ASSOCIATIVE IMAGE RECONSTRUCTION AS A METHOD OF FORMATION AND STABILIZATION OF THE ENERGY DISTRIBUTION IN A LASER BEAM

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The principles of formation of laser beams with a given transverse distribution of the field amplitude making use of modified correlation holographic systems have been analyzed. Such beams are intended for using in optical tweezers. Computer simulation was applied to study the effect of input beam distortions on the amplitude properties of the output beam.

Manipulation of micro- and nanoparticles, atoms and molecules, and the control over their mechanical motion by means of laser beams have already been used for a long time in fundamental physical researches, microelectronics, biology, and medicine [1]. The trapping and the retention of a microparticle in a laser beam are executed due to the forces of light pressure acting on the particle. When the induced dipole moment of the particle interacts with a spatially non-uniform electric field in the laser beam, there arises the so-called gradient force of light pressure, which is directed along the light field gradient. In many optical tweezers schemes, this force is crucial for the creation of effective traps and manipulators, because, in focused laser beams with large field gradients, it exceeds the force stemming from the light scattering by particles. That is why the spatial distribution of energy in a laser beam is of importance for the effective implementation of the laser trapping and the manipulation of small material particles.

In the early works dealing with the action of light pressure on small particles, laser beams with the Gaussian profile of intensity and the intensity maximum at the beam axis were used [2]. Later, the development of laser tweezers technique, the increase of the number of object categories allowed for the manipulation (transparent and opaque dielectric particles, metal particles, biological objects, and so on) gave rise to the necessity to form more complicated distributions of the optical field in laser beams for their use in optical tweezers. Laser beams with non-Gaussian field distributions are used today in schemes for the trapping and the retention of particles of different origins and dimensions, for transferring the rotational moment to particles, and so forth [3, 4]. A possibility of the stable retention of absorbing particles in a field that was a superposition of the Gaussian mode and the Laguerre–Gaussian one was shown in work [5].

A widespread method for the formation of laser beams with a given non-Gaussian transverse distribution of the light field amplitude is the application of computer-synthesized holograms. Such a hologram is a record of an artificially synthesized pattern of interference between the reference Gaussian beam and the objective beam with a given transverse distribution of the light field. When such a hologram is illuminated with the reference beam, the beam with a sought distribution becomes reconstructed. That is, the hologram transforms the Gaussian distribution of the field into a more complicated, non-Gaussian one [6]. To record synthesized holograms, it is convenient to use a liquid-crystal phase spatial light modulator.

Laser beams really used for the illumination of computer-synthesized holograms have deviations from the ideal distributions of their amplitude and phase, which were assumed in the program for the calculation of holograms. Therefore, from the application-oriented viewpoint on the problem of transformation of the transverse Gaussian light field distribution in a laser beam, it is important to consider an issue how sensitive the output field distribution is with respect to small variations of the amplitude and the phase of the input beam wave front.

A variety of tasks, where the use of optical tweezers is required, invoke the problem concerning the development of a universal (to a certain extent) coherent optical method to form laser fields with preassigned energy distributions over the beam cross-section and a controlled variation of these distributions in time, irrespective of the initial particle characteristics (dimensions, light scattering, and so on) in the tweezers field and the specific field parameters of the beams that were used to form this field.

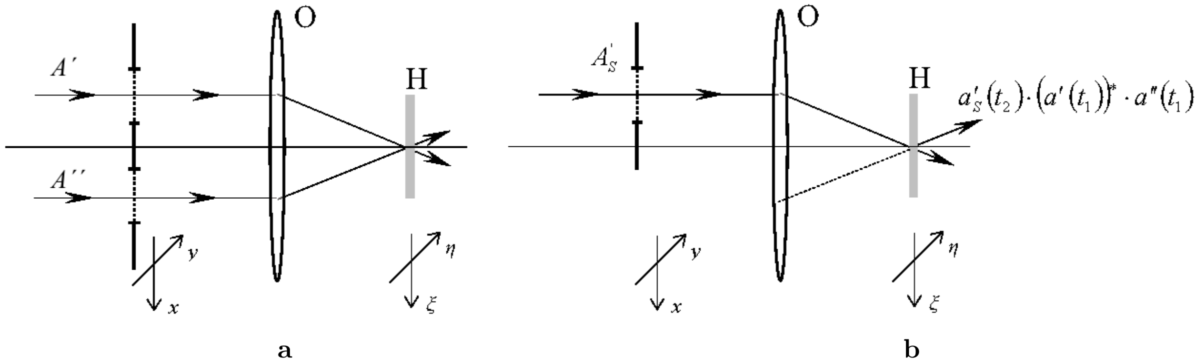

Fig. 1. Schemes of recording (a) and reconstruction (b) in a holographic correlator

Such an issue of the output field stabilization in the problems of laser field formation with a required structure has already been studied for a long time. In the first work on the formation of a beam from a multimode field by means of a hologram [7], it was shown that the applied scheme did not provide a sufficient stability of the output beam parameters, if the structure of the input field varied. Later, similar schemes with stationary holograms were used to stabilize (and minimize) the emission divergence of non-stationary laser sources with rather simple field configurations [8]. The stabilization of an output field structure (the optical information carrier) for more complicated patterns [9] was not intended to be used for technological purposes, because this procedure was characterized by considerable energy losses.

It was shown in work [10], the reconstruction of a holographic image, even at significant modifications and distortions of the reconstruction beam, can be carried out making use of the correlation principle of image restoration. As is known, the result of the optical correlator action [11] consists in that the correlation signal is maximal, provided that the input and the reference signal are identical. In this case, the input signal reproduces the reference wave, by diffracting at the hologram. The signal amplitude falls down, if the difference between the input and reference signals grows; at the same time, the similarity to the field structure of the reference wave is preserved to a certain extent. This fact can be used to develop noise-immune schemes to control the spatial distribution of the laser tweezers field.

In this work, bearing all the abovementioned in mind, we analyze the operation of a holographic scheme with the most promising spatial (diffuse) [12, 13] light modulator, as well as the corresponding computer-synthesized holograms [14]. The results of numerical experiments concerning the determination of the sensitivity of the output light field distribution in the laser beam at various phase and amplitude perturbations of the input beam are also reported.

1. Theoretical Basis of the Method

Interaction of three coherent light beams is used in a holographic correlator: two of them at the hologram record stage and the third one at the reconstruction stage. In the scheme of Fourier hologram recording, the angular spectra of two beams with the spatial distributions of the complex field amplitude at the input $A'(x_1, y_1, t_1)$ and $A''(x_1, y_1, t_1)$ are registered (Fig. 1). On the reconstruction, one uses one more beam, $A'_S(t_2)$, which forms an output signal, by diffracting at the hologram. According to such an algorithm, one may assert that the optical signals $A'(t_1)$ and $A'_S(t_2)$ correlate. The measure of their similarity is the third signal, $A''(t_1)$. Using the mathematical description of this algorithm, in the +1-th order of diffraction, we have a wave, whose field distribution just behind the hologram is proportional to the product of angular spectra of all the three signals, i.e. $a'_S(t_2)\,[a'(t_1)]^*\,a''(t_1)$. Accordingly, on the inverse Fourier transformation, we obtain a signal with the field distribution

$$A_{\rm out}(t_2) = \Im^{-1}\left\{[a'_S(t_2)\cdot(a'(t_1))^*]\cdot a''(t_1)\right\} =$$

$$= [A'_S(t_2)\otimes(A'(t_1))]*A''(t_1)\sim\delta(x,y)*A''(t_1) = A''(t_1) \quad (1)$$

at the correlator output. The notations $\Im$, $\otimes$, $*$, and * correspond to the operation of Fourier transformation, correlation, convolution, and complex conjugation, respectively.

In order that the signal $A''(x_1, y_1, t_1)$ be reconstructed exactly, it is necessary to standardize the correlation

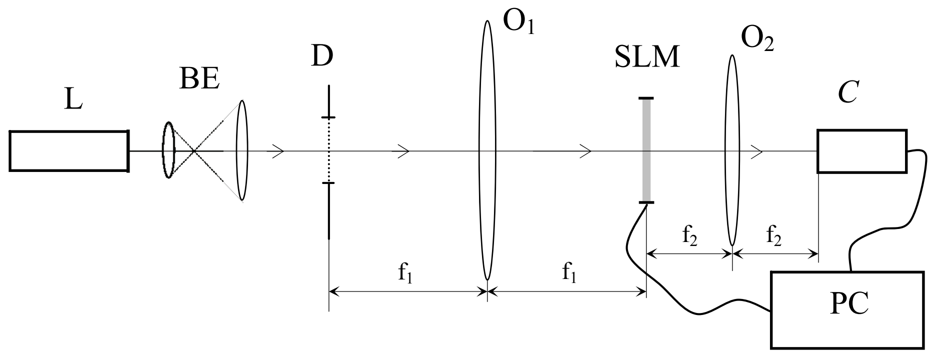

Fig. 2. Scheme of the optical tweezers field formation: laser L, beam expander BE, diffuser D, phase modulator SLM, objectives O_1 and O_2 for the Fourier transform of the field, CCD chamber C, and computer PC

the correlation distribution forms of signals $A'(t_1)$ and $A'_S(t_2)$, by approaching them to a δ-like distribution. Such a solution [8] is possible, provided that both these signals are previously subjected to the spatial phase modulation with the help of diffuser-multiplier D. In this case, the correlation distribution gets the form

$$[DA'(t_1)] \otimes [DA'_S(t_2)] \approx$$

$$\approx [D \otimes D][A'(t_1) \otimes A'_S(t_2)] \to \delta. \quad (2)$$

Then, practically irrespective of the structure of signals $A'(t_1)$ and $A'_S(t_2)$, we obtain the distribution $A''(t_1)$. If the latter is ascribed to the structure of a field that is required for optical tweezers, and time-dependent laser beams of whatever nature are considered as the signals $A'(t_1)$ and $A'_S(t_2)$, we obtain all preconditions for the dynamic stabilization of the field in optical tweezers to be fulfilled.

2. Modification of the Correlator Scheme

Hence, to stabilize the given distribution of the field at input signal perturbations, the correlator scheme should be modified in such a way, that, in order to use the laser radiation effectively, diffuser D with a structure that provides a purely phase distribution of the field over the artificial hologram should be used at the input. To make the control of the spatial field distribution more convenient, artificial holograms are used instead of involving the process of physical recording of a hologram onto a photosensitive medium. The artificial holograms are calculated by a formula, which has the form $[a'(t_1)]^* a''(t_1)$, and they can be reproduced making use of a computer-driven spatial phase modulator.

Provided such conditions, the correlator scheme looks like that depicted in Fig. 2. The computer is used to reproduce a phase transparency with the complex transmittance $[a'(t_1)]^* a''(t_1)$ on the phase modulator. Diffuser D, with the help of objective O_1, forms a field with distribution $a'_S(t_2)$ in the phase transparency plane. Then, the distribution $A''(t_1)$ describes the field in the optical tweezers, i.e. an image conjugate with the diffuser:

$$A''(t_1) = |A''(x,y)|\, e^{i\varphi''(x,y)}, \quad (3)$$

where $|A''(x,y)|$ is the amplitude part that describes the image, and the random function of coordinates $\varphi''(x,y)$ is the diffuser field phase. The function $A'(t_1)$ reproduces the distribution of the diffusive scattered field for an arbitrary (usually, plane) stationary laser beam at the input of the scheme:

$$A'(t_1) = e^{i\varphi'(x,y)}. \quad (4)$$

As in the previous case, the random function of coordinates $\varphi'(x,y)$ is the scattered field phase. The function $A'_S(t_2)$ reproduces the field distribution, provided that the filed varies in the course of lasing, or owing to deformations of the tweezers optical path, or that sort of thing. The quantity $|A'_S(t_2)|^2$ is the intensity of the actually obtained image of tweezers.

As a result, the Fourier objective displays a field on the photosensitive matrix of television camera C, and this field has to correspond to the +1-th diffraction order in the image of an ordinary correlator. It is this field that governs a required energy distribution in the tweezers, which, owing to the correlation mechanism of transformation, turns out insensitive to the variations of the wave front shape of the beam in the optical path of tweezers.

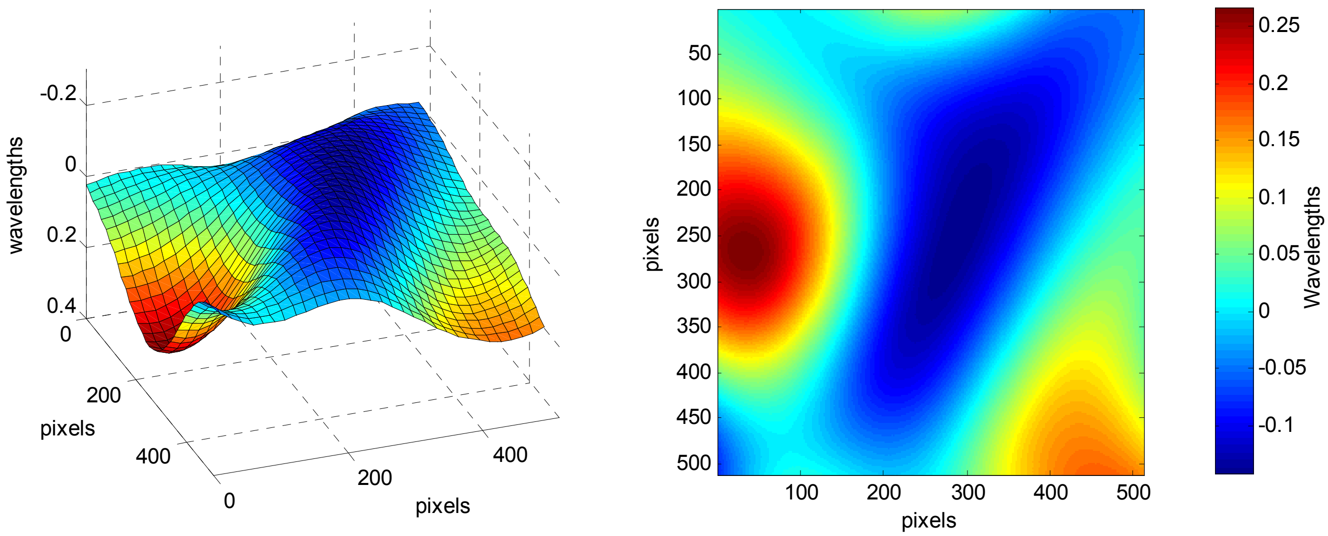

Fig. 3. Configuration of the perturbed wave front in a laser beam

3. Simulation of Experiment

The functioning of the scheme proposed was analyzed on the numerical simulation of experiments. The main issue was to reproduce various perturbations in the wave front of a laser beam. In our calculations, we used the MatLab-6.0r13 mathematics package. Namely, we applied it to images, which were formed by a 512×512 pixel matrix, to approximate varying wave fronts over the laser beam cross-section. An example of the given field distribution is depicted in Fig. 5,*a*.

The shape of the initial perturbation of the wave front used in the simulation is shown in Fig. 3. The magnitude of distortions changing in time is determined by the scale of the distribution over the axis Z, i.e. along the laser beam axis. For a specific distribution depicted in Fig. 3, it is a difference between the field oscillation phases at points, where the deviations of the actual wave front from the plane one are maximal. Note that the initial distribution encoded in the hologram was considered plane.

As a parameter that estimated the quality of the expected image, we chose a quantity

$$\overline{V} = \frac{\overline{I_{\max}} - \overline{I_{\min}}}{\overline{I_{\max}} + \overline{I_{\min}}}, \qquad (5)$$

which can be considered as the average contrast of the optical tweezers field. Here, $\bar{I}_{\max}$ and $\bar{I}_{\min}$ are the average intensities of the sections in the obtained tweezers image that correspond to the sections of the original image with maximal and minimal intensities, respectively.

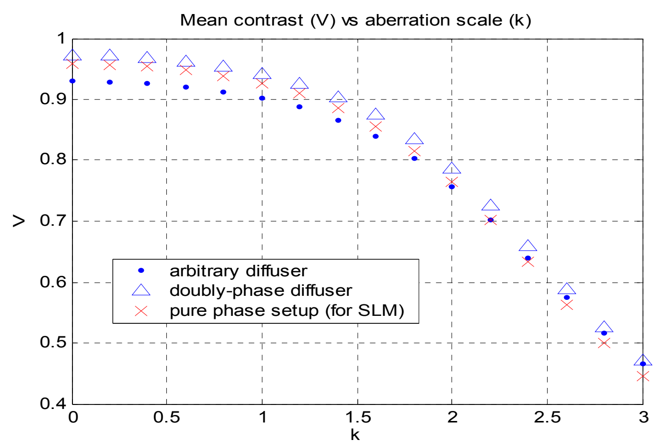

Fig. 4. Dependences of the average contrast in the generated energy distribution on the phase distortion magnitude

The result of simulation is shown in Fig. 4 as the plot of the dependence $V(k)$, where V is the average contrast determined by formula (5), and k the aberration change factor. The latter equals 0 in the plane wave case (in the absence of aberrations). For the initial aberration with phase perturbations of the wave front, the magnitude of which is demonstrated in Fig. 3, this factor was selected to equal 1. Perturbations for k-values different from 1 were simulated by carrying out the k-fold stretching of the initial aberration along the axis Z.

In the figure, we compare the plots for cases where the correlation scheme of the comparison of images with an arbitrary chosen diffuser was used and where the diffuse image of the tweezers field was formed. The latter

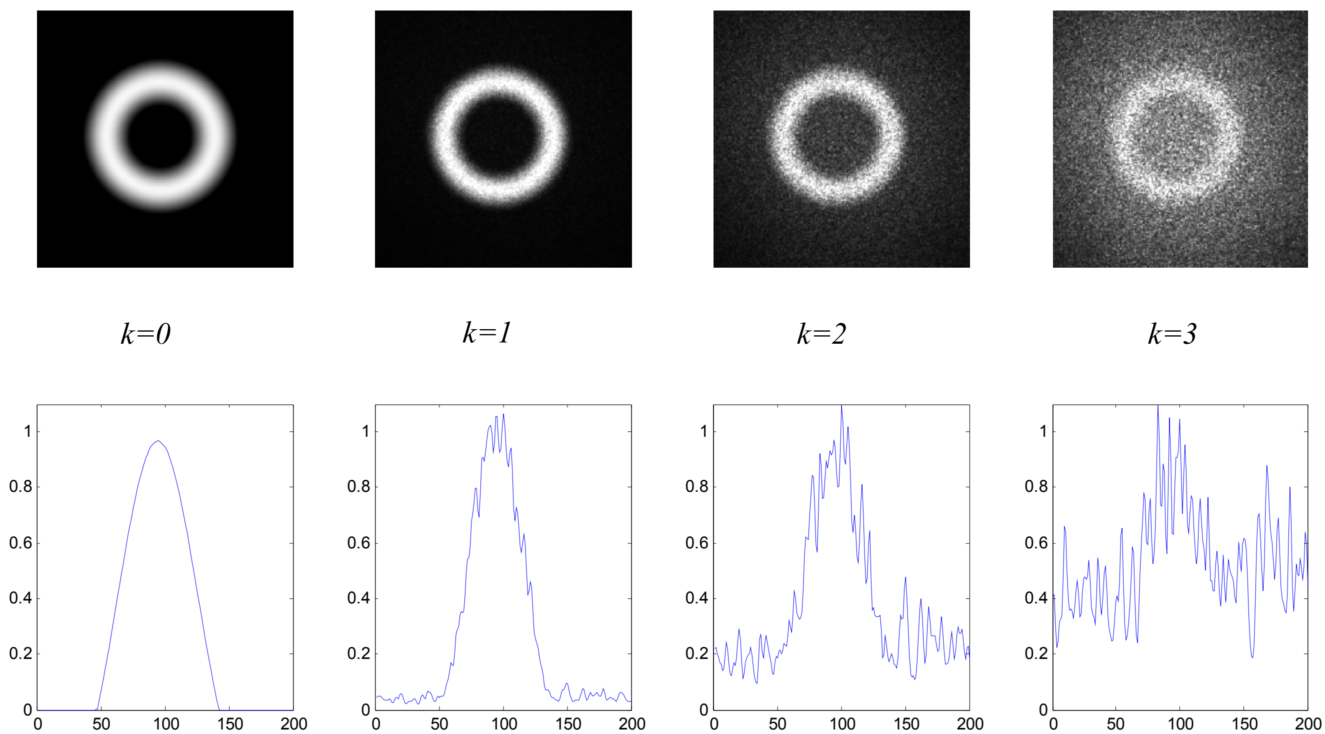

Fig. 5. Quality of the image obtained at various aberrations

was formed making use of another diffuser which also had a purely phase distribution in the angular spectrum. In the other case, the scheme corresponded to a condition of formation of the most stable and qualitative image of the tweezers. The coincidence of those plots testifies that the correlator scheme simultaneously meets the requirements of the laser beam variation and the formation of a qualitative image of the tweezers field.

The simulation was carried out for aberrations with the parameter $k \geq 3$. In this case, the average contrast decreased down to values lower than 0.5. We consider such a quality of the image insufficient to be used in the tweezers field.

For visualization, Figs. 5,*b* to *d* give illustrations that demonstrate the influence of aberrations with the parameters $k = 1$, 2, and 3, respectively, on the quality of the generated images. The lower part of this figure contains plots that illustrate the corresponding energy distributions along the radius of ring-like images. These plots testify that, starting from the value $k = 2$ and above, a certain mechanism to eliminate the field speckle structure from the image is to be provided.

4. Conclusions

In this work, we have considered a correlation scheme intended for the formation and the stabilization of a given light field distribution in a laser beam. The specific feature of the scheme is its enhanced stability with respect to deformations of the wave front in the input laser beam. The functional capabilities of the scheme, where a phase spatial transparency is applied, allow the calculations of transforming phase structures to be simplified, and lasers with a small coherence length, which are of little use for the operation in traditional holographic schemes, to be used. The results obtained are also useful for the determination of limits, where the correlation approach in the case of the field formation in optical tweezers can be applied.

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АСОЦІАТИВНЕ ВІДНОВЛЕННЯ ЗОБРАЖЕННЯ ЯК МЕТОД ФОРМУВАННЯ ТА СТАБІЛІЗАЦІЇ РОЗПОДІЛУ ЕНЕРГІЇ У ЛАЗЕРНОМУ ПУЧКУ

А.Г. Держипольський, О.В. Гнатовський, А.М. Негрійко

Р е з ю м е

Проаналізовано принципи формування лазерних пучків із заданим поперечним розподілом амплітуди поля, призначених для використання у оптичних пінцетах, за допомогою модифікованих кореляційних голографічних схем. Шляхом комп'ютерного моделювання досліджено вплив збурень вхідного пучка на амплітудні характеристики вихідного поля.