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OPTIMAL CONTROL OF LIGHT BEAM PHASE IN MICROCOMPUTER-SPATIAL LIGHT MODULAR SYSTEM

M. A. VORONTSOV, A. F. NAUMOV and V. P. SIVOKON

Abstract—A microcomputer controlled focusator producing uniform illumination in the plane of focusing is realized. This focusator is an optically controlled liquid-crystal mask that performs space-time modulation of light. The signal that controls the intensity distribution is computed by a gradient method of optimization of an error functional. The modulator is interfaced with the microcomputer via an input–output imaging system with a spatial resolution of 256 × 256 elements. Uniform illumination of an annular zone is shown to be feasible in practice. The focusator system can be controlled in the dynamic mode.

Among the optical elements designed to form light fields with a given distribution of intensity in the image plane, kinoforms have received wide acceptance [1]. The kinoform enables one to produce a time-invariant optical field. Certain applications require that the optical elements be variable to form a distribution of intensity variable in time in a particular way. This may be done with some limitations by flexible mirrors controlled by a computer [2]. However, the spatial resolution of a controlled mirror surface is comparatively low so that a sufficiently complex phase profile cannot always be formed.

To overcome this difficulty we have synthesized variable phase masks with a space-time light modulator (STLM) controlled by a computer through a special cathode-ray tube (CRT). The phase profile that provides a specified distribution of intensity in the focusing domain was calculated by optimizing the functional of error [3]

$$J = \int\int [I_u(\mathbf{r}') - I_s(\mathbf{r}')]^2 \, d^2\mathbf{r}', \qquad (1)$$

where $I_s(\mathbf{r}')$ is the specified distribution of intensity in the image plane $\mathbf{r}' = (x', y')$, $I_u(\mathbf{r}')$ is the distribution of intensity corresponding to the actual phase profile $U(\mathbf{r})$, and $\mathbf{r}' = (x', y')$ is a vector in the plane of STLM. Having optimized the functional (1) we determined the phase focusator profile $U_0(\mathbf{r})$.

The space-time light modulator was an optically controlled liquid-crystal transparency with a GaAs photoconductor harnessing the electrooptical S-effect for its operation [4]. The phase of the light wave reflected from the transparency was controlled by modulating the brightness on the CRT screen which was interfaced with the photoconductor of the STLM by means of glass fibre planes and immersion liquid (glycerol). The working aperture size 19 × 19 mm was decided by the dimension of the image on the CRT screen. The resolution of the STLM–CRT system, as measured at the half-height of the frequency-contrast characteristic, amounted to about 2 lines mm^{-1}. The comparatively low resolution of this system is associated with the fact that the radiant sensitivity maximum of the photoconductor and the maximum of the radiant excitance of the SRT phosphor (K-77) do not coincide.

The schematic representation of the experimental setup is shown in Fig. 1. A collimated light beam of the He–Ne laser is reflected from the dielectric mirror of the transparent immediately behind the layer of liquid crystal. The polarization vector of the light wave coincides with the initial orientation of the liquid crystal, thus allowing for the phase modulation of the light wave. The phase retardation in the liquid crystal layer is given by

$$U(\mathbf{r}) = 2kd[n_0 - \Delta n(\mathbf{r})], \qquad (2)$$

where $k = 2\pi/\lambda$ is the wavenumber, d is the layer thickness, $\Delta n(\mathbf{r})$ is the variation of the refractive index induced by a CRT brightness distribution that represents the illumination which controls the state of the photoconductor and n_0 is the unperturbed value of the refractive index.

We selected an operating regime of the transparency such that the variation of the refractive

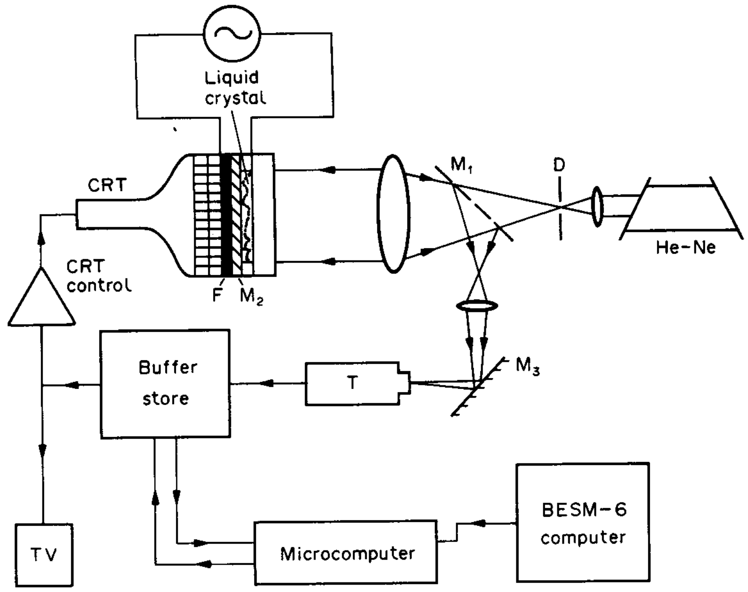

Fig. 1. Schematic diagram of the experimental setup: D, aperture; M_1, semitransparent mirror; M_2, dielectric mirror of STLM; F, photoconductor; M_3, rotation mirror; T, TV camera; TV, display.

index $n(\mathbf{r})$ was proportional to the brightness of the control image $B(\mathbf{r})$. Then

$$U(\mathbf{r}) = \gamma B(\mathbf{r}) + \varphi_0(\mathbf{r}), \tag{3}$$

where γ is a coefficient of proportionality and $\varphi_0 = 2kdn_0$ is the stationary phase shift. The phase $\varphi_0(\mathbf{r})$ defines the optical property of the transparency as an element for light beam phase control.

The required brightness distribution control $B(\mathbf{r})$ was computed on a BESM-6 computer and represented as a numerical array of 256 × 256 elements. This array was loaded into the buffer store connected with the microcomputer. The contents of this store was displayed on the CRT screen by means of digital to analog converters. In order to control the distribution of intensity at the region of focusing, the TV image was input into the computer.

In our experiment with an initial Gaussian beam of radius a for which

$$I(\mathbf{r}) = I_0 \exp(-r^2/a^2), \tag{4}$$

we sought to produce an almost uniform (supergaussian) distribution of intensity

$$I_s(\mathbf{r}) = I_0 \exp[-(x/b_f)^{10} - (y/b_f)^{10}] \tag{5}$$

at some distance z from the modulator, within a square of side $2b_f$. Such requirements are typical for a number of applications where a light beam with a uniform distribution of intensity is desired. As a rule the focusing spot size $2b_f$ is much less than the width of the initial beam. In view of the symmetry of the problem the phase function of the focuser, $U_0(\mathbf{r})$, may be represented as the product $\Phi(x)\Phi(y)$. We sought the function $\Phi(x)$ and $\Phi(y)$ as decompositions in Hermite polynomials $H_j(x)$ and $H_j(y)$, namely,

$$\begin{aligned} U_0(\mathbf{r}) &= \Phi(x)\Phi(y) \\ &= \sum_j \alpha_j H_j(x/a) \sum_j \alpha_j(y/a) \exp(-x^2/2b^2 - y^2/2b^2). \end{aligned} \tag{6}$$

The first four even Hermite polynomials were retained, for $j = 2$, 4, 6 and 8. The coefficients of the decomposition found by minimizing the functional (1) on a BESM-6 computer are as follows: $\alpha_2 = 0.735$, $\alpha_4 = 0.726$, $\alpha_6 = -1.099$ and $\alpha_8 = -0.743$ [3].

To synthesize the specified phase profile, the photosensitive layer of STLM received the distribution of brightness in agreement with Eq. (6), as shown in Fig. 2(A). The value of b was taken equal to 1.5. As a result the 2-mm square in the image plane was illuminated as shown in Fig. 2(C). For comparison the initial distribution of intensity is shown in Fig. 2(B).

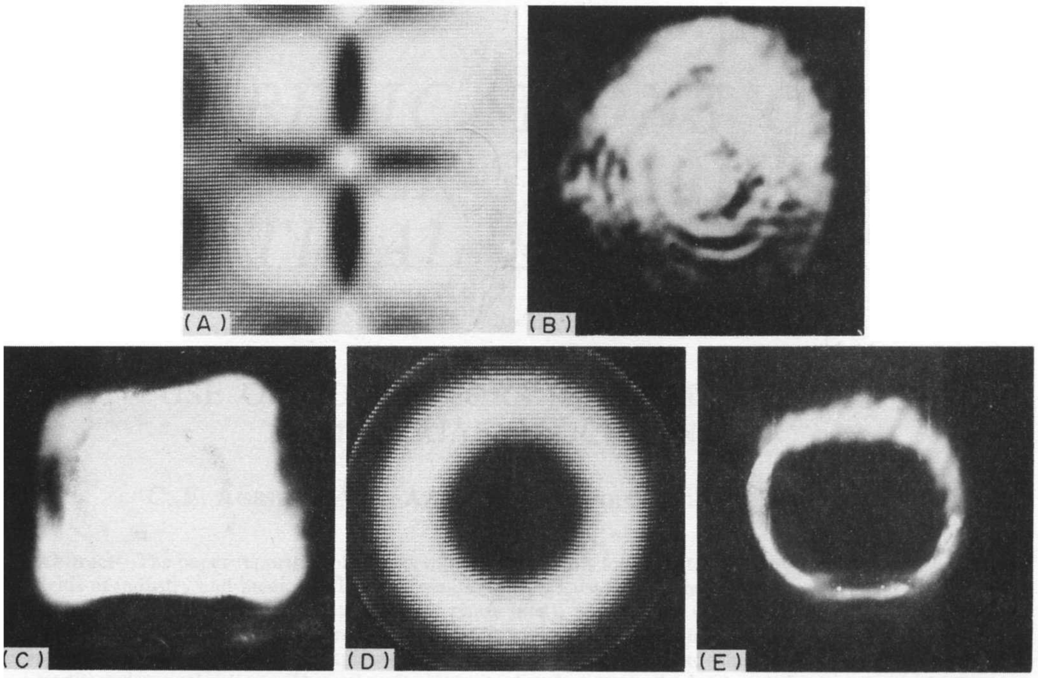

Fig. 2. Experimental patterns. The controlled distributions of brightness $B(\mathbf{r})$ on the CRT screen for focusing into (A) a rectangle and (D) a ring. The corresponding distributions of intensity $I_u(\mathbf{r}')$ for focusing into (C) a rectangle and (E) into a ring. (B) The initial distribution for $B(\mathbf{r}) = \text{const}$.

The distribution obtained in this experiment differs from the theoretical pattern because the initial beam was not exactly Gaussian and some aberrations were present in the optical system, primarily due to the optical inhomogeneity of the transparency.

In order to focus the light beam into an annular zone, the phase profile (brightness distribution on the CRT screen) was taken as the sum of the first three even polynomials of Černike

$$U_0(\mathbf{r}) = \sum_{j=1}^{3} \beta_j Z_j(\mathbf{r}). \tag{7}$$

The controlling distribution of brightness on the CRT screen at $\beta_1 = 1$, $\beta_2 = -50$, $\beta_3 = 50$ and the resulting distribution of laser beam intensity in the image plane are shown in Fig. 2(D,E).

These experiments demonstrate that computer controlled optical elements are a promising proposition for the synthesis of intensity distributions of coherent radiation. The major problem remaining consists in the development of space-time light modulators of high optical quality.

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