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Dynamics of particles trapped by dissipative domain walls

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1. Introduction. Nonlinear localized structures have been attracting much attention in recent time because of the two reasons. The first one is fundamental interest to their rich variety in physical systems of different natures, including hydrodynamics, plasma physics, biology and nonlinear optics, see [1–4]. And the second reason of high interest in nonlinear localized structures is their potential applications in many fields, including information optical processing [5, 6], optical fiber communications [7], and optical manipulation [8, 9].

One of the most interesting localized structures are switching waves, or alternatively "domain walls", connecting different stationary spatially homogeneous states. The direction and the velocity of the domain wall motion strongly depends on the pumping intensity. But there is a special value of pumping intensity characterized by zero velocity of the domain wall and it is called Maxwell point. Near the Maxwell point the domain walls are able to create different bound states, such as bright or dark solitons [10–12].

Another important effect of domain walls is reported in [13]. It is demonstrated that under biharmonical pumping the direction and the velocity of the domain wall can be controlled by changing only the mutual phase between the harmonics, it is so called "ratchet effect".

In this Letter we suggest a new strategy of optical manipulation of small particles by dissipative domain walls. This problem is closely related to the manipulation of the particles by dissipative bright solitons considered in [8, 9]. This Letter is devoted to the formation, stability and the dynamics of the bound states of the particles and the domain walls. Special attention is paid to the influence of the ratchet effect on the processes of particle capturing and on the possibility to use ratchet effect for nanoparticles manipulation.

We considered a nonlinear Fabry–Perot resonator pumped by the coherent light with a dielectric particle, located in the surface. Such resonators provide bistability and existence of bright solitons and domain walls, see [10–15]. A particle on the surface of resonator is attracted in the area of higher intensity because of the gradient force [16] and in [8, 9] it is demonstrated that dissipative solitons in considered system are able to steadily capture particles and transport them in desirable direction.

The optical field of the considered resonator is described in the slow varying amplitude approach by the Schrödinger equation with the nonlinearity of saturable type, dissipation and pumping:

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

where C is diffraction coefficient, E is a complex amplitude of optical field in the resonator, P is an amplitude of laser pumping, γ is decay rate, α is the nonlinearity coefficient; δ is laser detuning from resonant frequency, ϵ is coordinate of the nanoparticle. Parameter ω defines width of the particle shadow located at $x = \epsilon$, f relates to the transparency of a particle: if $f = 0$, then the particle is transparent and if $f = 1$, then the particle is opaque. The viscous motion of particle under the gradient force is described by the following equation for the particles' coordinate:

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

In our model we use the typical assumption that the dragging force acting on the particle is proportional to the gradient of the intensity of the optical field, the coefficient η accounts for the interaction strength. Let us note that for mathematical convenience we use the dimensionless variables.

We performed numerical simulations with the parameters insuring the existence of the domain wall. We focus on the dynamics of the domain walls with particle under uniform and time-independent pumping $P(x,t) = P_0$. Since the uniform states connected by the

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domain walls are not equivalent in the terms of intensities, the particle location relative to the wall is important. In dependence of particles transparency and location several scenarios of interaction are possible, from successful particle trapping as in Fig. 1a, to the full stop of the domain wall by the particle as in Fig. 1b.

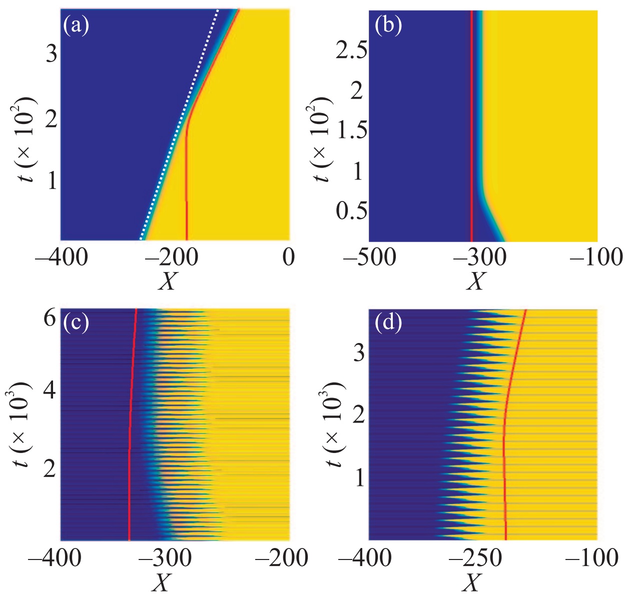

Fig. 1. (Color online) (a) – The particle is captured by the moving domain wall, $f = 0.005$, $P = 5.1$. (b) – The particle stops the domain wall, $f = 0.07$, $P = 5.2$. (c), (d) – The particle is captured by the domain wall driven in motion by the ratchet effect with parameters $a_1 = a_2 = 0.1$ and $\Omega = 0.05$. For (c) $\theta = 0$ and $f = 0.002$, for (d) $\theta = \frac{\pi}{2}$ and $f = 0.005$. For all panels other parameters are following: $\alpha = -10$, $\delta = -0.3$, $\gamma = 1$, $C = 16$, $\eta = 0.7$, and $\omega = 10$

Also we consider the influence of the biharmonic signal on the dynamics of the domain walls with particles interaction. The time-dependent spatially uniform pumping has the following form:

$$P = P_0 + a_1 \sin(\Omega t) + a_2 \sin(2\Omega t + \theta), \quad (3)$$

where P_0 is time independent component of the signal, Ω is frequency of the first harmonic and θ is mutual phase difference between two harmonics.

Under the action of biharmonic pumping signal it is possible to control the velocity of domain wall not only by changing the amplitude of the pump but also by changing mutual phase of the harmonics, see [13]. This effect is especially important in the vicinity of the Maxwell point. If time-independent part of pumping intensity is close to Maxwell point, then by changing the mutual phase θ it is possible to change not only velocity of the domain wall, but also its direction of propagation. In case if $\theta \approx 0$ the domain wall propagates in the direction of extension of the area of higher intensity, and in case if $\theta \approx \pi/2$ the domain wall moves in the opposite direction, see Fig. 1c, d.

From Fig. 1c, d it is seen that trapping of particles by oscillating front is also possible. The domain walls moving because of the ratchet effect have very slow velocities what makes it possible to achieve high accuracy of particle manipulation.

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