SIMULATION OF PROCESSES IN A LASER SYSTEM: PREDICTIONS OF NEW EFFECTS OF THE OPTICAL SYNERGETICS

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In this paper we show the possibility of cyclic self-transformation to occur in an interferometer with Kerr nonlinearity. This prediction follows from the results of computer simulations of morphogenesis in such an interferometer. We also present here grounds for the concept of round-trip instability which we consider to be the cause of cyclic phenomena. Influence of a spread in the starting rates of different processes, $V_j = \mathrm{d}U_j/\mathrm{d}t$ at $t = 0$, on the dynamics of a multicomponent system has been determined and a normalized measure, θV, of such a spread in V_j is proposed. Depending on θV value the process occurring can be periodic, nonperiodic, or a multilevel stationary (i.e. with different U_j) process.

The origin of synergetics is closely connected with the studies of processes in lasers. One of the founders of synergetics G. Haken considers laser as a prototype of the system which creates a complex spatiotemporal structure in the self-organization process. Transition from non-coherent laser radiation to the coherent one is an example of self-organization. At the present stage of development of synergetics laser as an object for study gives up its place to laser as a factor which causes new classes of self-organization processes. Formation processes in a ring-shaped optical interferometer containing one or several spatially separated nonlinear media[1] is related to a number of similar processes. This paper continues the computer experiments described in Refs. 2–4. We were interested in a possibility and peculiarities of manifestation of stationary regimes of optical structures generation in such an interferometer.

The interferometer containing a medium with Kerr nonlinearity and providing two-dimensional large-scale transformations of field in the feedback circuit (Fig. 6.19 in Ref. 1) is suitable not only for natural study of the phenomenon of transformation of input Gaussian beam into a complex dynamic spatiotemporal structure but also for simulation of evolution of this structure, i.e., the phase distribution $U(x, y, t)$ over the cross section of a light beam. Nonlinear parabolic equation with a shifted spatial argument (see Ref. 1) is used as a model:

$$\partial U(x, y, z)/\partial t + U(x, y, z)/\tau = d\Delta_{\perp}U(x, y, z) + K[1 + \gamma\cos(U(x', y', t) + f_0)]/\tau. \quad (1)$$

The coordinates x' and y' are connected with x and y by the relations:

$$x' = \alpha(x\cos\Delta + y\sin\Delta),$$
$$y' = \alpha(y\cos\Delta - x\sin\Delta),$$

where α is the change of the laser beam scale; Δ is the field turn in the feedback circuit.

When the initial phase distribution is $U(x, y, 0) = \sin(4\pi x)\sin(4\pi y) + 1$ (rad); the relaxation time of nonlinear part of the refractive index is $\tau = 0.001$ s; the diffusion coefficient is $d = 10^{-3}$ mm^2/s; the nonlinearity parameter is $K = 4.084$; the visibility of the interference pattern is $\gamma = 1$; the constant phase difference is $f_0 = 0$; $\alpha = 0.8$; $\Delta = 50°$, a periodic transformation of optical structures, we call the cyclic self-reorganization, is possible. On the whole, the dynamics of formation is as follows.

As a result of the transient process (with the duration about τ), a two-tail spiral is formed. Then this spiral is spontaneously modified not going to a stochastic state. By the time $t_A = 9.5\tau$ (when simulating the optical morphogenesis the interval 10τ is estimated as a time of reaching a stationary state[2]) the structure A (Fig. 1) is formed.

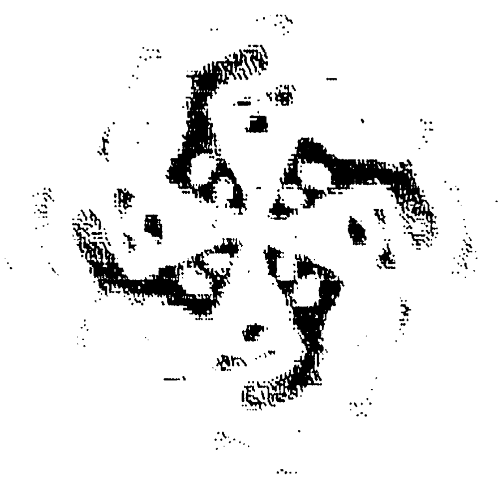

FIG. 1.

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Then A is replaced by a continuos sequence of the optical self-reorganizing structures. At time $t_{A1} = 14\tau$ the structure A_1 is formed which is indistinguishable from the structure A. Then a continuos sequence of the phase distributions $U(x, y, t)$ is repeated cyclically with the period $T = t_{A1} - t_A \cong 4.5\tau$.

The cyclic self-reorganization is maintained when the diffusion coefficient d varies within the interval $(2...3)\cdot 10^{-3}$ mm^2/s. At certain stages of the cyclic self-reorganization the four-lobe structure, which rotates as a whole unevenly in velocity by an angle of 10–20° during the time about τ, is observed.

An increase in d to the magnitudes about 10^{-2} mm^2/s leads to a spontaneous transition from a two-tail spiral to a two-lobe structure (at $t \cong 2\tau$) instead of the cyclic self-reorganization. This structure is modified by division of lobes (at $t \cong 4\tau$) to the four-lobe structure, which performs the counter-clockwise incomplete rotation as a whole with the half-period $T_4/2 = (14 \pm 2)\tau$. By the time $t \cong 24\tau$ this structure is transformed spontaneously into the three-lobe structure which experiences a stationary clockwise rotation with the period $T_3 = (12 \pm 2)\tau$ during the observation time $t \cong 100\tau$. An estimation of the rotation velocities of these structures and determination of the rotation direction by formulas from Refs. 5 and 6 for the unit radius of a ring gives for an optical reverberator $T_4 \cong 15\tau$ and $T_3 \cong 10\tau$, respectively, and shows that directions of rotations are opposite.

The simulation assumes that in the nonlinear interferometer with a two-dimensional feedback a cyclic development of the spatiotemporal instability is possible. This instability leads to rotation of the structures[1,3] but without their cyclic self-reorganization (the rotation takes place in the case of a one-dimensional narrow ring-shaped beam too[1,5,6]) under certain conditions, while under other conditions it leads to a cyclic self-reorganization but without the rotation of the structures, and for third type of conditions it leads to a rotation-cyclic transformation of these structures. That is why this instability should be called as the rotation-cyclic or “round trip” instability.

Study of the processes in active spatially separated optical systems is an important aspect of investigation of the dynamics of the optical structures. In contrast to the optical arrangement with a successively placed nonlinear media proposed in Ref. 1 (Fig. 6.6) we consider an optical arrangement with parallel placed nonlinear media, shown in Fig. 2, for the case of three media. The optical fields E_1, E_2, and E_3 interact in these media due to a partial and (or) complete transmission of radiation from one subsystem to another with the eight mirrors M which are shown in Fig. 2 by short solid lines. For simplicity and reduction of the number of parameters being varied we select the case of the negligibly small-scale interaction of the optical fields in the nonlinear medium when the diffusion coefficients $d_j = 0$. Under these assumptions the model of a multicomponent system can be written in the form:

$$dU_j/dt = K_j[1 + \gamma_j \cos(U_l + f_{0j})]\tau_j - U_j/\tau_j, \qquad (2)$$

where $j = 1, 2, 3, \ldots, N$; $l = 2, 3, N, \ldots, 1$. In accordance with Ref. 1, U_j is the wave phase difference in the jth nonlinear medium; $n_j = n_{0j} + n_{2j} |E_j(\mathbf{r}, t)|^2$, $K_j = n_{2j} I_{INj} kL_j (1 - R_j)$; k is the wave number; L_j is the medium length; I_{INj} is the radiation intensity at the input of the jth medium; R_j is the reflectance of the interferometer mirrors for radiation in the jth channel; $f_{0j} = kL_j n_{0j}$.

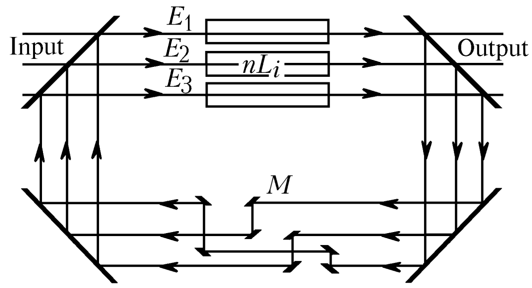

FIG. 2.

Different quantitative characteristics can describe an influence of differences in the subsystem parameters and initial conditions U_{0j} on the process dynamics. Evidently, it is the most simple to take into account such quantities as a whole using the starting rates of the processes in the subsystem $V_j = dU_j/dt|_{t=0}$ equal to magnitudes of the right-hand side of Eqs. (2) at $t = 0$. The differences in the starting rates V_j can be described using the relations between them. The normalized measure of the difference in the starting rates V_j can be one of the difference characteristics. This measure will be used in further operations.

$$\theta V = \frac{N \sqrt{\sum_{j=1}^{N-1} (|V_j| - |V_{j+1}|)^2 + (|V_N| - |V_1|)^2}}{\sum_{j=1}^{N} (|V_j|)}, \qquad (3)$$

where N is the number of subsystems. It is obvious, that in the case of identity of the subsystem parameters and initial conditions ($U_{0j} = U_0$) the normalized measure $\theta V \equiv 0$.

To elucidate the influence of differences in the process starting rates $V_j = dU_j/dt|_{t=0}$ on the multi-component system dynamics, Eqs. (2) were solved by the Runge-Kutta-Merson numerical technique.[7] The assigned values U_{0j} were the initial conditions when integrating Eqs. (2). If U_{0j} are set and all parameters in Eqs. (2) are known, then the starting rates V_j calculated as the right-hand sides of Eqs. (2) for $t = 0$ are set also. In its turn, knowledge of the value V_j allows the difference measure θV to be calculated by formula (3).

The simulation showed that when the process starting rates in the subsystems (when $\theta V \equiv 0$) are the same, only a stationary motion occurs in the threecomponent system. In this test case the phases U_j are naturally the same.

If, however, the parameters of the subsystems are identical but the initial conditions U_{0j} are different, or vice versa, then (depending on the value θV) six more types of evolution of the multi-component system can occur.

For $0 < \theta V < 0.001$ first the initial process of reaching the value U_j takes place, then the transient process with the stationary (and identical) phase $U_j = U_{st}$ (TPSP) is realized. The following condition was used as a criterion of this process stationarity:

$$|dU_j/dt|/U_j < 0.01. \quad (4)$$

As the simulation has shown, duration t_s of TPSP by the criterion (4) depends on the degree of starting rates inequality θV as:

$$t_s = -A \ln\theta V - B. \quad (5)$$

This law was obtained by the approximation of the dependence shown by curve *3* in Fig. 3. The value t_s is normalized by the time unit; the values $\theta V^{1/5}$ are plotted on the abscissa for a convenience; the constants in Eq. (5) are $A = 2.09$ and $B = 14.77$. For this case $N = 3$, $\tau_j = 1$ s, $\gamma_j = 0.8$, $K_K = 5$, $f_{0K} = U_{02} = U_{03} = 0$; the value θV changes depending on U_{01}. The relation (5) keeps valid for variation of the number of nonlinear media, only the constants in this relation change. Curves *1* (the case of two and four media) and *2* (the case of five media) are presented in Fig. 3 for a comparison. The constants A and B in Eq. (5) are equal to 0.50 and 4.45; 0.51 and 4.11; 0.72 and 5.63, respectively.

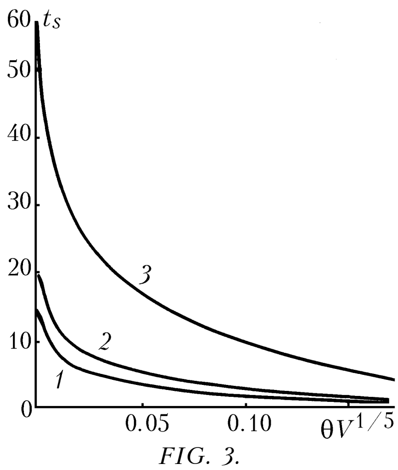

FIG. 3.

After TPSP three alternative versions of the phase dynamics are possible: nonperiodic, periodic, and stationary processes of "different levels". In this case the values U_K are different that distinguishes the stationary process of "different levels" from TPSP.

No threshold, i.e. minimum θV value, for nonidentity has been found starting from which the process stationarity maintains during a long time. This fact well agrees with the relation (5).

Within the interval of values θV [0.001, 1] after the initial process of reaching the value $U_K$the transient process with the stationary (and the same) value $U_K = U_{st}$ (with limited duration t_s) has not recorded. Depending on the difference in the process starting rates in the subsystems the nonperiodic, periodic, or stationary process of "different levels", i.e., with various values of $U_K$can occur.

The value $\theta V = 1$ is a kind of a boundary, since for $\theta V > 1$ in all numerical experiments performed the nonperiodic processes have not been observed.

Thus, the dynamics type which is proposed to be called as "limited stationarity regime" is possible both in the one-component and multi-component nonlinear optical systems. The adjective "limited" implies, first of all that this regime (in both systems) exists in a certain domain of the parameters and initial conditions; secondly, it means that its duration (in the multi-component system) does not exceed certain value. The term "stationarity" specifies a clearly expressed periodicity of formation (in the one-component system) or even a constancy of the phase in TPSP operation.

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