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Complex dynamics of optical solitons interacting with nanoparticles

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The localized nonlinear patterns in the systems with gain and loss are refereed as dissipative solitons [1, 2]. The formation of the localized dissipative structures is provided not only by the balance of the spreading and the narrowing of the wave but also by the balance of the driving force and the losses in the system. A pump of energy is essential and the solitons are defined by the properties of the system, rather than by the initial conditions [3]. That is why the dissipative solitons can be easily controlled and are interesting from the practical point of view for their potential applications in optoelectronic devices [4, 5].

One of the recent proposed applications of the optical solitons is optical trapping [6]. Nowadays optical trapping [7–9] and transporting [10–14] is actively developing field and many new effects, that can be used for the trapping, for example such as optical hook [15], is presented. In [6] it is proposed to use optical solitons for manipulation of nanoparticles placed in or on the top of the resonator excited by a powerful holding beam. The solution in the form of a bound state of a soliton and a particle is found, and the stability of the states is studied. It is shown that the bound states can be dynamically stable and, thus, can be observed experimentally.

In the present Letter we consider the dynamics of the solitons carrying more than one particle and investigate mutual interaction of the solitons with the trapped particles.

The system of interest is a nonlinear Fabry–Perot resonator pumped by the coherent light with a dielectric particle, located in the surface. The system of this type can be described by a generalized nonlinear Schrodinger equation for the optical field. The viscous dynamics of the particle can be obtained via the solution of an ordinary differential equation for the centre mass of the particle [6]:

$$\frac{\partial}{\partial t}E - iC\frac{\partial^2}{\partial x^2}E + \left(1 - i\delta + i\frac{\alpha}{1+|E|^2}\right)E = \\ = \left(1 - \sum_m f e^{-(x-\epsilon_m)^2/\omega^2}\right)P, \tag{1}$$

$$\frac{\partial}{\partial t}\epsilon_m = \eta\frac{\partial}{\partial x}|E(\epsilon_m)|^2, \tag{2}$$

where E is a complex amplitude of optical field in the resonator, C is diffraction coefficient, P is complex amplitude of laser pumping, α is coefficient of nonlinearity; δ is laser detuning from resonant frequency, ϵ is coordinate of nanoparticle. Parameter ω is width of a particle shadow, f is a transparency coefficient of a particle: if $f = 0$, then particle is transparent and if $f = 1$ then the particle is opaque. The coefficient η defines the ratio of the dragging force acting on the particle to the field intensity gradient at the point of particle location.

The numerical simulations of collisions of soliton-particle bound states is performed. To force solitons with trapped particles to move towards each other a phase gradient of the holding beam $P = P_0e^{-ikx^2}$ is used. It is shown, that as a result of two-soliton collision one soliton is formed, but in dependence of transparency of the particles different outcomes are possible. If particles are transparent enough the resulting soliton successfully captures them, see Fig. 1a. If particles are too opaque the resulting soliton annihilates and particles get released, see Fig. 1d. In the intermediate case the resulting soliton and particles oscillate around some equilibrium point, see Fig. 1c. The result of the collision can be predicted by the stability analysis of the corresponding stationary state of single soliton with trapped particles, see Fig. 1b.

Also the interactions of solitons through rescattering on the particles is considered. The system of interest is two nonlinear wide-aperture resonators separated by a relatively thin gap. Each of the resonators is pumped by a holding beam, and we assume that the resonators do not interact with each other directly. However, if a particle is placed between them, then it feels the evanescent fields of the both resonators modes. That is why

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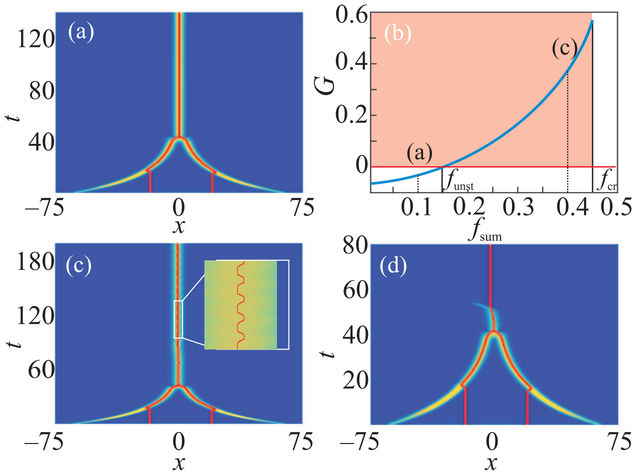

Fig. 1. (Color online) Collision of solitons with trapped particles under inhomogeneous pumping $P = P_0 e^{-ikx^2}$. Parameters: $P_0 = 5$, $k = 0.0002$, $\nu = 2.24$, $\delta = 1.5$, $\alpha = 15$. (a) – As a result of the collision of two initial solitons with trapped particles one soliton is formed, which successfully captures both particles, $f = 0.05$. A corresponding stationary state is stable, see panel (b). (b) – The dependence of the instability increment of the resulting soliton with captured particles on the collective transparency of the particles, where $f_{\text{sum}} = 2f$, because particles are the same. (c) – With more opaque particles ($f = 0.2$) the oscillating soliton with particles is formed as a result of two solitons collision. The inset shows the position of the particles with respect to the soliton. The soliton oscillates because corresponding stationary state is unstable, see panel (b). (d) – As a result of the collision both solitons annihilate, $f = 0.25$, because there is no corresponding stationary state

the particle can get attracted to the maximal intensity region of the field in each of the cavities. At the same time coupling to the particles decreases coupling of the holding beam to the guided mode of the cavity. Thus, the modes of the cavities can interact through the particles placed between them.

It is shown that in case of the solitons of same intensity the slower one takes all the particles. The slower soliton can steadily capture all the particles or just one, in dependence of transparency of the particles. If both solitons move with the similar velocities, in a result of interactions between solitons all trapped particles get released.

By considered effects it is possible, for example, to collect all the particles in the system by two counter-propagating solitons and then release the particles at some desirable point creating a cluster of particles; or to bring all the particles to the left or to the right edge of the cavity. In other words, the solitons can be used for a flexible and precise control over the particles. Such accurate many particle manipulation can be used in microfabrication.

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