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Dynamics of particles trapped by dissipative solitons

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Optical trapping [1–3] and transporting [4–8] of small objects by optical forces has been actively developing in the past several decades. Many new effects, that can be used for the trapping, for example such as optical hook [9], has been presented. Such optical transport can be widely used in many areas from optics [10], biological [11] and chemical [12] research, to microfabrication [13].

Optical trapping is based on the balance of two different types of optical forces. The first type is scattering forces, which push an object in the direction of light propagation; and the second type is gradient optical forces, which move an object along the gradient of light intensity [14]. If gradient forces are larger than scattering, then an object is pulled to the area of stronger light intensity and can be trapped by focused light. After trapping an object can be manipulated by moving light beam in a preferred direction.

In this letter a new concept of optical manipulation of a small particle by dissipative optical localized waves is proposed which opens new avenues for flexible control over nanoparticles dynamics governed by nonlinear effects. Further the localized waves are referred as solitons. First, the formation of the solitons can locally enhance the intensity of the field and thus allow to use less powerful holding beam. Secondly, changing the phase gradient of the holding beam (which is a relatively easy task) it is possible to move the solitons in a controllable way and if the particles are trapped by soliton, then the particles will be moved by it. This mechanism can potentially facilitate the manipulation of nanoobjects by light.

To implement this strategy of optical manipulation a series of problems are to be solved. Primarily, a suitable physical system providing the existence of the solitons and a corresponding mathematical model describing the formation of the solitons in the presence of nanoparticles have to be suggested.

The physical system considered in the present paper is a nonlinear Fabry–Perot resonator with dielectric nanoparticles placed on top of the resonator. Bistability and formation of the solitons in such resonators have been studied for many years theoretically [15–17] and experimentally [18, 19]. The schematic view of this system is shown in Fig. 1a. The resonator is pumped by a holding beam of coherent light. The nanoparticles partially screen the light exciting the resonator and at the same time spatially nonuniform distribution of the optical field in the resonator leads to the lateral force that drags a particle into an area with higher intensity. In turn, the nanoparticle creates a shadow which locally reduces the intensity of the coherent pumping of the optical mode which is able to affect the soliton.

As a mathematical model describing the dynamics of light and motion of the particle in such system, the Generalized Nonlinear Schrödinger equation with dissipation and pumping coupled to an ordinary differential equation is used:

$$\frac{\partial}{\partial t}E - iC\frac{\partial^2}{\partial x^2}E + (\gamma - i\delta + i\frac{\alpha}{1+|E|^2})E = \\ = (1 - fe^{-(x-\epsilon)^2/\omega^2})P, \quad (1)$$

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

where E – is a complex amplitude of optical field in the resonator, C – diffraction coefficient, P – amplitude of laser pumping, γ – decay rate, α – coefficient of nonlinearity; δ – laser detuning from resonant frequency, ϵ – coordinate of nanoparticle. Parameter ω defines width of a particle shadow, f defines transparency of a particle: if $f = 0$, then the 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 in the point of the particle location. For mathematical convenience the dimensionless variables are used.

The stationary localized solutions of the resting solitons with trapped particles were found and their stability is analyzed. It was found that in case of the spatially uniform pumping field the particle always destabilize the soliton, regardless of the transparency of the particle. Depending on the parameters of the particle such instability can either destroy the soliton or set the soliton in motion. This motion is affected by two effects, the first one is the attraction of the particle to the soli-

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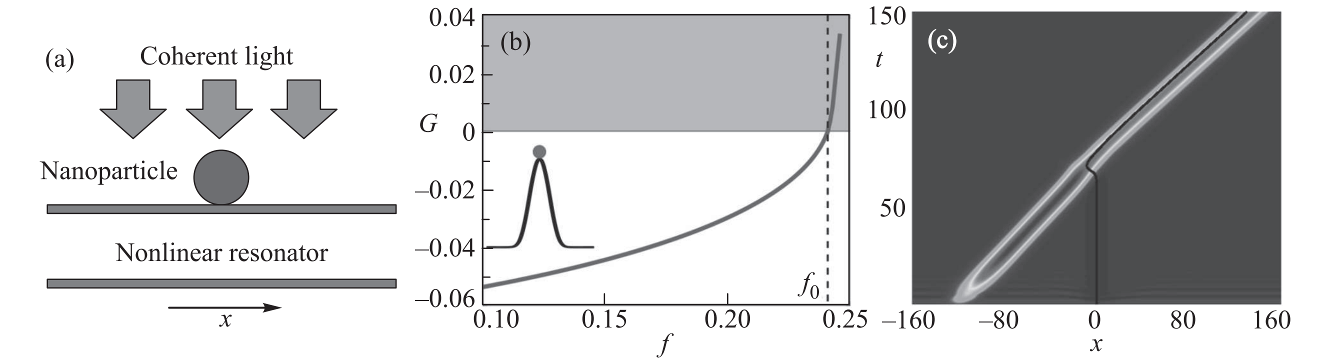

Fig. 1. (Color online) (a) – Schematic view of a Fabry–Perot resonator with a nanoparticle on the upper translucent mirror. (b) – Instability increment of the resting soliton with a particle placed in the center of soliton, pumping field has phase dependence on coordinate in the form $P = P_0 e^{-ikx^2}$. Parameters: $\nu = 0.7$, $E_0 = 1$, $\delta = 0.3$, $\gamma = 0.2$, $C = 16$, $\alpha = 3$, $k = 0.005$. (c) – Successful capture of a particle by a moving soliton. Pumping field $P = P_0 e^{ikx}$, where $k = 0.04$, $f = 0.3$, other parameters are the same as in (b)

ton and the second one is repelling the soliton from the shadow created by the particle.

It is also shown that the resting solitons with the trapped particles can be stabilized by spatially nonuniform holding beams. In this case stability of the soliton depends on the transparency of a particle. If particle shadow is too deep then soliton collapses. The dependence of the increment of linear excitations on the transparency of the particle can be seen in Fig. 1b.

The dynamics of the solitons colliding with the particles is also investigated. The solitons are set in motion by the phase gradient of the holding beam. Stationary solutions of moving solitons with captured particles are found and it's dynamical stability is studied. Depending on the transparency of the particle and the velocity of soliton the collision can result in passing the soliton by the particle causing its displacement, in the trapping of the particle on the soliton, see Fig. 1c, or in the collapse of the soliton.

The possibility to obtain and control the motion of the stable complexes consisting of solitons with trapped particles opens new possibility of optical manipulation of the nanoobjects driving a variety of emerging applications, such as, e.g., non-linear optical tweezers, nanoparticles delivery over arbitrary trajectories, optically induced governing chemical reactions in microchambers, etc.

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