PHYSICAL REVIEW A **80**, 041808(R) (2009)

# Incoherent surface solitons in effectively instantaneous nonlocal nonlinear media

Barak Alfassi, Carmel Rotschild, and Mordechai Segev
*Physics Department and Solid State Institute, Technion, Haifa 32000, Israel*

(Received 20 January 2009; published 22 October 2009)

We demonstrate experimentally and theoretically random-phase surface solitons in effectively instantaneous nonlinear media. The key mechanism for self-trapping is played by a nonlocal nature of the nonlinearity, in contrast to other incoherent solitons involving time averaging. These incoherent surface solitons display features different from their bulk counterparts and from other surface waves.

DOI: 10.1103/PhysRevA.80.041808 PACS number(s): 42.65.Tg

Optical surface waves are localized waves residing at the interface between two media with different optical properties. They were observed under both linear and nonlinear conditions. In the linear case, they were found between metal and a linear dielectric medium [1] at the interface of a homogeneous medium and a lattice [2], and between isotropic and anisotropic materials [3]. In the nonlinear domain, surface waves were proposed in a variety of systems, e.g., Kerr media [4], waveguide arrays [5], metamaterials [6], optical amplifiers [7], etc., but until 2007 observed only in photonic lattices [8] and in bulk photorefractive [9]. Recently, surface solitons were explored in materials exhibiting a highly nonlocal nonlinear response [10–12], including observations of both coherent [10] and incoherent [11] surface waves. Among those, incoherent surface solitons are perhaps the most unique due to their close relation to incoherent bulk solitons, which were discovered in 1996 [13]. Since then, incoherent solitons were studied in numerous settings, in optics [14–16], matter waves [17], spin waves [18], etc. Until recently it was believed that optical incoherent spatial solitons can exist only in noninstantaneous nonlinear media, where the response time of the nonlinearity, $\tau$ is much slower than the characteristic fluctuation time $t_c$ of the incoherent field ($\tau \gg t_c$). The reasoning was that, only under such conditions, the nonlinear index change induced by the fluctuating beam would be stationary in the propagation direction, as necessary for guiding the multiple modes comprising the incoherent beam. Otherwise, when $\tau \leq t_c$ the speckled structure of the fluctuating field induces a rapidly varying fragmented index structure which breaks the beam apart. However, nonlocal nonlinearities can overcome this obstacle as was recently shown [19,20] with incoherent bulk solitons. The key ingredient of this trapping process is a highly nonlocal nonlinear response, which yields spatial averaging instead of the traditional temporal averaging provided by the noninstantaneous response.

Here, we present incoherent surface solitons in instantaneous nonlocal nonlinear media: self-trapped incoherent beams propagating at the interface between a linear medium and a highly nonlocal effectively instantaneous nonlinear medium. These incoherent surface solitons are fundamentally different from their bulk counterparts (e.g., absence of *statistical nonlinear diffraction* [19]), yet they do maintain some of the unusual properties associated with coherent surface solitons in nonlocal nonlinearities, such as absence of threshold, and attraction to the interface from afar [10].

Let us recall the features of incoherent bulk solitons in highly nonlocal instantaneous nonlinear media. In these materials, the nonlinear response is carried to regions beyond the range of localized beam: the refractive index change ($\Delta n$) at a given location is a function of the intensity at some nonlocality range surrounding that location. Nonlocal optical nonlinearities typically arise from a transport mechanism, such as heat [21,22], atoms in a gas [23], charge carriers [24], etc., or from long-range forces [25]. In bulk media, when the nonlinear response is highly nonlocal, the structure of the induced index change is approximately parabolic, depending only on the beam power, not on the actual details of the beam [19,20,26]. As long as the total beam power is fixed, any composition of guided modes of such induced waveguide will be guided and would not experience diffraction broadening. This idea holds also in instantaneous nonlocal nonlinear media even though the nonlinearity does respond to the random fluctuations of the phases and modal weights. When such a beam is comprised of a large number of modes, the random deflections caused by modal interference are minimized, and the self-trapped fluctuating multimode beam is in fact an incoherent soliton [19,20]. This is the main idea behind incoherent solitons in effectively instantaneous highly nonlocal nonlinear media.

Here we study incoherent surface wave in such effectively instantaneous highly nonlocal nonlinear media. For surface waves, the existence of an optical interface (in contrast to a homogenous bulk medium) breaks the symmetry of the problem, and some of the basic ideas holding in the bulk are no longer valid. For example, the presence of an interface implies that transverse momentum is not conserved. This has major implications: the nonconservation of transverse momentum eliminates the broadening associated with statistical nonlinear diffraction, a phenomenon that in the bulk poses an obstacle to the existence of instantaneous incoherent solitons [19,20]. Furthermore, the existence of instantaneous incoherent bulk solitons is based on the fact that the structure of the induced index change is approximately symmetric and parabolic. However, for surface waves, the asymmetric boundary condition for the boundary temperature, which is crucial for surface solitons in this medium [10], gives rise to an asymmetric induced index change. Hence, it is not at all clear that instantaneous incoherent surface waves would even exist. Altogether, the existence of such incoherent surface waves and their properties are far from being a straightforward extension of their bulk counterparts.

A linearly polarized self-trapped partially spatially incoherent beam can be expressed as a superposition of guided modes of the waveguide induced by the beam itself [11]

 

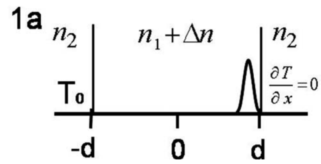


FIG. 1. Cross section of the sample with the temperature boundary conditions. The nonlinear medium is between $-d<x<d$, and the interface with the linear medium is at $x=d$.

$$\tilde{E}(x,z,t)=\sum_n \sqrt{P_n(t)}E_n(x,z)\exp[i\varphi_n(t)], \quad (1)$$

where $E_n(x,z)$ is the normalized modal amplitude $P_n(t)$ and $\varphi_n(t)$ are the modal power and phase. For simplicity, we analyze a $(1+1)D$ problem, where $z$ is the propagation direction and $x$ is the direction transverse to it. The interface is at $x=d$. The beam is spatially incoherent because $P_n(t)$ and $\varphi_n(t)$ vary randomly in time, on a time scale $t_c$. Note that the beam intensity at any instant of time is not $z$ invariant because the modes interfere while their propagation constants differ from each other, hence the resultant speckled pattern varies as the beam is propagating. Consequently, the induced waveguide at any instant of time is not necessarily $z$ invariant, hence neither are its guides modes $E_n(x,z)$.

We are interested in the case $\tau \ll t_c$, i.e., the response of the medium is instantaneous compared to the fluctuations time [19,20]. An incoherent beam is an ensemble average over a sequence of short time windows $t^r$ ($r=1,2,\ldots$ for the $r$th window), each of (average) duration $t_c$, where within each window the modal powers and phases are fixed: $P_n(t)=P_n^r$ and $\varphi_n(t)=\varphi_n^r$. Hence, each time window $t^r$ has a different realization of the field $E^r(x,z)=\sum_n\sqrt{P_n^r}E_n(x,z)\exp(i\phi_n^r)$. Thus, within each time window the modes interfere with different $P_n^r$ and $\varphi_n^r$ and yield a different speckle structure. The nonlinearity responds to each one of these patterns, instantaneously, because within each $t^r$, $E^r(x,z)$ is a coherent speckled beam.

Consider such an incoherent beam propagating at the vicinity of an interface between a linear medium and a nonlocal nonlinear medium [Fig. 1(a)]. Each mode $E_n(x,z)$ comprising the field at the interface evolves according to the Helmholtz equation in each medium separately, connected through the boundary condition at the interface:

$$\frac{d^2E_n(x,z)}{dx^2}+\frac{d^2E_n(x,z)}{dz^2}+k_0^2(n_1^2+2n_1\Delta n)E_n(x,z)=0 \quad (2a)$$

in the nonlinear medium ($|x|\leq d$) and

$$\frac{d^2E_n(x,z)}{dx^2}+\frac{d^2E_n(x,z)}{dz^2}+k_0^2n_2^2E_n(x,z)=0 \quad (2b)$$

in the linear medium ($|x|>d$). Here, $k_0$ is the vacuum wave number, $n_1$ and $n_2$ are the linear refractive indices in media 1, 2, and $|\Delta n|\ll n_1$. Experimentally, we use the thermal nonlinearity of lead glass [10,20], where $\Delta n$ is proportional to the temperature change $\Delta n=\beta(T-T_0)$, $T_0$ being the temperature at zero light intensity, and $\beta=dn/dT$ is the thermal coefficient of the refractive index. The beam is slightly absorbed, but the absorption coefficient $\alpha$ is very small ($\alpha\ll|\Delta n|k_0$) so that absorption can be neglected in the wave equation. The heat generated due to the absorption diffuses in the medium, with a time constant much shorter than the duration of the time window $t^r$. Under these conditions, the medium responds to the speckled field within each time window $t^r$. Hence, within each window $t^r$, one can neglect temporal transients and consider only the steady state where $\Delta n$ satisfies the time-independent heat (Poisson-type) equation [10]

$$d^2\Delta n(x,z)/dx^2=-\tilde{\kappa}I^r(x,z), \quad (3)$$

where $\tilde{\kappa}$ is a constant of the medium and $I^r=|E^r(x,z,t)|^2$ is the beam intensity within the $r$th time window. Equation (3) describes a highly nonlocal nonlinearity, where the nonlocality range is limited only by the finite sample size. In a thermal nonlinearity, surface soliton occur at the proximity of thermally insulating boundaries [10]. Therefore, we set the temperature boundary conditions to $\partial T/\partial x=0$ at the right (insulating) boundary, and a fixed temperature $T=T_0$ at the left boundary [Fig. 1(a)].

We now find the surface modes comprising the incoherent self-trapped beam at the interface. These modes jointly induce the waveguide ($\Delta n$) at the interface, and they also populate the guided modes of that waveguide self-consistently. Recall that modal interference here does contribute to $\Delta n$ because the nonlinearity is instantaneous. [Unlike noninstantaneous nonlinearities where $\tau\gg t_c$, [19].] To find the modal structure, we first find the modes of an induced $\Delta n$ where modal interference does not contribute and then use them as initial conditions (at $z=0$) to simulate the propagation by solving Eqs. (2) coupled to Eq. (3) numerically. When $\Delta n$ is $z$ independent, $E_n(x,z)=u_n(x)\exp(i\Gamma_n z)$ as for incoherent solitons in noninstantaneous nonlinearities [11]. To find the modes, we neglect the interference terms in $I^r$ in Eq. (3), getting $I=\sum_n\langle P_n\rangle|u_n(x)|^2$, where $P_n$ is the time-independent ensemble average $\langle P_n^r\rangle$ over many realizations. We use $I$ in Eq. (3), solve Eqs. (2) and (3) self-consistently with proper boundary conditions.

Having found the modes, we use them as initial condition to simulate surface solitons propagation in our instantaneous nonlinearity. To do that, we use these modes, including their interference, to obtain the intensity $I^r$ at each time interval $t^r$ as $I^r(x,z)=|E^r(x,z)|^2=|\sum_n\sqrt{P_n^r}u_n(x,z)\exp(i\Gamma_n z)\exp(i\varphi_n^r)|^2$. We substitute $I^r$ in Eq. (3), find $\Delta n$, and use it in Eqs. (2) in every simulation step. Since the beam and its speckles are much broader than the wavelength, we use paraxial propagation in the simulation, while tailoring the exponentially decaying wave function in the linear medium to satisfy boundary conditions [10]. In this manner, we simulate the propagation of every realization of $E^r$, which is a coherent multimode field within each short time window $t^r$. Note that $E^r(x,0)$ is a superposition of guided modes of the waveguide, $u_n(x,0)\equiv u_n(x)$, but now $u_n$ is no longer $z$ independent, and its propagation is governed by Eqs. (2) and (3).

With the procedure described above, we find numerically incoherent surface solitons comprising of the first three modes [Fig. 2(a)] and simulate their propagation. The parameters are taken from the experiments: $\lambda=488$ nm, $T_0=298$ K, and the interface is between lead glass ($n_1=1.8$) and air ($n_2=1$). When the nonlinearity is noninstantaneous,

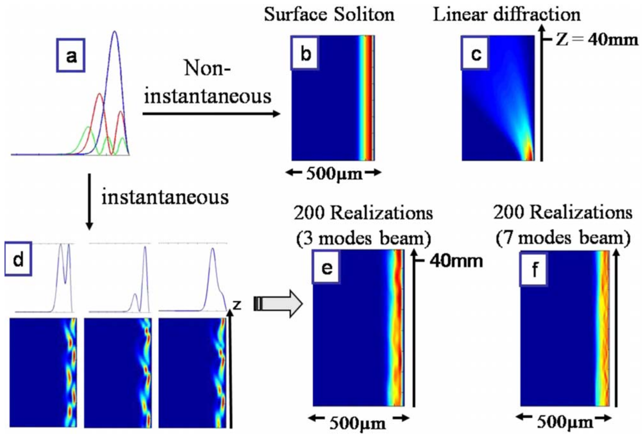


FIG. 2. (Color online) (a) Modes of a three-modal incoherent surface wave. (b)-(f) Top view. (b) An incoherent surface soliton in noninstantaneous media. (c) Low power linearly diffracting beam. (d) Propagation of three different realizations of the coherent speckled multimode beam in instantaneous nonlinear media. (e) The ensemble average over 200 realizations of the three-mode self-trapped surface wave. (f) The ensemble-averaged beam with seven modes.

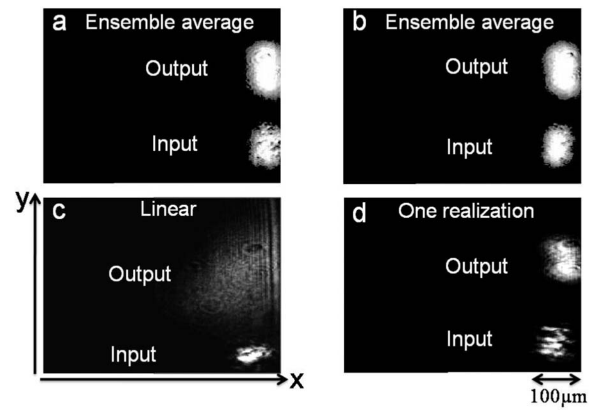


FIG. 3. Experiments: in all panels, the glass-air interface is at the right borderline of each panel. (a) Ensemble-average intensity at the input and output faces over 100 realizations demonstrating the incoherent surface soliton. (b) An input beam launched away from the interface attracts to it and self-traps there. (c) Low power linear diffraction of a specific realization. (d) Self-trapping of one specific realization for high power.

such an incoherent surface wave (FWHM $\approx 40$ $\mu$m) is propagating without diffraction, forming a stable surface soliton [Fig. 2(b) as in [11]]. For comparison, when the power of this beam is low, it broadens considerably [Fig. 2(c)]. As explained above, we use these modes as the initial condition to simulate surface soliton in our instantaneous nonlinearity, letting the beam evolve according to Eqs. (2) and (3) (including modal interference), which causes $\Delta n$ to evolve with $z$ as well. We simulate the evolution of multiple realizations of this trimodal beam, each within a short time windows $t^r$, where within each time window the modal powers and phases are fixed, but the initial modal phases are picked from a random-number generator. Figure 2(d) shows the simulated propagation of different realizations of the initial modal phases. As depicted in Fig. 2, each realization describes a different interference pattern between the modes, thereby exhibiting different initial intensity distribution [Fig. 2(d); the initial profile of each realization is sketched above the top-view simulation]. As shown in Fig. 2(b), although each realization is propagating at a different trajectory and with a different initial intensity profile, all realizations exhibit self-trapped propagation at the close proximity of the interface and are always attracted to the surface. [Surface solitons in this medium always attract to the surface, as can be intuitively understood by analogy of Eq. (3) with electrostatics [10,21].] When an ensemble average is taken over 200 random realizations [Figs. 2(e) and 2(f)], the time-averaged beam is self-trapped, forming a surface soliton. Examining Figs. 2(e) and 2(f), we notice that these surface waves do not exhibit the broadening associated with *statistical nonlinear diffraction* [19], which is pronounced for beams containing just a few modes in the bulk [20]. Here, as clearly shown in Fig. 2(e), the ensemble-averaged beam is localized at the close proximity of the interface, showing no broadening.

In the experiment, we use a lead-glass sample, with square $2\times 2$ mm cross sections and 83 mm in the propagation direction. Three of the transverse boundaries of the sample are thermally connected to a heat sink and maintained at room temperature, while one boundary is thermally insulating [10]. We generate the incoherent beam by passing a coherent laser beam through a diffuser before launching it into the sample. In this way, we can set the fluctuation time $t_c$ and the time window $t^r$ of the incoherent beam by controlling the diffuser. During a time window $t^r$ the beam passes the diffuser at a fixed location, resulting in a coherent multimode beam that is stationary in time, representing a specific random realization of the incoherent field. At the end of that particular time window, we abruptly change the position where the beam passes the diffuser and generate a different speckled pattern. The relation between patterns in different time windows is completely random. To work in the regime where the nonlinearity is instantaneous, we need $\tau \leq t^r$. Therefore, we set the time window $t^r$ to be longer than the response time of our thermal medium ($\tau \approx 0.1$ s). We monitor the propagation of this multimode beam after $\Delta n$ has reached temporal steady state within each time window $t^r$. Under these conditions, in each measurement we observe self-trapping of a specific random realization of the incoherent field. Figures 3(c) and 3(d) show the intensity distributions at the input and output planes of the sample for one typical random realization of the highly-speckled beam (the interface is at the right borderline of each panel). The input beam is $d=90$ $\mu$m FWHM, and the mean speckle size in it is $w=35$ $\mu$m. At low power, the beam diffracts linearly, broadening to $d=320$ $\mu$m [Fig. 3(c)]. At high power (2 W), the speckled beam self-traps [Fig. 3(d)], emerging at the same width as at the input plane. Notice that the fine details of each self-trapped output beam are different than those of its corresponding input beam due to modal beating and the surface effect. However, the trajectory of each self-trapped speckled beam always stays adjacent to the interface.

Carrying out multiple experiments with random realizations of the multimode beam and taking the ensemble average corresponds to monitoring the long time-scale behavior of an incoherent beam. The ensemble average taken over many realizations of the speckled beam [Figs. 3(a) and 3(b)] shows that the ensemble-average beam maintains its effective width. That is, not only did the "instantaneous" speckled beams self-trap within each time window, but the ensemble-average highly multimode beam displays stationary propagation, forming an incoherent surface solitons without any noticeable statistical nonlinear diffraction in both transverse directions. In the $x$ direction, as we showed theoretically [Figs. 2(e) and 2(f)], statistical nonlinear diffraction does not exist because this is a surface wave. In the other transverse direction, $y$, the beam is propagating as in bulk media, for which statistical nonlinear diffraction is suppressed because the beam is made of many modes, in which case the broadening associated with statistical nonlinear diffraction is negligible [19,20]. Figure 3(b) demonstrates attraction to the surface, which is unique to surface solitons in nonlocal nonlinear media [10]. The speckled self-trapped beam is always attracted to the surface even when the beam is initially launched away from the interface. To highlight this, we launch a sequence of speckled beams away from the surface, while keeping their launch trajectory parallel to the $z$ axis. The self-trapped speckled beams move to the interface and stick to its vicinity, exiting the medium at the same position as if they were launched at the proper position of a surface soliton.

As demonstrated in the simulations and in the experiments, the broadening effect associated with statistical nonlinear diffraction, which occurs in the bulk [19,20], is arrested in the case of the incoherent surface soliton. This is mainly due to the asymmetry of the induced profile of $\Delta n$ at the vicinity of the interface. Under such conditions, the initial linear momentum of the various random realizations of the multimode beam is not a conserved quantity. In the bulk, the trajectory of the $\Delta n$ is determined solely by the modal composition (amplitude and phase), and the transverse momentum is a conserved quantity. However, for self-trapped surface waves, the spatial symmetry is broken by the interface. The asymmetric $\Delta n$ exerts a force on the beam, changing its initial transverse momentum, always bending the beam toward the interface. The broken symmetry arrests the broadening associated with statistical nonlinear diffraction.

To conclude, we demonstrated incoherent surface solitons in effectively instantaneous nonlocal nonlinear media. This new concept applies to nonlocal nonlinearities responding faster than the fluctuation time of the incoherent beam, $t_c$. A system for observing such surface solitons in a fast-responding medium would be the interface between a dielectric and a semiconductor amplifier [24], where the response time is ~ps, and the incoherent beam could fluctuate even at ~ns rates. Ensemble-average experiments imply looking at the output beam with ordinary camera (integration time $\geqslant t_c$), whereas single-shot experiments would be carried out with fast camera to capture individual frames (integration time $< t_c$). This concept paves the way to possibilities, combining ideas from three arenas: surface waves, stochastic nonlinear waves, and nonlocal nonlinearities. The ideas presented here are relevant also beyond optics. For example, recent work revealed highly nonlocal nonlinearities in Bose-Einstein condensates [27].

This work was supported by an Advanced Grant from the European Research Council (ERC) and by the Israel Science Foundation (ISF). B.A. is grateful to the Azrieli Foundation for financial support.

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