Interactions between self-channeled optical beams in soft-matter systems with artificial nonlinearities

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We demonstrate optical interactions between stable self-trapped optical beams in soft-matter systems with pre-engineered saturable self-focusing optical nonlinearities. Our experiments, carried out in dilute suspensions of particles with negative polarizabilities, show that optical beam interactions can vary from attractive to repulsive, or can display an energy exchange depending on the initial relative phases. The corresponding observations are in good agreement with theoretical predictions.

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In general, beams of light tend to diffract during propagation. Under appropriate conditions, this universal broadening effect can be arrested through a nonlinear light–matter interaction, which locally modifies the refractive index properties of the material involved. In this regime, a self-trapped optical beam is possible, capable of maintaining its initial size characteristics over several diffraction lengths [1,2]. Typically, such self-channeled optical beams or spatial solitons are governed by a nonlinear Schrödinger-type equation and result from some type of self-focusing nonlinearity. Yet, even though a plethora of nonlinear mechanisms can induce self-focusing effects, not all of them lead to stable beam self-trapping. For instance, when the nonlinearity is of the Kerr-type, only one-dimensional solitons are stable while their two-dimensional (2D) counterparts are known to undergo catastrophic self-focusing collapse [3]. As indicated in previous studies [1], stable self-trapping in 2D settings is only possible provided that the effective nonlinearity saturates with the optical intensity. As previously demonstrated in several studies, biased photorefractive crystals [4,5] and atomic sodium vapor systems [6] represent quintessential examples of such saturable nonlinear materials.

Recently, the nonlinear optical properties of dielectric nano-suspensions have attracted considerable attention [7–16]. In this class of artificial material systems, the nonlinearities can be exceedingly high. This was first shown by Smith *et al.* in a polystyrene nano-suspension arrangement where the effective nonlinear coefficient was found to be approximately 10^5 times that of CS_2 [17]. In dielectric nano-suspensions, two main mechanisms can contribute to beam self-trapping, light scattering effects (i.e., optical gradient forces) [7–12], and thermal effects, which mainly act by virtue of thermophoresis [18,19]. In the case where gradient optical forces are involved, a self-focusing nonlinearity is established through a driven particle migration [9]. This is true irrespective of whether the refractive index of the suspended nanoparticles is higher or lower than that of the surrounding liquid medium. In both regimes, the refractive index of the system will be elevated within the beam region inducing a waveguide capable of self-trapping the optical field [7,9]. Over the years, spatial solitons and their interactions have been extensively studied in a variety of nonlinear materials [1,2]. Yet, as of now, only a handful of experimental results concerning the propagation and interaction of such self-trapped beams in these nano-suspension systems have been reported. Part of the reason for this is every study has been carried out in suspensions with positive polarizabilities, where, the refractive index of the particles, n_p, is higher than that of the ambient liquid, n_b, and hence the self-focusing nonlinearity ends up to be super-critical. As a result, spatial soliton collapse occurs and propagation becomes unstable. If, on the other hand, $n_b > n_p$ (negative polarizability), the self-focusing nonlinearity of the colloidal suspension turns out to be saturable, leading to stable beam propagation [9,11]. In this latter case, because the particles are expelled away from the beam center, Rayleigh scattering losses can drastically drop leading to a highly desirable self-induced transparency effect.

Clearly, it will be of importance to synthesize artificial dielectric nano-suspensions with negative polarizabilities where the nonlinear dynamics of stable self-trapped channels can be easily observed [20]. In this Letter, we demonstrate the optical interaction of self-trapped beams in pre-engineered colloidal solutions with negative polarizabilities. This is realized by dispensing polytetrafluoroethylene (PTFE) particles in a diluted glycerin solution which provides a saturable optical nonlinearity. Along with the demonstration of the self-trapping effects, we explore, both theoretically and experimentally, the coherent interactions between the nonlinear self-trapped beams. Our results may pave the way toward controllable light–matter interactions in dilute dielectric nano-suspensions.

To carry out our experiments we focus a $\lambda_0 = 532$ nm laser beam into a 5 mm long glass cuvette filled with a suspension of PTFE particles with an average diameter of 200 nm. The beam propagation dynamics through the

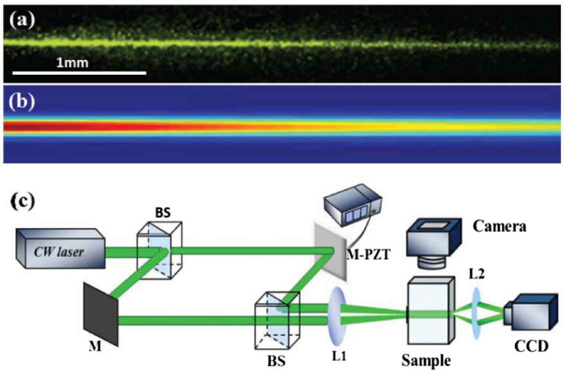

Fig. 1. Self-trapped beam propagation through a PTFE nano-suspension: (a) experimental results, (b) theoretical model, and (c) experimental setup used.

sample are visualized via scattered light and recorded by a top-view camera as shown in Fig. 1. To produce a colloid with a negative polarizability [9], PTFE nanoparticles with a refractive index of $n_p = 1.35$ were suspended in a mixture of glycerin and water having a 4:1 weight ratio resulting in an effective background refractive index of $n_b = 1.44$. Owing to saturation, stable beam self-trapping occurs at an input power level of 2 W as clearly shown in Fig. 1(a). This beam can maintain its initial FWHM of 12 μm over several diffraction lengths, and does so in a stable manner. Our experiments indicate that these effects are purely due to optical forces, thus ruling out any thermal effects from optical dissipation [20].

To model this process, we use the fact that locally, the effective index of such a colloidal medium can be described by $n_{\text{eff}} = (1-f)n_b + fn_p$ where f stands for the particle volume filling factor. A successful approach to this problem should allow one to express f as a function of the optical intensity, I, in the presence of thermal diffusion effects and multiparticle interactions necessary to stabilize the colloidal system [12]. As shown in [9,11], in the presence of gradient optical forces, the filling factor of a negatively polarizable suspension obeys a Boltzmann distribution to a good approximation, i.e., $f(I) = f_0 \exp(\alpha I/4k_bT)$. In this equation, α represents the particle polarizability [21], k_bT is the thermal energy, and f_0 is the unperturbed filling factor of the medium in the absence of any illumination. This expression clearly indicates that if $\alpha > 0$ ($n_p > n_b$), the particles will be attracted to the beam center, and if $\alpha < 0$, the particles will be expelled outward. Optical wave propagation in such a system obeys a nonlinear Schrödinger-like equation [9]:

$$i\frac{\partial\phi}{\partial z} + \frac{1}{2k_0 n_b}\nabla_\perp^2\phi + k_0(n_p - n_b)f\phi + \frac{i\sigma f}{2V_p}\phi = 0, \quad (1)$$

where ϕ is the electric field envelope, $k_0 = 2\pi/\lambda_0$, σ is the Rayleigh scattering cross section [22], and V_p is the volume of each individual particle. The saturable nature of the nonlinearity is apparent in Eq. (1) when $\alpha < 0$. Additionally, in this regime the scattering losses drop at higher-intensities as evidenced by the last term in this equation. Equation (1) is solved numerically for the parameters used in our experiments when $f_0 = 0.3\%$. The numerical results are illustrated in Fig. 1(b) and are in very good agreement with the experimental observations of Fig. 1(a). In this particular case, the beam remains self-trapped without any noticeable divergence up to eight diffraction lengths (4 mm). We now investigate the interaction dynamics between two adjacent self-trapped beams. These effects are studied experimentally in the aforementioned PTFE suspension up to a propagation distance of 3 mm. To do so, we first consider the case where the two self-channeled beams are π out of phase and each one conveys again 2 W and has a FWHM of 13 μm. The separation between these two beams is taken to be 13 μm. The distance between the two parallel beams is adjusted by a translating mirror while the relative phase between them can be finely adjusted by driving the piezoelectric transducer, which the second mirror is mounted on [Fig. 1(c)]. A numerical simulation [Fig. 2(a)] of this process indicates repulsion, a very common characteristic of soliton interactions under such circumstances [1,2,23,24]. The expected transverse position of these light beams at the input and output facets of the cuvette is depicted in Figs. 2(b) and 2(c). The electromagnetic fields of the two out of phase beams interfere at the center and this in return modulates a refractive index gradient in the soft-matter system, causing the beams to diverge away from each other. Experiments at low powers reveal considerable diffraction [eight-fold expansion, Fig. 2(d)] while stabilization occurs at 2 W. As depicted in Figs. 2(e) and 2(f), the distance between the two beams increases from 13 to 29 μm because of repulsion in accordance with the results of Fig. 2(a). This is contrasted with the output position a single soliton will have in the absence of the other as experimentally revealed in Fig. 2(g). We next consider the scenario where the two neighboring beams copropagate in phase. As our simulations show, in this artificial nonlinear system, the two soliton beams are now attracted to each other during propagation [Fig. 3(a)]. In this case, the separation between these two beams is 26 μm at the input [Fig. 3(b)] while at the output, it is expected to decrease to 15 μm [Fig. 3(c)] after 3 mm of propagation. This predicted behavior is verified experimentally [Figs. 3(d) and 3(e)] in a system having the same parameters used previously. What is interesting in this material configuration is that the two beams remain stable even during merging,

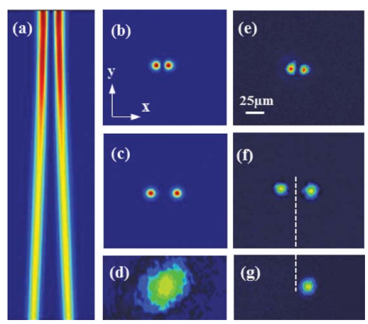

Fig. 2. Repulsion of two π out of phase, 13 μm apart, self-trapped beams in a PTFE nano-suspension. (a)–(c) Numerical simulations of repelling beam interaction, (b) beam profile at the input, and (c) output. (d) Beam diffraction at low powers (linear regime). (e), (f) Corresponding experimental snapshots. In (g), one beam is blocked before the cuvette. In this case, the beam remains at the same distance from the dashed line.

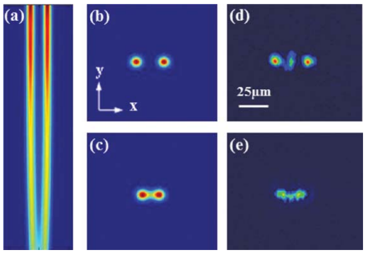

Fig. 3. Interaction of two in-phase self-trapped beams with an initial 26 μm separation after 3 mm of propagation. (a)–(c) Numerical simulations indicate attraction. (b) Combined beam profile at the input and (c) output. (d), (e) Shows corresponding experimental results at the input and output, respectively.

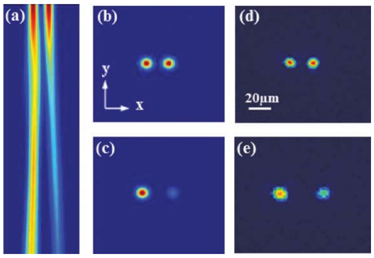

Fig. 4. Interaction of between two $\pi/2$ out-of-phase, self-trapped beams after 3 mm. (a)–(c) Numerical simulations show power exchange between the two beams. (d), (e) Corresponding experimental results display similar behavior for the same initial conditions.

something that would have been impossible in a nanosuspension with a positive polarizability. Finally, we study interactions when the relative phase between the two wavefronts is $\pi/2$ and their separation distance is 20 μm at the input. Theoretical and experimental results are presented in Fig. 4 under the same conditions used before. In this case, the beams affect each other in a more complex manner. Not only do they repel each other, but they also exchange energy through a four-wave mixing process [24].

In conclusion, we have demonstrated the optical interactions of a self-trapped beam with a PTFE colloidal suspension exhibiting a saturable nonlinearity. In addition to self-trapping effects, the coherent interactions between two self-channeled beams have been experimentally studied. This ability to synthesize pre-engineered saturating nonlinear soft-matter systems may now allow a systematic study of physical kinetic effects in the presence of optical forces exerted by self-channeled beams.

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