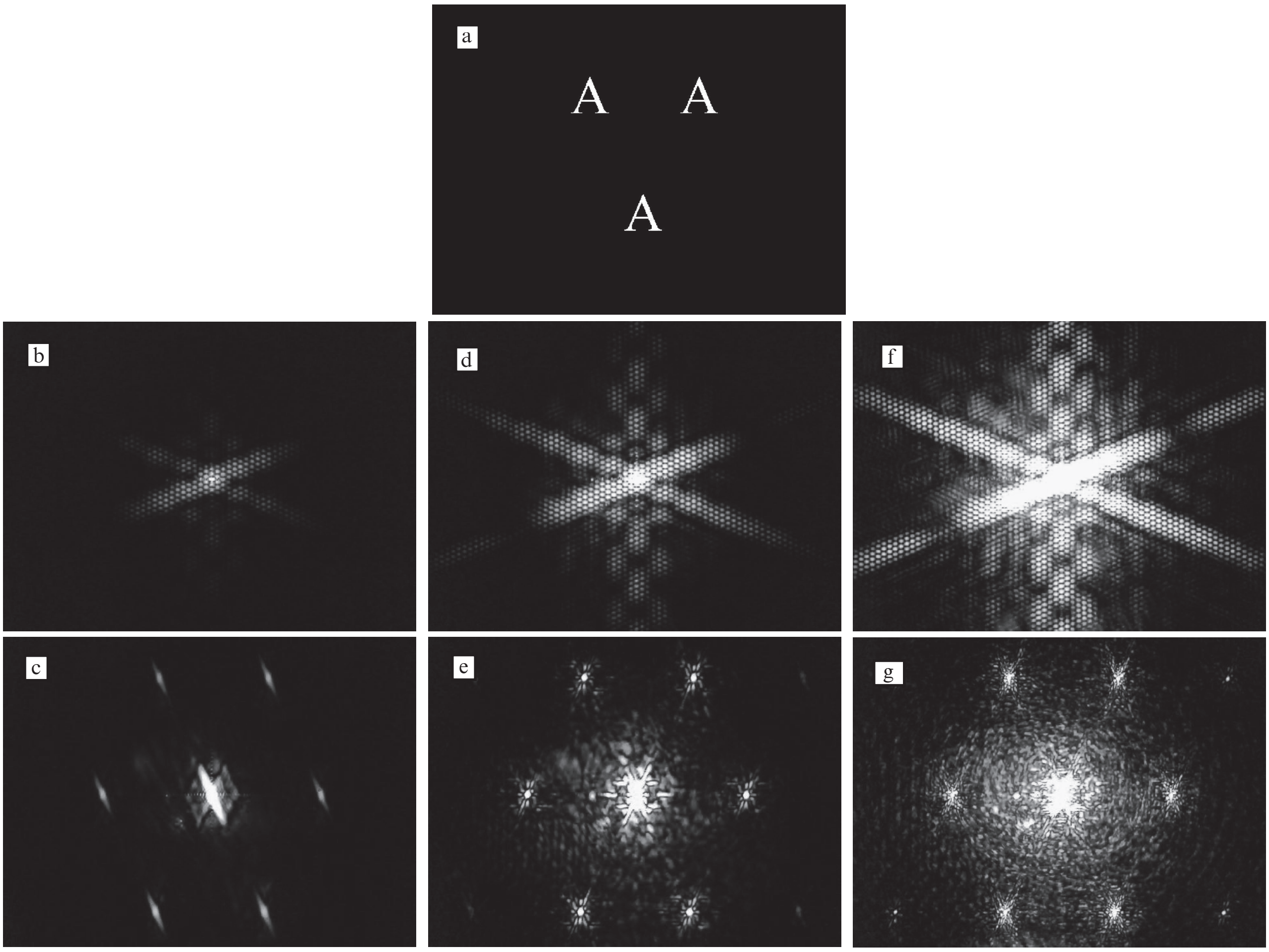

Figure 4. (b, d, f) Joint spectra and (c, e, g) JTC output signals at increased level of joint spectrum limitation for equal two input and one reference signals at the JTC input (a).

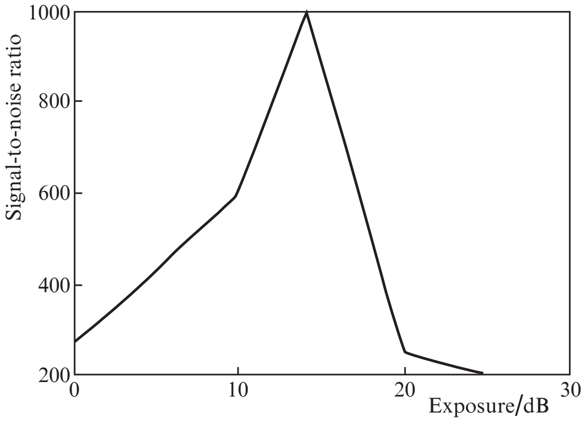

Figure 5. Variation of the signal-to-noise ratio at the JTC output vs. exposure in the detection of joint spectrum intensity.

ima in the correlation domain is about 17 dB for two signals both in the case of photodetector limitation and under binarisation of the joint spectrum. The maximal dynamic range was reached in the nonlinear mode of correlator operation, which in the case of a joint spectrum limited by photodetector was provided by a constant high level of the reference signal at the JTC input over the whole dynamic range of input signal amplitude variation. The nonlinear mode of correlator operation is more thoroughly considered in our work [12].

Thus, the experiments performed show that the JTC with limitation of joint spectrum intensity by a photodetector is as good as the JTC with spectrum binarisation with respect to the dynamic range, signal-to-noise ratio, shape of output signal, and other parameters and does not require additional time for computer processing of signals in the spectrum plane or system complication.

4. Appropriateness of the phase modulation at the input for increasing the discrimination capability of the JTC

It is believed that one of the drawbacks of the JTC with amplitude modulation (AM) in the input plane is impossibility of recognising input images against a bright background and close objects, one of which is part of the other, for example, letters F and E or C and O. It was proposed to overcome the difficulties by using phase modulation (PM) at the JTC input instead of amplitude modulation [9]. Under PM, the correlation response from any section of the input signal domain including the bright background, which phase distribution does not coincide with that of a reference signal, will have a lower value than the autocorrelation response of the reference

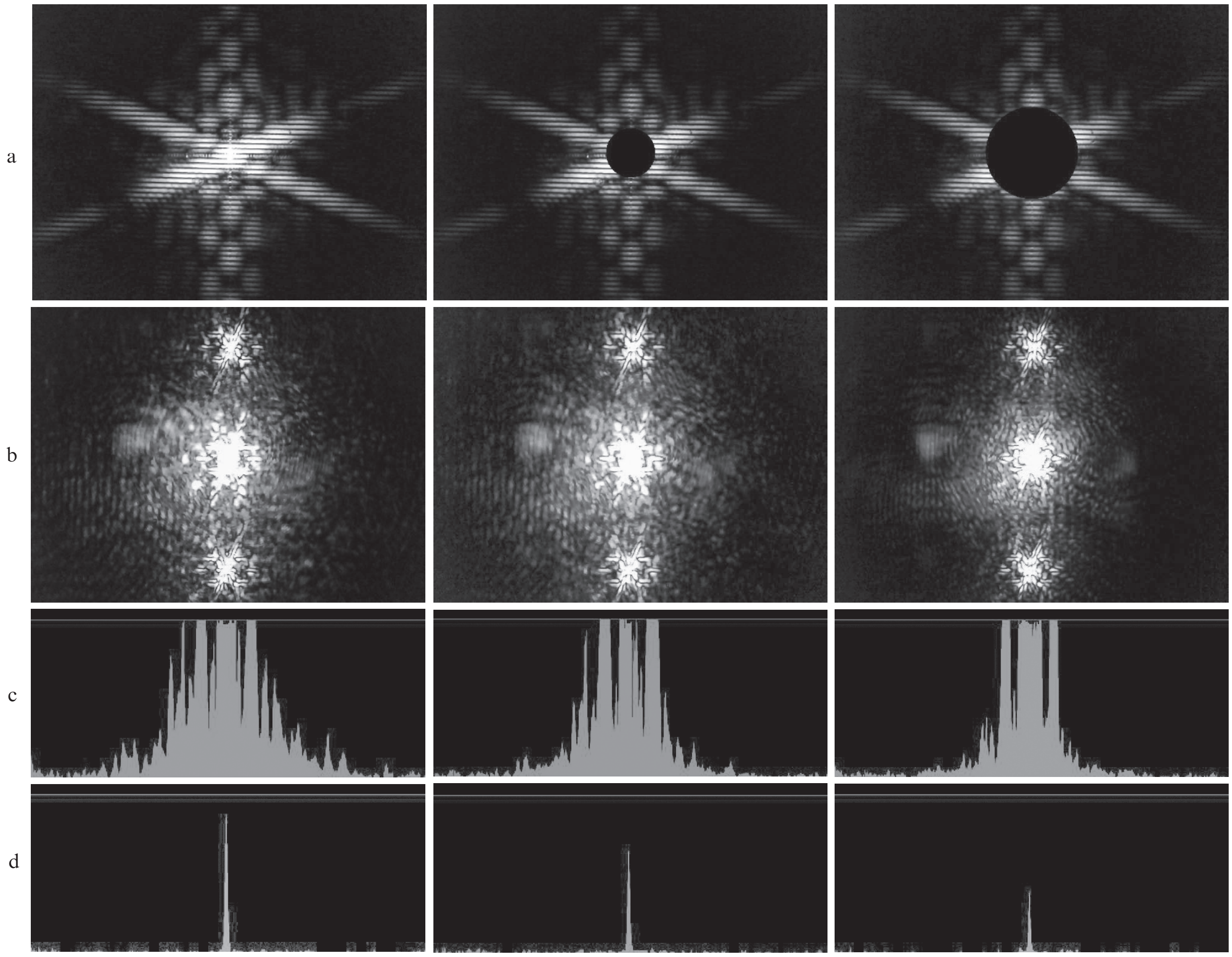

Figure 6. Noise and signal changes at the correlator output at different dimensions of the blocked domain in a low-spatial-frequency range of the joint spectrum (left – without blocking): joint spectra (a), light distribution in the JTC output plane (b), cross-section of the correlation maximum without attenuation (noise estimate) (c), and cross-section of the correlation maximum with attenuation (signal estimate) (d).

signal. Hence, in the case of PM, a bright background at the JTC input does not disturb its operation.

At the same time, it is recommended to block low-frequency components of the joint spectrum in the JTC with PM. The employment of this approach, as well as limitation of low-frequency components in nonlinear processing of the joint spectrum, leads to contouring of the images included in correlation and weakens the response from slowly varying background both in the case of phase and amplitude modulation.

Properties of the JTC with amplitude and phase modulation were compared in a series of experiments. JTC signals for linear and nonlinear modes of joint spectrum intensity detection are shown in Figs 7 and 8 in cases of amplitude and phase modulation at the input. JTC input signals (Figs 7a and 7d) were comprised of binary images of letters O and C, which cannot be distinguished by an ordinary correlator with AM, and a white square imitating a bright background. Letter C was the reference signal. In the case of the phase input, a substantial part of the input plane did not participate in the formation of a joint spectrum due toa superimposed binary grating $0-\pi$ (corresponds to black and white lines in Fig. 7d) [9].

Joint spectra and distributions in the correlation domain are presented in Fig. 7 for a close-to-linear mode of joint spectrum intensity detection. In the case of AM (Figs 7b and 7c), the correlation maxima of close signals $C\star O$ and $C\star C$ are not distinguished in the value (left and right signals in Fig. 7c), whereas two maxima with large amplitudes corresponding to the background interference are in the centre of the distribution. In a linear mode of recording input signals with PM (Figs 7e and 7f), the correlation signals from close signals are distinguished (Fig. 7f), and the background interference is substantially less according to the simplest theoretical analysis [9].

If the JTC operates in a nonlinear mode with limitation of a photodetector-limited low-frequency part of the spectrum then, as one can see from Fig. 8b, in the case of AM it can distinguish similar images (letters C and O) by the values of the correlation maxima (in the autocorrelation case, the amplitude of the signal $C\star C$ is greater), whereas the interference from the background is small. The value of background interference can be estimated from Fig. 8c where the output JTC signal is presented without a white square at the input. As discussed above, the nonlinear mode of joint spectrum detection is preferable in recognition tasks, in which case the problem of reducing noise from a slowly varying bright background is simultaneously solved and the employment of PM is not necessary.

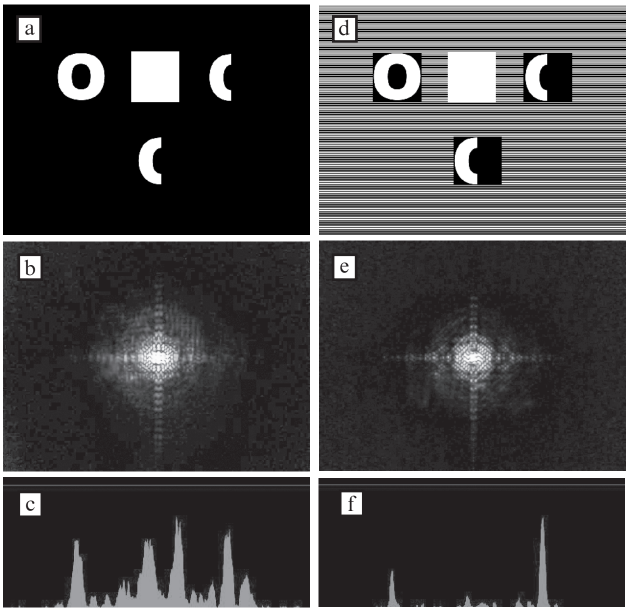

Figure 7. JTC signals under amplitude (left) and phase (right) modulation at the input for the linear mode of joint spectrum intensity detection: (a, d) signals at the JTC input, (b, e) joint spectra, and (c, f) cross section of the correlation signal.

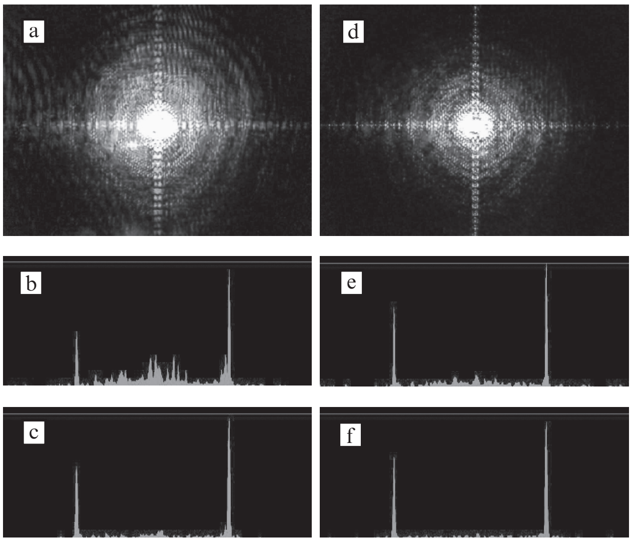

Figure 8. JTC signals under amplitude (left) and phase (right) modulation at the input for the nonlinear mode of joint spectrum detection: (a, d) joint spectra, (b, e) cross section of the correlation signals shown in Figs 7a and 7d, and (c, f) for input signals without white square.

Signals at the JTC output in the case of PM in the nonlinear mode of joint spectrum detection are presented in Figs 8e and 8f. In the case of PM as well as AM, an increase in the joint spectrum amplitude and limitation of its low-frequency components also result in an increase of the amplitudes and narrowing of the correlation maxima at the JTC output. According to experiments, dependence of the signal-to-noise ratio on exposure is similar to that in the case of AM (Fig. 5). Note that the signal-to-noise ratio and ratio of the signal to the interference from the background were greater (approximately twice) in the case of PM than in the case of AM. For binary signals, it is related to a greater energy of the reference signal with PM (a letter inside a background rectangular with a nonzero signal value) as compared to AM (a letter against the background with nonzero level).

We have obtained similar results by comparing JTC operation with AM and PM at the input and a smooth (instead of the binary one) character of the input signals. We used input distributions in the form of 'cosine on a base' signals with linear frequency modulation, etc. When the AM signal is not binary but smoothly varies, a PM signal at the JTC input is obtained by using the AM-to-PM transform function [9]. This function for the LC array is presented in Fig. 9.

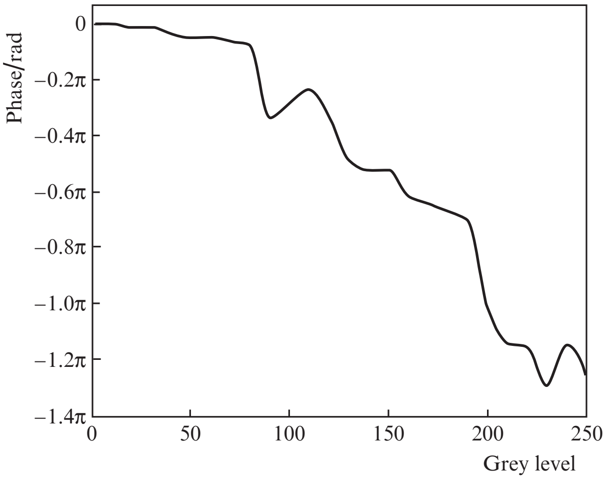

Figure 9. Phase delay in the employed LC array as a function of control signal.

In Fig. 10, one can see an example, where signals at the correlator input (cosine on a base), detected joint spectra, and the corresponding output signals in cases of AM and PM in the linear mode of detection. In the case of phase input, the correlation function is somewhat narrower than in the case of AM, which is not surprising because the PM signal spectrum is wider. In the nonlinear detection of a joint spectrum as well as in processing binary modulated signals, the JTC output signals became narrower and increased in amplitude (by a factor of approximately 20 in these experiments). The value of the correlation function maximum in the case of PM was either equal to or slightly exceeded that in the case of AM, depending on the signal shape and detection conditions.

Thus, a comparison of JTC operation under AM and PM at the input has shown that PM has no substantial advantages if JTC operates in the nonlinear mode of joint spectrum detection, which is usually preferable. Sometimes, PM has a certain advantage in the signal-to-noise ratio at the JTC output, whereas its technical realisation is more complicated due to the necessity of eliminating the background in forming input signals and different adjustment required for the direct and inverse Fourier-processors when the former operates under PM and the letter under AM.

5. Conclusions

From results of the experimental study of the JTC with a liquid-crystal SLM discussed above, we may draw the following conclusions:

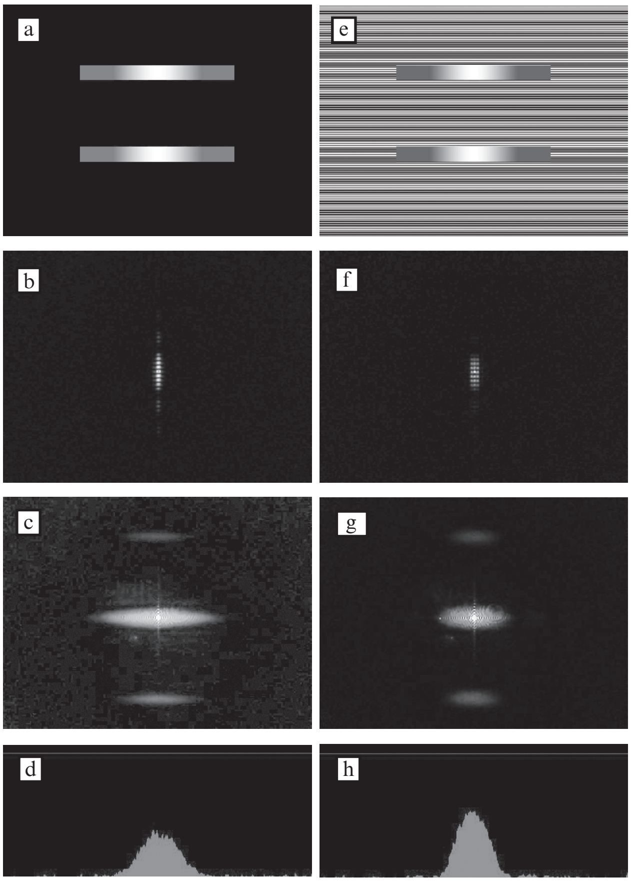

Figure 10. (a, e) JTC input signals (cosine on a base), (b, f) detected joint spectra, (c, g) output signals, and (d, h) their cross sections for the amplitude (left) and phase (right) modulation at the input in the case of joint spectra detection in the linear mode.

– the possibility of improving JTC characteristics due to the nonlinear processing of joint spectrum intensity was experimentally confirmed: increasing the amplitudes of correlation maxima, signal-to-noise ratio, enhancement of correlator discrimination capability;

– the proposed method of limiting the intensity of a joint spectrum by a photodetector presents a simple realisation of spectrum nonlinear processing, which was previously assumed to rely on computer processing or employment of special devices for light modulation; with this method, no additional time is wasted on processing of a joint spectrum and no additional modulation devices are needed.

– the method of limiting the joint spectrum intensity by a photodetector improves the JTC characteristics not less efficiently than the earlier suggested binarisation method with an optimally chosen threshold and the method for blocking low-frequency spectrum components;

– the range of joint spectrum intensities, in which the parameters of JTC output signals keep the required operation values is about 10 dB; this intensity range can be easily provided for a wide variation of JTC input signals due to a constant (high) level of the reference signal (image);

– the dynamic range of JTC input signals (images) depends on the number of simultaneously processed similar signals, and in the case of two signals it is ~20 dB;

– the JTC with SLM based on a LC array from a video projector can operate both with amplitude and phase modulation at the input; with PM, the discriminating capability of image distinguishing in the linear mode of joint spectrum detection increased;

– in the nonlinear mode of joint spectrum intensity detection, which improves JTC characteristics in cases of both amplitude and phase modulation, advantages of PM are insignificant (a small increase in the signal-to-noise ratio), whereas the complexity of realisation gives rise to doubt upon expedience of its employment in a JTC.

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