Optical encryption of series of images using a set of encryption keys using scheme operating with spatially-incoherent illumination based on two LC SLMs

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Abstract. Optical encryption and numerical decryption of series of test images using a set of different encryption keys is carried out using scheme operating with spatially-incoherent illumination based on two LC SLMs. Results of experiments on images optical encryption and numerical decryption are presented. Satisfactory average decryption error over 49 encrypted images equal to 0.20±0.05 is achieved.

1. Introduction

Methods of optical encryption have been attracting researchers attention for many years [1–12]. Most of them operate not only with light intensity, but also with its phase. Original method from whom many varieties were created is double random phase encoding technique [1–6]. Its best feature is transformation of spectrum of image to be encrypted into white spectrum with random phase mask, also, encryption key, which is point spread function (PSF) of second random phase mask, has also white spectrum, consequently encrypted image also has white spectrum. This ensures best security with given number of elements and phase levels a random phase mask. Unfortunately, there are also serious disadvantages in form of holographic setup to register not only light intensity distribution, but also its phase and speckle noise coming with coherent illumination. These factors results in bad decryption quality in optical implementations. Elimination of these disadvantages is possible via usage of incoherent illumination instead of coherent one. In this case, phase registration is not required and speckle noise is gone.

Optical encryption with spatially-incoherent illumination technique was presented in [7]. Its basic principle consists of placing diffractive optical element (DOE) into optical imaging system. DOE acts as an encryption element, its PSF as an encryption key. Light passing through DOE forms convolution of object image and DOE PSF in photosensor plane. This convolution is encrypted image. This principle was used for the first time in [13] not for encryption purpose though, but to improve optical-digital system characteristics. Later, similar principle was used for optical-digital correlators [14,15] in [16].

Optical encryption in spatially incoherent light with two liquid crystal (LC) spatial light modulators (SLM) was experimentally implemented in [12] and later with better quality in [17]. However, despite
the fact that satisfactory quality of decryption was achieved, this claim was based on only few encrypted images. It must be supported with sufficient number of experiments. Therefore, purpose of this paper is optical encryption and numerical decryption of series of test images using a set of different encryption keys using scheme operating with spatially-incoherent illumination based on two LC SLMs.

The rest of the paper organized as follows. In Section 2 experimental setup of optical image encryption with digital information input and dynamic encryption key based on two LC SLMs is described. In Section 3 results of optical encryption and numerical decryption of series of test images using a set of different encryption keys are presented. Main results are given in Conclusion.

2. Experimental setup of optical image encryption with digital information input and dynamic encryption key based on two LC SLMs

Optical encryption with spatially incoherent illumination is based on optical convolution. Mathematical description is given in detail in [18].

Experimental setup of optical image encryption with spatially incoherent illumination is presented in Fig. 1.

![Figure 1. Scheme of optical image with spatially incoherent illumination](image)

Spatial coherence is destroyed by rotating scatterer (ground glass) RS. SLM1 serves for display of image to be encrypted. SLM1 and SLM2 are located in focal planes of lens L3. SLM2 is used for display of encryption DOE. SLM2 and photosensor allocated in focal planes of lens L4. Optical convolution of SLM1 image and PSF of DOE displayed on SLM2 forms on photosensor.

Specifications of experimental setup are given in [18].

3. Experiments on optical image encryption

Set of 7 test images used in experiment on optical encryption is shown in left column of Fig. 2. They have 128×128 elements and 256 halftones.

Direct search with random trajectory (DSRT) method [19–22] was used for encryption keys generation as described in [20]. Seven encryption keys were used in experiments. They had 64×64 elements and 2 gray levels. Their normalized average energy (NAE), i.e. ratio of matrix mean value to its maximum value, equaled to 0.005.

After encryption keys generation, kinoforms with PSF containing these keys were synthesized using Gerchberg-Saxton method [23–25]. Due to intensive zero diffraction order, which occurs due to SLM temporal phase fluctuations [26–28], useful first diffraction order was placed in the corner of restoration field so that image contained within zero diffraction order was located outside camera shaft. Kinoforms had 1080×1080 elements and 256 phase levels. One of the encryption keys and corresponding kinoform are shown in Fig. 3.
Figure 2. Original images (left), encrypted images (middle) and decrypted images (right)
Total of 49 encrypted images was obtained because each original image was encrypted with seven different keys. Examples of encrypted images (one for each original image) are shown in middle column of Fig. 2.

Inverse filter with Tikhonov regularization [29] implemented in MATLAB programming environment was used for digital decryption. In capacity of smoothing function the maximum value of PSF power spectrum was used.

Decrypted images are contaminated with intense interference fringes (see Fig. 4a) which are probably caused by double reflection in protective glass plate mounted right in front of camera’s photosensor. To eliminate interference fringes, Fourier spectrum filtration was used (see Fig. 4c and Fig. 4d). Filtered decrypted image is shown in Fig. 4b. It can be seen that fringes are gone from filtered image. This filtration was used for all decrypted images. Examples of decrypted images (one for each original image) are presented in right column of Fig. 2.

Figure 3. One of the encryption keys (a) and corresponding kinoform (b)

Figure 4. Decrypted image contaminated with interference fringes before (a) and after (b) filtration, and corresponding Fourier spectra (c) and (d)
NSTD [30] between decrypted images and original ones were calculated to assess quality of decrypted images.

NSTD values of all 49 decrypted images are presented in Fig. 5. It can be seen that NSTD values substantially differ between different images and less so for one image but different encryption keys. Averaged NSTD values for 7 images are given in Table 1.

Table 1. Averaged NSTD values for 7 images

| Image number | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|--------------|----|----|----|----|----|----|----|
| Average NSTD | 0.154 | 0.212 | 0.234 | 0.271 | 0.155 | 0.231 | 0.145 |
|              | ±0.007 | ±0.005 | ±0.012 | ±0.008 | ±0.015 | ±0.012 | ±0.007 |

Figure 5. NSTD values of all 49 decrypted images

Conducted experiments demonstrate successful optical encryption and numerical decryption of series of test images using a set of different encryption keys. Decrypted images are contaminated with interference fringes. Fourier spectra filtration was used to eliminate them. NSTD values of 49 decrypted images lie in range 0.14÷0.27. Average NSTD value equals to 0.20±0.05.

4. Conclusion

Optical encryption and numerical decryption of series of test images using a set of different encryption keys is carried out using scheme operating with spatially-incoherent illumination based on two LC SLMs.

Seven test images with 128×128 elements and 256 gray-levels and seven encryption keys with 64×64 elements and 2 gray levels were used in experiments. Keys normalized average energy, i.e. ratio of matrix mean value to its maximum value, was to 0.005.

Results of experiments demonstrate successful optical encryption and numerical decryption of series of test images using a set of different encryption keys. Decrypted images are contaminated with interference fringes. Fourier spectra filtration was used to eliminate them. NSTD values of 49 decrypted images lie in range 0.14÷0.27. Average NSTD value equals to 0.20±0.05.
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