Selecting optical patterns with spatial phase modulation

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Optical pattern selection by use of spatial phase modulation is investigated experimentally in a photorefractive feedback system. A feedback mirror with spatially periodic phase modulation is used for selection of different spatial patterns. Local phase modulation is used to create patterns with coexisting spatial symmetries. The experimental results are consistent with numerical simulations based on a model with a cubicly nonlinear medium.

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Great attention has been paid recently to the control of spatiotemporal dynamics in spatially extended nonlinear systems.[1-8] As with previous studies of controlling temporal chaos,[9-14] there are two main schemes for manipulating pattern formation: feedback and nonfeedback methods. In the first, signals that are proportional to the difference between the output of the system and the target pattern are fed back to the system to achieve the control process. The magnitude of the control signal decreases as the system approaches the desired target. After convergence to the target, the control system becomes essentially nonintrusive.

The nonfeedback method to control pattern formation consists of applying external spatial perturbations to the system to break the symmetry and then enhance the stability of the desired pattern.[5,8] Although this method is intrusive because more or fewer variations are introduced than in the original system, it is a powerful way to control unstable patterns because of its experimental feasibility from the point of view of practical usefulness.

In this Letter we demonstrate, on the basis of experiment and numerical simulations, the successful selection of optical patterns by introducing spatial phase modulation into the backward-propagating beam in a photorefractive pattern-forming system.[15,16] The phase modulation, as a spatial perturbation, effectively suppresses the hexagonal patterns that are seen in the unperturbed system and stabilizes normally unstable patterns with the symmetry of the applied perturbation.

Our experimental arrangement is shown in Fig. 1. A crystal of iron-doped $KNbO_3$ measuring $l = 5.2$ mm along the c axis was illuminated by a frequency-doubled Nd:YAG laser with an output power of 30 mW at a wavelength of $\lambda = 532$ nm. The laser beam was focused to a spot with a Gaussian diameter of $\sim$0.4 mm on the crystal and polarized parallel to the crystal a axis to take advantage of the r_{13} electro-optic coefficient. The counterpropagating pump beam was generated by reflection from a computer-controlled liquid-crystal spatial light modulator with a reflectivity of 30%.[17] The modulator was positioned at the end of the cavity formed by two lenses with focal lengths $f_1 = 100$ mm and $f_2 = 380$ mm. The cavity was adjusted to give a virtual separation d of the modulator several millimeters from the end of the crystal. The spatial instability in this geometry is due to the formation of reflection gratings with a wave vector of magnitude $k_g = 2k_0 n$, where $n \simeq 2.3$ is the index of refraction of the crystal and $k_0 = 2\pi/\lambda$. The crystal was oriented such that the beam reflected from the modulator was amplified by the forward-propagating beam. The local phase of the reflected light from the modulator can be shifted by a video signal applied to the cathode ray tube of the modulator; the magnitude of the phase perturbation depends on the bias voltage applied to the liquid-crystal light valve. The effective magnitude of the spatial wave vector of the phase modulation at the virtual modulator position was chosen to be $k_m = 190\ \text{mm}^{-1}$ to match the spatial frequency of the unperturbed hexagonal pattern. The modulation signals were composed of sine functions to minimize high-order diffraction. The phase-modulation depth was much less than 2π, and we adjusted it by measuring the intensity in the first-order sidebands diffracted from the modulator. In the experiment, the intensity of each diffracted sideband relative to the zero-order reflected light spot was adjusted to approximately 2%, 1%, and 0.7% for roll, square, and hexagonal modulations, respectively.

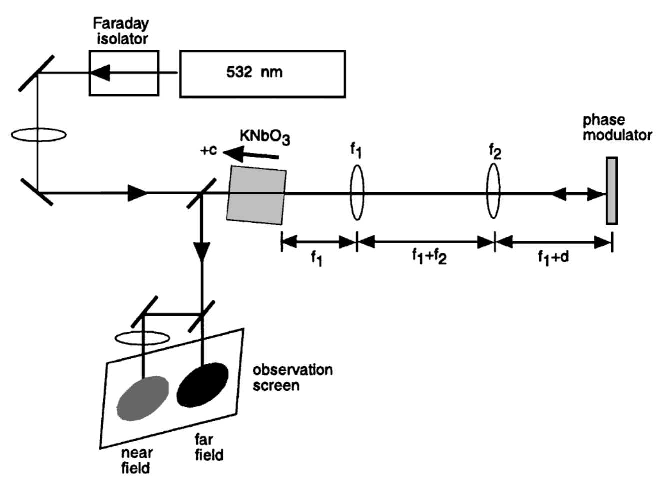

Fig. 1. Experimental setup.

The first and second columns of Fig. 2 show experimental near-field and far-field images obtained with different phase modulations. With no modulation we obtained the normal hexagonal pattern as shown in Fig. 2a. Using a single sinusoidal modulation leads to the formation of stable rolls, as shown in Figs. 2b–2d. Square patterns were obtained by use of a modulation composed of two orthogonal sinusoidal waves, as shown in Fig. 2e. The direction of the wave vector of the controlled pattern follows that of the modulation. We can qualitatively understand the process of pattern selection by considering that the exertion of phase modulation on the backward beam leads to the enhancement of the desired modes. At the same time the weak phase modulation effectively suppresses the hexagons that are observed in the absence of modulation, so the observed patterns are not merely the unperturbed hexagons overlaid with the structure imparted by the phase modulator.

To investigate the local effect of the perturbation, we observed patterns in the presence of spatially segemented phase modulation. Figure 3a shows the pattern with roll modulation exerted only on the left half of the backward beam. Figure 3b shows the pattern obtained with hexagonal modulation on the left half and roll modulation on the right half. Figure 3c shows the pattern obtained with hexagonal modulation on the left half and square modulation on the right half. The near-field images show the local effect of the perturbations, and the far-field images show a combination of wave vectors that are due to both parts of the segmented patterns. These results demonstrate that patterns can be controlled locally with spatial perturbations.[5]

We use a simplified model, based on a transmission-grating mediated interaction in a thin slice of a sluggish medium with cubic nonlinearity,[18] to capture the essential features of the observed phenomena. The numerical model does not accurately represent the reflection-grating mediated nonlinearity that is present in the experiment. Nonetheless the photorefractive interaction is approximately described by a saturable cubic nonlinearity with a finite spatial-frequency response. Previous experience[6] has shown that the simplified model is sufficient to capture generic aspects of the observed patterns.

The nonlinear refractive index δn is described by

$$\left(\tau \frac{\partial}{\partial t} + 1\right)\delta n = D\nabla^2 \delta n + \gamma \frac{|F|^2 + |B|^2}{1 + |F|^2 + |B|^2}, \qquad (1)$$

where τ is the relaxation time of the medium, D is the diffusion coefficient, γ scales the strength of the nonlinearity, and F and B are the forward and backward optical fields, respectively. The influence of the nonlinear medium located at $z = 0$ on the optical fields is given by $F(x, y, 0^+) = F(x, y, 0^-)\exp(i\delta n)$ and $B(x, y, 0^-) = B(x, y, 0^+)\exp(i\delta n)$. Free-space diffraction, together with the phase modulation in the backward beam, is calculated with

$$\frac{\partial}{\partial z}\begin{bmatrix} F(x, y, z) \\ B(x, y, z) \end{bmatrix} = \pm \frac{i}{2k}\nabla^2 \begin{bmatrix} F(x, y, z) \\ B(x, y, z) \end{bmatrix}. \qquad (2)$$

The spatial phase modulation is exerted on the backward-propagating field in the form

$$B(x, y, z_m) = \sqrt{R}\, F(x, y, z_m)\exp[i\phi(x, y)], \qquad (3)$$

where z_m and R are the longitudinal coordinate and the intensity reflectivity of the modulator, respectively, and $\phi(x, y)$ is the spatially modulated phase. As in the experiment, $\phi(x, y)$ is composed of sinusoidal functions, e.g., $\phi(x, y) = \alpha \cos(kx)$ for a roll modulation, where α is the modulation amplitude. In the simulation we take $\alpha = 0.2, 0.15, 0.1$ for the roll, square, and hexagonal modulations, respectively.

The results of the numerical simulation with Eqs. (1)–(3) are shown in Figs. 2 and Fig. 3. In both experiment and calculations the nonlinearity was held fixed and the intensity was adjusted to $\sim$50% above the linear instability threshold. The near-field and far-field intensity distributions obtained after an initial transient are shown in the third and the fourth columns, respectively, of Figs. 2 and Fig. 3. The numerical results demonstrate good qualitative agreement with the experimental observations. In particular, the relative amplitudes of the far-field components are similar in the experimental and the numerical studies. From both the experimental and

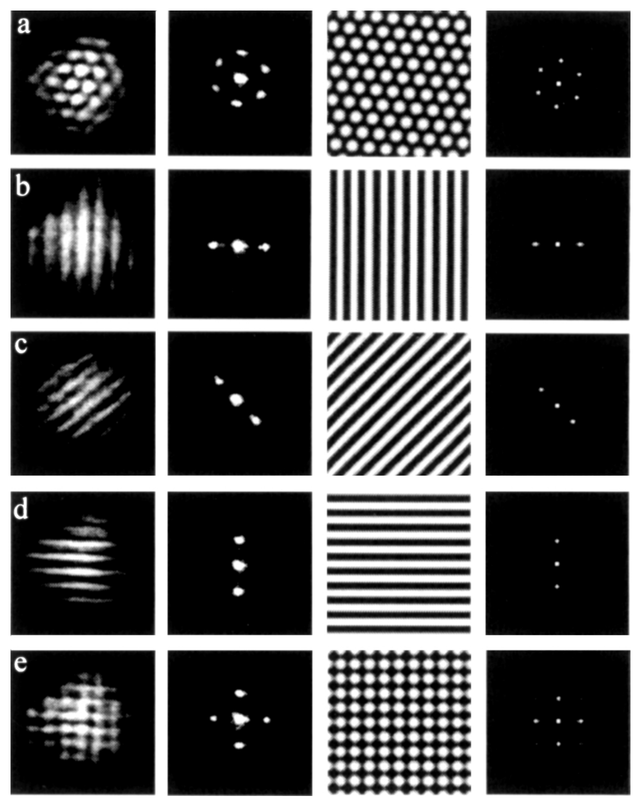

Fig. 2. Selecting optical patterns by spatial phase modulation: a, hexagons obtained without modulation; b–d, rolls obtained in the direction of the modulation; e, squares obtained with modulation composed of two perpendicular sinusoids. The input intensity was $\sim$50% above the threshold. Columns from left to right: experimental near field, experimental far field, numerical near field, and numerical far field.

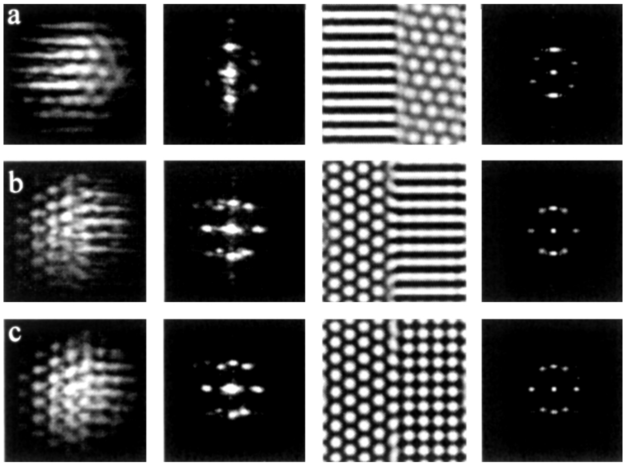

Fig. 3. Selecting patterns with spatially segmented modulation: a, patterns with a roll modulation on the left half and without modulation on the right half; b, patterns obtained with hexagonal modulation on the left half and roll modulation on the right half; c, patterns obtained with hexagonal modulation on the left half and square modulation on the right half. Columns from left to right: experimental near field, experimental far field, numerical near field, and numerical far field.

the numerical results given above we can see that the patterns can be effectively manipulated, although the spatial phase modulation is small.

In conclusion, we have demonstrated experimentally the effectiveness of spatial phase modulation in controlling optical patterns in a photorefractive nonlinear system. Not only otherwise unstable patterns but also locally controlled patterns can be obtained by use of weak spatial phase modulation.

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