O.V. GNATOVSKYY,[1] A.M. NEGRIYKO,[1] V.O. GNATOVSKYY,[2] A.V. SIDORENKO[3]
[1]Institute of Physics, Nat. Acad. of Sci. of Ukraine
(46, Nauky Ave., Kyiv 03680, Ukraine; e-mail: vgnatovskyy@ukr.net)
[2]Taras Shevchenko National University of Kyiv
(64, Volodymyrs'ka Str., Kyiv 01601, Ukraine)
[3]State enterprise "Design Institute Ukrmetrotunelproekt"
(21, Vorovs'kyi Str, Kyiv 01054, Ukraine)

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CROSS-CORRELATION METHOD FOR THE FORMATION OF LASER ENERGY FIELDS WITH COMPLEX DISTRIBUTIONS

A new method for the formation of complex spatial distributions of the laser energy over the surface of a flat target is proposed. Its peculiarity consists in that the required phase structure of the laser beam is formed in two stages. After the Fourier transformation, this beam generates the required energy distribution. The method is intended to be used in the optical tweezers probe. It satisfies the main criteria of applicability. In particular, the method provides a small divergence of the beam; it is stable with respect to phase distortions in the optical path of the probe and adapted to dynamic changes in the field energy distribution by means of controllable phase transparencies.

Keywords: diffraction field, controllable correlation function, controllable phase transparencies

1. Introduction

Plenty of modern practical tasks are associated with a necessity to generate and use specific spatial distributions of laser-emitted energy. In this case, one should distinguish between the methods used for the transmission and the processing of coherent optical patterns, on the one hand, and the methods applied for the formation of required energy distributions over the surface of technological targets, on the other hand, because their implementations can be somewhat different. This concerns, in particular, various simplifications, admissible approximations, and so forth.

The method studied in this work is intended to be applied in the optical tweezers probe, i.e. to generate various light traps created for the manipulation of small particles. Therefore, it has to possess capabilities to create various energy distributions, to vary those distributions dynamically on the real-time scale, and to focus the generated beams on a minimally possible area of the specimen. In addition, the methods for the formation of a required energy distribution in the probe has to be adapted to modern technical devices that satisfy such requirements.

It is premature now to talk about the methods that would meet such a wide set of requirements. It is so because even the most amazing, in the authors' opinion, results concerning the long-range transport of particles [1, 2] were obtained for rather simple configurations of the light field in a probe.

In this work, we will analyze a possibility of creating a universal technique to produce various complicated energy distributions at the target of an optical tweezers probe. The method is based on the idea to form a required wave front by consecutively transforming the input beam with the help of several simple diffraction elements.

Two approaches to the formation of laser fields compose a background of the method proposed. One of them consists in smoothing an arbitrary relief of the laser-beam wave front with the help of a transparency with a complex-conjugate relief [3, 4]. Another method is based on obtaining the energy distribution of a laser field in the form of a line as a result of the convolution of two raster structures. It is either a helical beam of the lowest index that is invariant to longitudinal translations [5] or a delta-like peak in the spatial autocorrelation function for the complicated complex-valued amplitude of a laser field [6, 7]. Such a peak is stable with respect to distortions of the wave front of a laser beam.

The mentioned background also includes technological achievements in the domain of fabrication of diffraction optical elements with a high diffraction efficiency and a simple binary relief of their surface [8, 9].

2. Theoretical Background of the Method

Let a light field with the complex amplitude $A(\tilde{x}, \tilde{y})$ and the required energy distribution $E(\tilde{x}, \tilde{y}) = |A(\tilde{x}, \tilde{y})|^2$ be formed as a result of subjecting the diffraction field $a(\xi, \eta)$ to the Fourier transformation $\hat{\mathcal{F}}$,

$$A(\tilde{x}, \tilde{y}) = \hat{\mathcal{F}}\{a(\xi, \eta)\}. \tag{1}$$

Optically, this case can be realized with the use of an objective lens at the illumination of an optical transparency that has the transmission function $a(\xi, \eta)$ and is located in the front focal plane (ξ, η) of the objective lens. The field $A(\tilde{x}, \tilde{y})$ is formed in its back focal plane $(\tilde{x}, \tilde{y})$.

We propose to create the diffraction field $a(\xi, \eta)$ as a product of two fields, $m_1^*(\xi, \eta)$ and $m_2(\xi, \eta)$, i.e.

$$a(\xi, \eta) = m_1^*(\xi, \eta)\, m_2(\xi, \eta). \tag{2}$$

This would correspond (see Fig. 1) to the diffraction of the field $m_2(\xi, \eta)$ at a beforehand fabricated diffraction element with the transmission function $m_1^*(\xi, \eta)$, where the asterisk means the operation of complex conjugation.

The left-hand part of the schematic diagram is an optical cascade consisting of objective lens O_1 with the front, (x, y), and back, (ξ, η), focal planes. This cascade, after a plane wave has passed through modulator $M_2(x, y)$, provides the formation of a beam with the angular spectrum $m_2(\xi, \eta)$.

The synthesized diffraction field $a(\xi, \eta)$ (2) is transformed by the second optical cascade consisting of objective lens O_2 with the front, (ξ, η), and back, $(\tilde{x}, \tilde{y})$, focal planes. The required energy distribution $E(\tilde{x}, \tilde{y}) = |A(\tilde{x}, \tilde{y})|^2$ is observed in the plane $(\tilde{x}, \tilde{y})$.

Let the field distribution $m_2(\xi, \eta)$ be selected in the form

$$m_2(\xi, \eta) = m_1(\xi, \eta)\, \varepsilon(\xi, \eta), \tag{3}$$

where $m_1 = \hat{\mathcal{F}}\{M_1\}$ and $\varepsilon = \hat{\mathcal{F}}\{E\}$. According to the convolution theorem, this distribution can be obtained by the Fourier transformation of the field

$$\hat{\mathcal{F}}\{M_1(x, y) \otimes E(x, y)\} = m_1(\xi, \eta)\, \varepsilon(\xi, \eta), \tag{4}$$

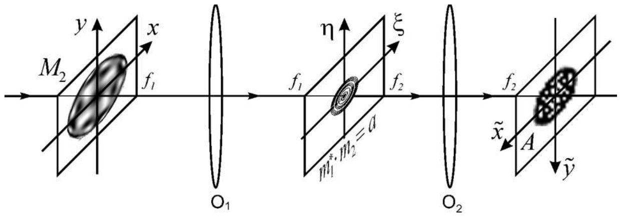

Fig. 1

where $\otimes$ denotes the convolution operation. The distribution $\varepsilon(\xi, \eta)$ corresponds to the sought energy distribution $E(\tilde{x}, \tilde{y}) = |A(\tilde{x}, \tilde{y})|^2$, and $m_1(\xi, \eta)$ corresponds to the angular spectrum of the field that is formed, when a plane wave passes through the spatial phase modulator $M_1(x, y)$. Taking Eqs. (2)–(4) into account, we obtain

$$\hat{\mathcal{F}}\{a(\xi, \eta)\} = [M_1(x,y) * M_1(x, y)] \otimes E(x,y) \approx$$
$$\approx \delta(x, y) \otimes E(x,y) = E(\tilde{x},\tilde{y}). \tag{5}$$

The structure of modulator M_1 should be selected so that its spatial autocorrelation function $M_1 * M_1$ would correspond to the physical distribution of a field taken in the form of a sharp delta-like peak (a bright point against the weak uniform background). Just such properties are designated by the sign of the approximate equality in Eq. (5).

If the diffraction field $a(\xi, \eta)$ is synthesized from two multipliers, we have a possibility of using a number of different complete sets of diffraction converters M_1 and M_2 for its formation, with the phase structures of the both having an identical level of complexity. This circumstance allows the functional capabilities of modern controllable phase transparencies to be used to their full extent. In our correlation scheme, their task is reduced to the restoration of simple phase distributions.

It is important to note that the proposed scheme is rather stable with respect to possible changes of the field phase in its optical path. Such changes can be described by substituting the spatial autocorrelation function $M_1 * M_1$ by the cross-correlation function $M_1 * \tilde{M}_1$, which is close to the former and where possible phase variations are taken into account in $\tilde{M}_1$. This cross-correlation function also has a delta-like maximum, but the intensity of the latter is somewhat weaker. As a result, the signal-to-noise ratio becomes worse, but the required spatial configuration of energy persists. Just this scenario was observed in experiments.

3. Experimental Results

The experimental researches were carried out on an installation, the optical diagram of which is shown in Fig. 2. The radiation emitted by a helium-neon laser LG (a wavelength of 6328 Å and a power of 10 mW) passes through a 40-fold telescopic system T, which forms a beam with the plane wave front and the uniform energy distribution over a beam cross-section. The beam diameter equals 20 mm. After having passed through a beam splitter cube BS, this beam forms two beams that are required for the hologram recording. Modulator M_1 is mounted in the signal beam channel, in the front focal plane of objective lens O_1. Hologram Γ is arranged in the back focal plane of objective lens O_1. The plane reference wave directed onto a hologram by mirror Dz interferes here with the angular spectrum of modulator M_1. This hologram has the transmittance proportional to $m_1^*(\xi,\eta)$ in the reference beam direction. Therefore, the beams formed with the help of objective lens O_2 were observed in this direction and registered, with a required magnification, in the back focal plane of objective lens O_2 (the observation plane $(\tilde{x},\tilde{y})$).

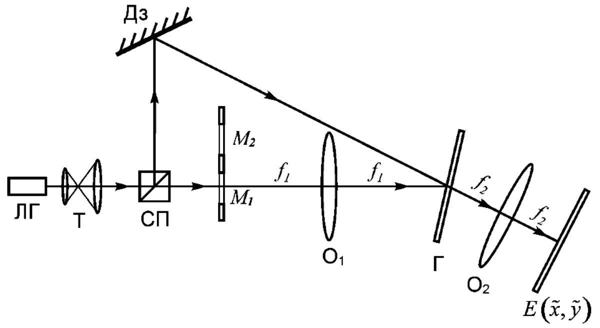

Fig. 2

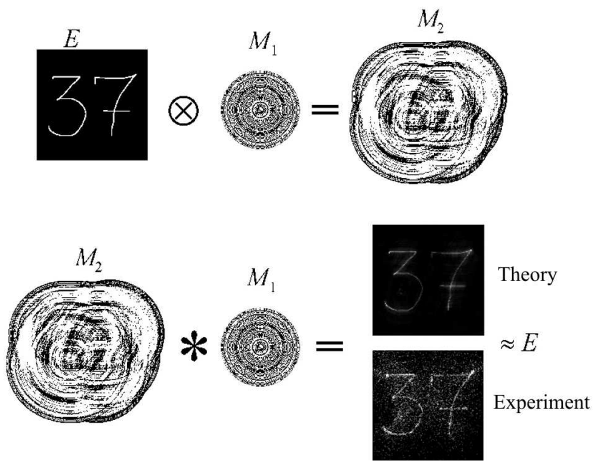

Fig. 3

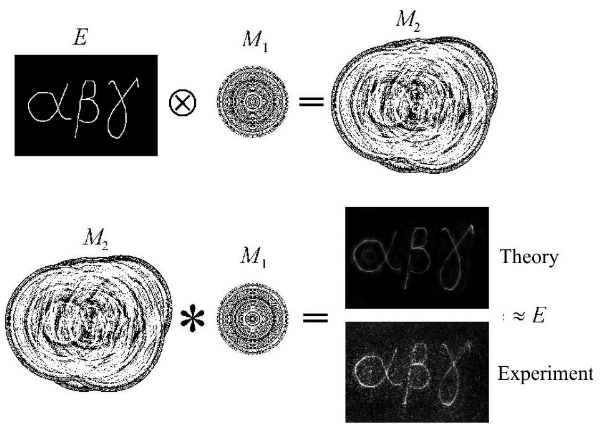

Fig. 4

The calculated modulators M_1 and M_2 were reproduced on a printer in the form of black-and-white photo-masks, and the latter were afterward photographed on the "Mikrat 900" photographic film with a required reduction (down to 3–15 mm). After the bleaching, the obtained slides acquired a required phase relief in the range of values $[0,\pi]$. The hologram was registered on "Mikrat VRL" photographic plates. After the photographic plate was treated, the hologram was bleached and returned to the place of registration, and the beam splitter cube was removed from the beam path. Then, the scheme was ultimately adjusted with the help of transverse microshifts of the hologram to obtain a bright point of light (the correlation peak $M_1 * M_1 \approx \delta(\tilde{x},\tilde{y})$ (5)) in the observation plane. Taking advantage of a stage allowing transverse microshifts, modulator M_2 was introduced into the laser beam instead of modulator M_2, and the beam with the required energy distribution was reproduced in the observation plane.

Notice that the holographic creation of the transparency $m_1^*(\xi,\eta)$ is not optimum from the viewpoint of energy efficiency at the beam formation. In further practical applications of our method, it is expedient that either an artificial hologram with the required profile of a phase relief or a kinoform corresponding to the phase distribution $m_1^*(\xi,\eta)$ should be used.

Some patterns of formed distributions are depicted in Figs. 3 and 4. The corresponding generatrix width for figure forms – in our case, these were figures and letters – corresponded to the minimum possible divergence of the light beam determined by the diameter of the active aperture of hologram $m_1(\xi, \eta)$. The aperture amounted to 5–10 mm depending on the content of generated images.

4. Conclusions

A workability of a two-stage method proposed for the formation of a diffraction field and its transformation into a beam with required spatial distribution of energy has been experimentally proved. The method allows rather complicated plane energy distributions that correspond to the minimum possible diffraction-induced divergence of radiation to be formed even under phase-distortion conditions.

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О.В. Гнатовський, А.М. Негрійко, В.О. Гнатовський, А.В. Сидоренко

МЕТОД КРОС-КОРЕЛЯЦІЙНОГО ФОРМУВАННЯ СКЛАДНИХ РОЗПОДІЛІВ ЕНЕРГІЇ ЛАЗЕРНИХ ПОЛІВ

Р е з ю м е

У роботі досліджено новий метод формування складних просторових розподілів лазерної енергії на плоскій технологічній мішені. Особливістю методу є двоступінчатість процесу утворення потрібної фазової структури лазерного пучка, який після фур'є-перетворення утворює потрібний розподіл енергії. Метод призначений для подальшого використання в зонді оптичного пінцета і відповідає головним критеріям для практичної реалізації – забезпечує малу розбіжність сформованого пучка, є стійким до спотворень фази поля, зумовлених оптичним трактом зонда, адаптований до динамічних змін розподілів енергії поля за допомогою керованих фазових транспарантів.