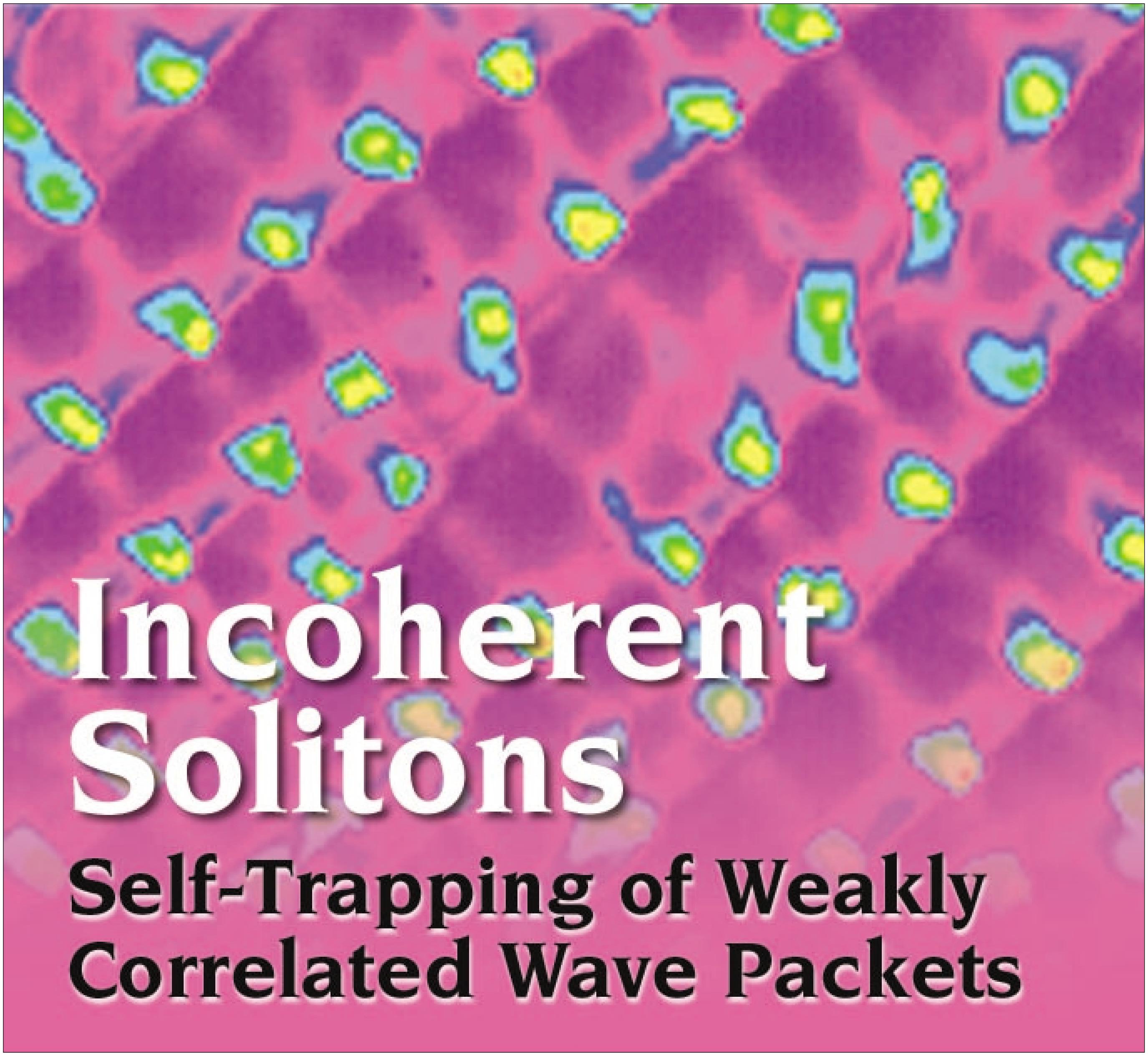

Incoherent Solitons

Self-Trapping of Weakly Correlated Wave Packets

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Solitons are fascinating entities that are known to exist in many different branches of physics. They represent self-localized wave packets that do not expand while propagating in a dispersive environment. The localization (self-trapping) relies on a nonlinear effect, and it can result from a variety of nonlinear mechanisms. In general, solitons exhibit a rich, particlelike behavior that is clearly manifested during their interactions (collisions). Despite their diversity, solitons are a universal phenomenon and thus share many common features. In their most frequent realization, these particlelike wave packets are fully coherent entities. In this case, given the soliton phase at a particular location as well as the frequency of the carrier wave, one can deterministically predict the phase everywhere (at any given point in space and time) upon the soliton.

Partially coherent beams occur in abundance in nature—their coherent counterparts are the exception.

Yet wave packets need not necessarily be coherent. In fact, partially coherent beams occur in abundance in nature—their coherent counterparts are the exception. As an example, one can focus a light beam from a natural source (such as the sun or an incandescent light bulb) into a

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narrow spot. Can such a partially incoherent beam self-trap in a nonlinear medium? Or, in a more general context, can a weakly correlated "ensemble of particles" (incoherent wave packet) form a self-trapped entity under the action of nonlinearity? In this short article, we will provide an updated overview of incoherent solitons, a new and exciting branch of nonlinear science that just five years ago seemed only an oxymoron. Now, almost six years after incoherent solitons were first observed experimentally,[1] it is well established that these random-phase and weakly correlated self-trapped entities exhibit a host of unique properties that have no analog whatsoever in the coherent regime.

Until 1995, all solitons in all branches of science were excited from coherent sources. In 1996, however, Matt Mitchell *et al.* at Princeton demonstrated for the first time self-trapping of a partially coherent beam upon which the phase varied randomly in space and time.[1] In that experiment, a quasi monochromatic, partially spatially incoherent light beam was employed. The wave front originated from a laser and was subsequently passed through a rotating diffuser that introduced a new random phase pattern every 1 μs. The beam was then launched into a slowly responding photorefractive crystal and, under appropriate conditions, the beam envelope self-trapped into a single, nondiffracting narrow filament. The fact that the self-trapped beam was indeed partially incoherent was manifested in its diffraction properties. The input beam was 30 μm FWHM and, in the absence of self-trapping, it diffracted to 102 μm after 6 mm of propagation in the medium. Had this same beam been fully coherent, it would have diffracted only to 36 μm after the same propagation distance. One can better appreciate the degree of partial coherence of this beam by considering the ratio between the beam diameter and the field's correlation distance (or speckle size), in this case around eight. Yet this partially incoherent wave packet, which exemplifies an ensemble of weakly correlated particles, was found to self-trap (thus in essence forming an incoherent spatial soliton), when a proper nonlinearity was employed. In the experiment cited in Ref. 1, the nonlinearity used was of the photorefractive screening type (see article by Crosignani and Salamo in this issue). Applying 550 volts between electrodes separated by 6 mm distance resulted in the self-trapping of this partially coherent beam, which maintained a constant width of 30 μm throughout propagation (Fig. 1). In a subsequent experiment, Mitchell and Segev demonstrated that an incoherent white light beam, i.e., a beam that is both temporally and spatially incoherent, can also self-trap.[2] In this experiment, the self-localized state originated from a simple incandescent light bulb that emitted light in the 380-720 nm wavelength range (Fig. 2).

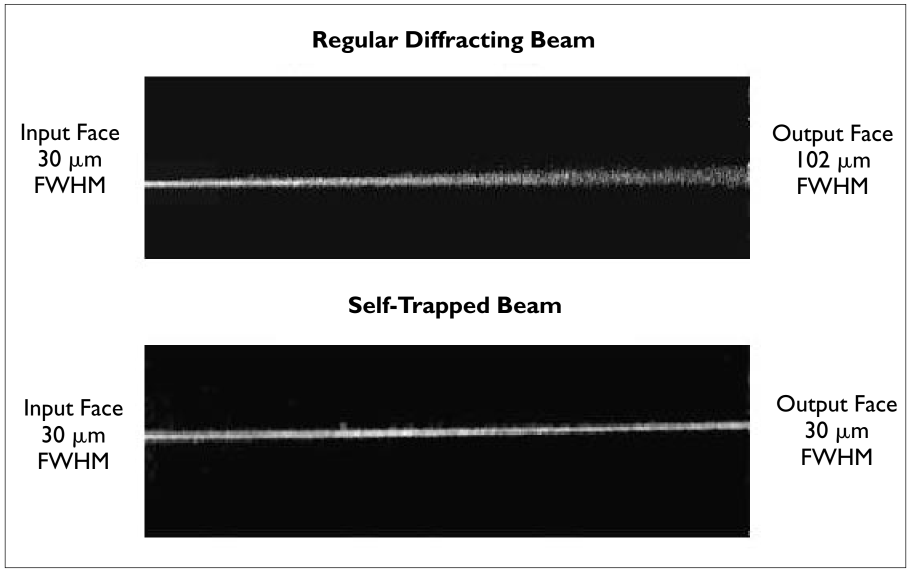


Figure 1. Top view photographs of a normally diffracting incoherent beam (*above*) and of a self-trapped incoherent beam (*below*) [*from Ref. 1*].

Theories, theories...

The experiments demonstrating the existence of incoherent solitons took the soliton community by surprise. This is because typically in most soliton research (including research outside the field of optics), all the experiments were preceded by the development of a theory predicting the main effects. In our case, however, experiments have demonstrated beyond a doubt that incoherent solitons do indeed exist.[1,2] Yet, something quite important was still missing: a theory! The experiments, based on insight and intuition, gave at best only a limited number of clues as to how a theory could be developed. Only one thing was certain: the theory of incoherent solitons had to be derived from first principles (Maxwell equations), without relying on any known soliton theory. Within a year, two different theories had been developed to describe incoherent solitons: the coherent density theory[3] and the modal theory.[4] The coherent density theory is, by its very nature, a dynamic approach better suited to the study of the evolution dynamics of incoherent solitons, their interactions, instabilities, etc., as they occur in experimental setups. In this formalism, the incoherent field is described by means of an auxiliary nonobservable function from which one can deduce the optical intensity distibution as well as the associated correlation statistics.[3] The modal theory, on the other hand, by virtue of its inherent simplicity, became the method of choice in terms of identifying incoherent solitons, their range of existence, and correlation properties.[4] One year later, yet another theory describing the propagation of mutual coherence was proposed.[5] Interestingly enough, even though at first sight these three theoretical approaches seem to be unrelated, they are in fact formally equivalent.[6] In addition to these exact theories, another, more simplified, ray-optics approach has been suggested.[7] This ray-optics formulation of incoherent solitons almost fully coincides with early studies on random-phase solitons in plasmas.[8] But ray optics can only provide simple and very limited information about incoherent solitons, because all phase information is absent. For example, a ray-transport method cannot describe the coherence properties of a partially coherent soliton since it views such an entity

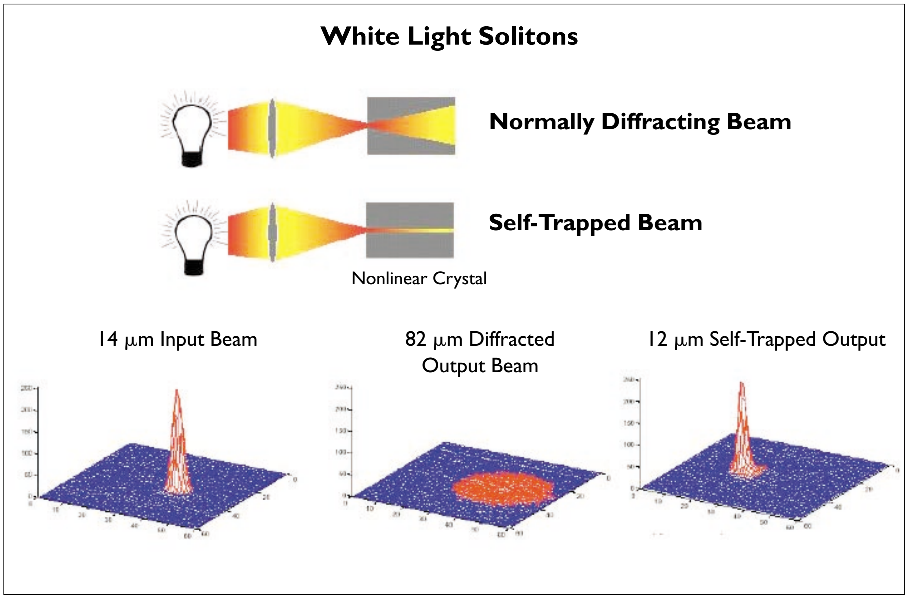


Figure 2. Self-trapping of an incoherent "white" light beam [from Ref. 2].

as a bundle of completely uncorrelated rays, nor can it explain incoherent dark solitons.

The theories explaining incoherent solitons made it very clear that they are not some kind of esoteric creatures, but rather a rich new class of solitons the existence of which is relevant to many diverse fields outside nonlinear optics. For example, incoherent modulation instability effects, soliton clustering and incoherent pattern formation relate to many systems in nature: from clustering in a cooled atomic gas to self-supported "stripes" of electrons in semiconductors, and to gravitationallike effects. In fact, the underlying physics relates to any weakly correlated wave system having a noninstantaneous nonlinearity.

To understand incoherent solitons, one must first understand several aspects of incoherent light. A spatially incoherent beam is nothing but a multimode (or "speckled") beam, the structure of which varies randomly with time. The beam consists of many tiny bright and dark "patches" (thus the notion of multimode) caused by random phase distribution. The envelope of this beam is defined by the time-averaged intensity. To illustrate how a spatially incoherent beam is "perceived" by a slow nonlinear material, consider a detector array (e.g., a human eye) which monitors the beam. When this detector responds much slower than the characteristic phase fluctuation time, all it will "see" is the time-averaged envelope. Such an incoherent beam diffracts much more than its coherent counterpart of the same beamwidth, since each tiny patch, or speckle, contributes to the diffraction of the beam's time-averaged intensity envelope. In the limiting case in which the speckles are much smaller than the beamwidth, the diffraction is dominated by the degree of coherence, i.e., the size of the speckle, rather than by the diameter of the beam's envelope.

It is important to emphasize that a partially coherent beam cannot self-trap in a system with an instantaneous nonlinearity. If an incoherent beam is launched into a self-focusing nonlinear medium that responds instantaneously, then each small speckle tends to form a small "positive lens" that will in turn capture a small fraction of the beam. These rapidly varying bright-dark features on the beam induce tiny waveguides that intersect and cross each other in a random manner.

The net effect is that the beam breaks up into small fragments and self-trapping of the beam's envelope does not occur. It is therefore obvious that only non-instantaneous nonlinear media can support incoherent solitons.

For self-trapping of an incoherent beam to occur, several conditions must be satisfied. First, the response time of the nonlinear medium must be much longer than the random fluctuation time across the incoherent beam. Such a nonlinearity responds to the time-averaged envelope and not to the instantaneous "speckles" that constitute the incoherent beam.[1] Second, the multimode (speckled) beam should be able to induce a multimode waveguide via the nonlinearity. Otherwise, if the induced waveguide is able to support only a single guided mode, the incoherent beam will simply undergo spatial filtering, radiating all of its power except for the small fraction that coincides with that guided mode. Third, as with all solitons, self-trapping requires self-consistency: the multimode beam must be able to guide itself in its own induced waveguide.[4] This means that the time-averaged intensity of the beam must consistently correspond to a superposition of the time-averaged populations of the guided modes in the nonlinearly induced waveguide, which is precisely the main idea behind the modal theory of incoherent solitons.[4]

Dark incoherent solitons

The real achievement of the theories explaining incoherent solitons was in their ability to come up with exciting new predictions. The first such prediction was the existence of incoherent dark solitons. Based on knowledge of coherent dark solitons,[9] a fundamental one-dimensional (1D) coherent dark soliton state is only possible if a transverse π phase shift exists at the center of the dark stripe. On the other hand, a dark beam with an initially uniform transverse phase is known to break into two, branching gray solitons, i.e., it leads to a Y-junction soliton. Furthermore, 2D coherent dark solitons (or vortex solitons) require a helical transverse phase structure. In a conceptual perspective, extension of the idea of dark coherent solitons to dark incoherent solitons has raised a number of difficult questions. If dark incoherent solitons do indeed exist, is their phase structure important (as it is for coherent dark solitons) or is it irrelevant (as it is for bright incoherent solitons, upon which the phase is fully random)? And, if the phase does play a role, how can it be "remembered" by these incoherent entities throughout propagation? Although in 1998 the existence of bright incoherent solitons was already well established, the existence of dark incoherent solitons was not clear at all. Dark incoherent solitons were predicted by use of the coherent-density method.[10] These simulations demonstrated that for a single dark incoherent soliton to exist, an initial transverse π phase jump was required. In addition, it was found that the fundamental dark incoherent soliton is always gray; coherent dark solitons, on the other hand, can be "black," i.e., possess zero intensity at the center. These results, although not providing detailed answers to the questions raised above, did suggest that dark incoherent solitons should exist, and indeed their existence was demonstrated experimentally soon thereafter.[11,12]

The experiments[11] employed the rotating diffuser method to generate partially spatially incoherent light. After passing through the rotating diffuser, the soliton-forming beam was reflected from a phase mask (a $\lambda/4$-step mirror), which generated a dark notch on a broad, partially incoherent background. The notch-bearing beam was launched into a biased, photorefractive crystal. Self-trapping of the dark notch was observed at a bias voltage adequate to introduce the screening nonlinearity necessary to balance the diffraction by self-defocusing. Typical experimental results of self-trapping of a 1D dark incoherent beam are shown in Fig. 3. As predicted,[10] the fundamental incoherent dark soliton was always gray. Thus, unlike coherent dark solitons which can be either black or gray, dark incoherent solitons are always gray [~40% grayness in Fig. 3 (c)]. In all cases, it was found that the grayness of these solitons depended on their degree of coherence. The more incoherent these solitons are, the grayer they are and the higher the nonlinearity required to achieve self-trapping. Another striking difference between incoherent and coherent dark (or bright) solitons is the nature of the temporal response of the nonlinearity. Coherent spatial solitons can occur in either instantaneous or non-instantaneous nonlinear media, but incoherent spatial solitons require a non-instantaneous response. For example, Fig. 3 (d) shows what happens when the rotation of the diffuser is stopped and the nonlinearity is allowed to reach steady state. The self-defocusing medium responds to the stationary speckles by fragmenting the beam and prohibiting self-trapping of the dark notch. This experiment is equivalent to launching the incoherent beam into an instantaneous self-defocusing medium. Thus, as emphasized earlier in this article, *all* incoherent solitons require a non-insantaneous nonlinearity. Self-trapping of an incoherent

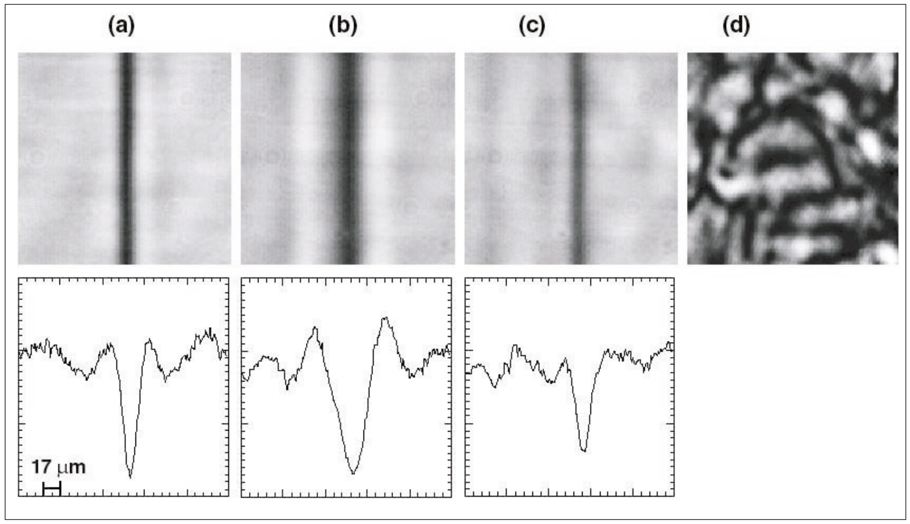


Figure 3. Self-trapping of a dark stripe borne upon a partially incoherent beam [from Ref. 11]. Shown are photographs and beam profiles of (a) the input beam, (b) the diffracted output beam, and (c) the self-trapped output beam. Shown in (d) is the output beam when the nonlinearity is "on" and the diffuser is stationary, illustrating fragmentation of an incoherent dark stripe in an instantaneous self-defocusing medium.

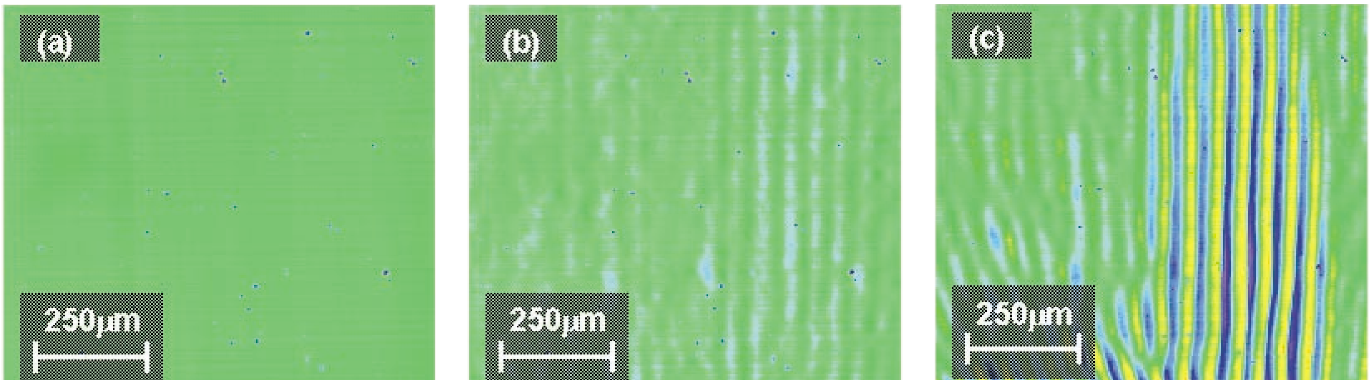
dark notch critically depends on the degree of coherence. When the beam is spatially more incoherent, the self-trapped notch becomes grayer and a higher nonlinearity is needed for trapping.[11]

Subsequent studies revealed that the initial phase distribution at the center of the dark notch is crucial to the evolution of a dark incoherent soliton.[12,13] If the phase at the center of the input beam goes through a π phase jump, a single dark (gray) incoherent soliton emerges.[11,13] But if the phase is continuous across the input dark notch, then *two* gray incoherent solitons emerge in the form of a Y [Ref. 12]. In other words, the evolution of a partially coherent dark beam is determined by the initial phase at the very center of the notch. Surprisingly, in the midst of statistical phase fluctuations, the incoherent notch-bearing beam "remembers" its initial phase imprint and evolves accordingly. To better understand this behavior, one has to resort to the modal theory of dark incoherent solitons.[13] The principles of this theory are identical to those involved in describing bright incoherent solitons, but with one major difference: unlike bright incoherent solitons which are made up solely of guided modes (bound states), dark incoherent solitons involve, in addition, a continuous belt of even and odd radiation modes. Inside the dark notch, symmetry implies that the odd radiation modes dominate. A π phase jump at the center of the notch gives preference to the excitation of the odd modes and facilitates the observation of such incoherent dark solitons. The modal theory of incoherent solitons also explains why dark incoherent solitons are always gray: since both even and odd radiation modes coexist at the same weight, the even modes provide a non-zero intensity (grayness) at the center.[13]

Along with the first experimental observation of (1+1)D incoherent dark solitons, self-trapping of a (2+1)D incoherent dark beam (a 2D void in the incoherent background) was also demonstrated.[11] By analogy with (1+1)D dark incoherent solitons that require a π phase jump at the center, the (2+1)D incoherent beam had a vortex–type phase profile. This was accomplished by passing the incoherent beam through a helicoidal phase mask before launching it into the non-instantaneous nonlinear crystal. At sufficiently high self-defocusing nonlinearity, the 2D dark beam self-trapped.

Coherence properties of incoherent solitons

Perhaps the most fascinating feature of incoherent solitons is their coherence structure. The fact that the phase at any given point on the soliton is not deterministic but random, and how the phase at one point correlates with the phase at any other point on the beam, are described by a distribution function known as the spatial



coherence function or the correlation function. This characteristic property of incoherent solitons is in sharp contrast with coherent solitons, upon which all points are fully correlated at all times. The coherence properties of incoherent solitons can be calculated theoretically using either one of the three approaches described above.[3-6] Interestingly, when two (or more) incoherent solitons interact, their coherence properties are affected. It is therefore possible to use interactions between incoherent solitons[14,15] as well as interactions between incoherent and coherent solitons to manipulate in space the coherence properties of the optical field.[16]

The correlation properties of bright incoherent solitons are rather simple.[4] At the wide central region of a bright incoherent soliton (where the intensity is high), the correlation distance is short and more or less constant. But at the margins of the soliton, where the local intensity decays exponentially, the correlation distance increases monotonically. This is because a bright incoherent soliton is made up of guided modes (bound states). In the center, many guided modes contribute to the local field, and because the modes are uncorrelated, the local correlation distance is short. At the margins of the soliton, on the other hand, where the guided modes decay exponentially, the field is dominated by the farthest reaching mode (i.e., the highest guided mode). Thus, far from the center of the soliton, only the highest mode survives and the correlation distance is infinite since the beam becomes fully spatially coherent.

The coherence properties of dark incoherent solitons are almost "opposite" to those of their bright counterparts[13]: the correlation distance varies dramatically inside and near the dark notch, whereas far from the center it attains a constant value. This is a manifestation of the way radiation and bound states are spatially distributed within the dark notch.

Another important element arising from the analysis of incoherent solitons is the fact that the self-trapping process itself can reshape the statistics of the incoherent beam. This property is clearly manifested by the fact that the correlation function of these solitons is coordinate dependent. Unlike the radiation generated by most natural incoherent sources (such as the sun), which exhibit nonlocalized statistics, or in other words, the correlation distance does not depend on the absolute location, for incoherent solitons the correlation distance varies as a function of position across the beam. It is therefore natural to ask whether it is possible to "engineer" the coherence properties of an incoherent beam through the self-trapping process or via soliton interactions. The answer is a definite "yes." In a recent paper[16] it was predicted that the spatial coherence of a partially incoherent light beam could be greatly enhanced through an energy-conserving interaction (with no absorption or gain) with a dark spatial soliton. The process itself is rather simple: a broad, partially incoherent bright "signal" beam copropagates with a dark soliton and interacts with it. During this interaction, a portion of the incoherent beam is trapped within the dark notch of the dark soliton, thus forming a sharp intensity spike. In this region, the correlation distance can dramatically increase by at least two orders of magnitude. Thus, by use of either a coherent or an incoherent dark spatial soliton, incoherent light can be effectively "cooled" (have its entropy reduced) locally at any arbitrarily chosen point on a partially incoherent wave front.

Modulation instability and pattern formation

Modulation instability (MI) is a universal process that appears in most nonlinear wave systems in nature. Because of MI, small amplitude and phase perturbations caused by noise grow rapidly under the combined effects of nonlinearity and diffraction (or, in the temporal domain, dispersion). As a result, a broad optical beam (or a quasi-cw pulse) tends to disintegrate during propagation, leading to filamentation[17-19] or to breakup into pulse trains. Since MI typically appears in the same parameter region in which bright solitons occur, the emerging filaments tend to form soliton trains. MI is therefore largely considered a precursor to soliton formation. Over the years, MI has been investigated in numerous nonlinear processes. Yet MI was always considered an inherently coherent process that could only appear in nonlinear systems with a perfect degree of spatial and temporal coherence. After the discovery of incoherent solitons, it was natural to wonder whether MI could also take place with incoherent light beams, or in a broader sense, whether patterns would form spontaneously (from noise) in a nonlinear, weakly correlated, multiparticle system? Early in 2000, we found[20] that modulation instability does indeed occur in such systems, but only if the "strength" of the nonlinearity exceeds a specific threshold set by the spatial correlation (coherence) function. After the first experimental observations of incoherent MI,[21,22] the development of pattern formation ideas in such systems took several unexpected turns.

The intuitive explanation for the presence of a threshold for incoherent MI is in fact intriguing and, in retrospect, rather

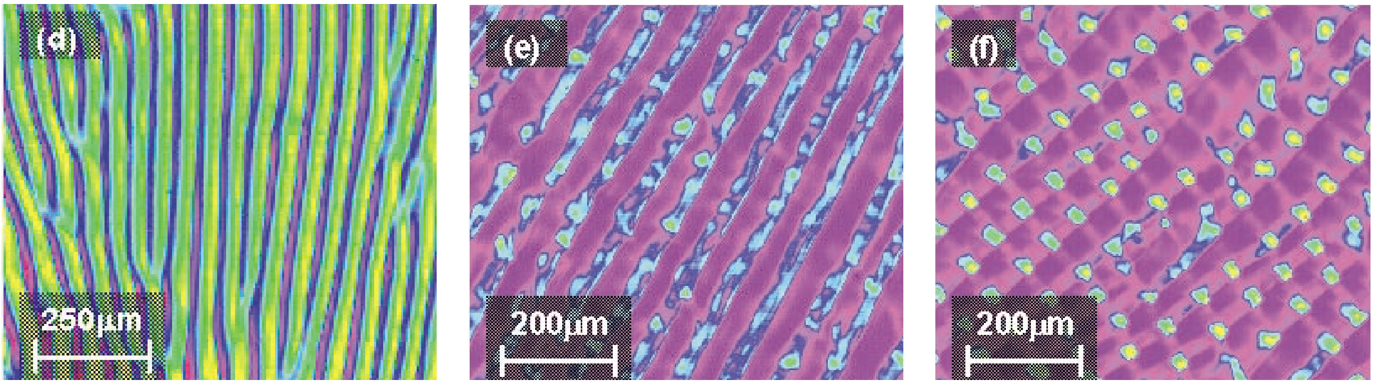


Figure 4. Modulation instability of an incoherent wave packet [from Ref. 21]. Shown is the intensity structure of a partially spatially incoherent beam at the output plane of the nonlinear crystal. The sample is illuminated homogeneously with partially spatially incoherent light with a coherence length of 17.5 μm. The displayed area is 1.0 x 1.0 mm^2 (a-d) and 0.8 x 0.8 mm^2 (e,f), respectively. The size of the nonlinear refractive index change of the crystal is successively increased from (a) $\Delta n_0=0$ (the linear case), to (b) $3.5*10^{-4}$, (c) $4.0*10^{-4}$, (d) $4.5*10^{-4}$, (e) $9*10^{-4}$ (e), and (f) $1*10^{-3}$. The plots (b-d) show the cases (b) just below threshold (almost no features), (c) at threshold (partial features), and (d) just above threshold (features everywhere) for 1D incoherent MI that leads to 1D filaments. Far above this threshold, at a much higher value of nonlinearity, the 1D filaments become unstable (e), and finally become ordered in a regular 2D pattern (f).

simple. Consider first a fully coherent and linear system, and imagine a periodic perturbation superimposed on a uniform intensity beam. Since the system is linear and coherent, the modulation depth (visibility) of this perturbation neither grows nor decays during propagation, because all points on the beam are fully correlated with one another. If, consequently, some self-focusing nonlinearity—no matter how weak—is added to the system, every maximum in the perturbation induces a positive index change in its vicinity. Thus, every intensity maximum narrows (self-focuses), the modulation depth of the perturbation grows, and modulation instability occurs. Coherent MI will take place even if the magnitude of the nonlinearity is very small, because in such a coherent system, there is no mechanism that suppresses the MI growth. This is why coherent MI has no threshold for its existence. Now consider a linear, partially incoherent wave system, and imagine again a perturbation superimposed on a uniform intensity beam. In this case, the perturbation naturally decays because different points on the beam behave like independent sources and the modulation depth of the perturbation diminishes with propagation. Adding some self-focusing nonlinearity to this system provides a means of increasing the modulation depth of the perturbation. Whether the modulation depth of the perturbation will increase or not during propagation depends on the relative rates of the two conflicting processes: the "washout" effect that results from incoherence and the self-focusing that tends to amplify the perturbation. When the two effects balance exactly, the perturbation maintains its initial modulation depth. This is the threshold point. If the self-focusing tendency is stronger than the effect of incoherence, then the perturbation grows and MI occurs. This is the intuition behind incoherent MI and its dependence on the correlation function. Interestingly, this seems to be the only known MI process that has any threshold in a unidirectional propagation scheme (to distinguish from the threshold effects that occur in cavities).

The first theoretical paper on incoherent MI[20] was followed by the first experimental observation[21] that confirmed many of the predictions, including the observation of very pronounced threshold effects. Incoherent MI does indeed occur above a specific threshold which depends on the coherence properties (correlation distance) of the beam and leads to a periodic train of 1D filaments. At a higher nonlinearity, incoherent MI displays a 2D instability and leads to the appearance of self-ordered 2D lattices of light spots. A typical experimental result depicting incoherent MI is shown in Fig. 4. When the nonlinearity is large enough to allow for MI, the homogeneous light distribution at the output face of the sample becomes periodically modulated and starts to form 1D filaments of incoherent light. Figure 4 shows the beam intensity at the output plane of the nonlinear crystal. The correlation distance of the incoherent light is 17.5 μm. Figure 4 (a) depicts the output intensity without nonlinearity. Cases (b), (c), and (d) correspond to a value of nonlinearity just below the threshold for 1D incoherent MI, at threshold, and just above the threshold. This demonstrates beyond any doubt the existence of incoherent MI and that incoherent MI occurs only when the nonlinear index change exceeds a well-defined limit. In particular, Fig. 4 (c) shows exactly at threshold a mixed state, in which order and disorder coexist. This is a clear indication that the nonlinear interaction undergoes an order-disorder phase transition. These phenomena were predicted by incoherent MI theory.[20] But the experiments also revealed new features. When the nonlinearity is further increased, the filaments become unstable [Fig. 4 (e)] and start to break into an ordered array of spots (2D filaments) as shown in Fig. 4 (f). In all the pictures in this figure, the correlation distance is much shorter than the distance between two adjacent stripes, or filaments. This is a clear demonstration that patterns can also form in weakly correlated nonlinear multiparticle systems.

The dependence of the MI threshold on the coherence properties of the beam was also studied experimentally.[21] The experiments have shown that for a fully coherent beam, MI occurs even with extremely small nonlinearities since coherent MI has no threshold. But when the correlation distance is reduced, a well-defined threshold is observed. The transition through the threshold is always abrupt. The experiments have also clearly demonstrated that with decreasing correlation distance, the MI threshold shifts towards a higher value of nonlinearity.

Research on incoherent modulation instability has recently revealed an intriguing new development: soliton clustering.[23] Soliton clustering occurs spontaneously as the "by-products" of the breakup of the weakly correlated beam continue to interact during propagation. The solitonic filaments emerging from incoherent MI attract one another, eventually leading to the formation of clusters of solitons, or in other words, aggregates of fine-scale structures. The solitons cannot "fuse" to form one big spot of light because, due to MI, the large, self-focusing nonlinearity breaks up broad beams into tiny filaments. However, these small solitonic filaments interact, and when the separation distance between them is larger than the correlation distance, their interactions are fully incoherent, and the force among solitons is always attractive. As a result, these solitons aggregate in clusters of fine-scale structures.[23] This clustering phenomenon has no counterpart with solitons in coherent systems because the interactions between coherent solitons are phase dependent: they may either attract or repel one another, depending on their relative phase. As a result, the filaments arising from coherent MI do not cluster together; instead, the presence of repulsive forces leads to almost evenly spaced solitons in a quasi-ordered lattice structure.[23] Thus, the phenomenon of soliton clustering can occur only in incoherent (or weakly correlated, random-phase) systems.

The fascinating phenomena of incoherent MI and soliton clustering are not unique to optics. In fact, these effects should occur in many other nonlinear systems of weakly correlated particles. In all such systems, patterns can form spontaneously provided the nonlinearity is larger than a threshold value, which in turn is set by the correlation distance. For example, we expect that patterns will form in a cooled atomic gas even at temperatures at which the atoms have independent degrees of freedom (and cannot be described by a single wave function, as in the Bose-Einstein condensate). At least for atoms with attractive collision forces (a negative scattering length), such patterns should form.[24] In other areas of physics, in fact, there are already indications that such patterns do exist in disordered, many-body nonlinear systems. For example, experiments have revealed a large anisotropy in the resistivity of a 2D electron system.[25] The observed anisotropy is attributed to the combination of nonlinear transport and weak disorder,[26] which is exactly the transport equivalent of nonlinearity and incoherence in optical systems. It seems likely that the spontaneous emergence of patterns in various fields of science indicates that pattern formation in nonlinear weakly correlated systems is a universal property. It is a gift of nature that in optics we can study it directly, visualizing every minute detail of the physics involved while at the same time being able to isolate the underlying effects.

Future prospects

Self-trapping of incoherent wave packets is a research area that has been around for barely five years. Yet in this short time, several new processes that have no analog whatsoever in the coherent regime have been brought to light. The rapid progress in this new area of incoherent solitons presents a number of interesting fundamental ideas as well as possible applications. For example, coherence engineering can be used to tame 2D soliton transverse instabilities.[27,28]

In addition, there is the exciting possibility of using self-trapped light beams from incoherent sources, such as light-emitting diodes, for reconfigurable optical interconnects and beam steering. It is already evident that these phenomena can be observed in many other areas of physics[29,30] in which nonlinearities, stochastic behavior, and statistical (ensemble) averaging are involved. We believe that, as has happened so often in the history of science, the best is yet to come.

Dedication

Moti Segev dedicates this article to his friend Yair Mordechai, 43, of Kibbutz Shluhot, Israel, who was slain October 2001 in a suicide bomb attack at the gates of his Kibbutz. By stopping the suicide bomb attack at the gates, Yair saved the lives of innocent people, including many children who were in the community dining room at the time of the attack. He is survived by his wife Iriya and five children. May his sacrifice lighten the way to a real peace.

References and notes

1. M. Mitchell, Z. Chen, M. Shih, M. Segev, Phys. Rev. Lett. **77**, 490 (1996).
2. M. Mitchell and M. Segev, Nature, **387**, 880 (1997).
3. D. N. Christodoulides, T. Coskun, M. Mitchell and M. Segev, Phys. Rev. Lett. **78**, 646 (1997).
4. M. Mitchell, M. Segev, T. Coskun, and D. N. Christodoulides, Phys. Rev. Lett. **79**, 4990 (1997).
5. V.V. Shkunov and D. Z. Anderson, Phys. Rev. Lett. **81**, 2683 (1998).
6. D. N. Christodoulides, E. Eugenieva, T. Coskun, M. Segev, and M. Mitchell, Phys. Rev. E **63**, R35601 (2001).
7. A.W. Snyder and D. J. Mitchell, Phys. Rev. Lett. **80**, 1422 (1998).
8. A. Hasegawa, Phys. Fluids 18, **77** (1975); **20**, 2155 (1977).
9. See review on dark solitons by Yu. S. Kivshar and B. Luther-Davies, Physics Reports **298**, 81 (1998).
10. T. H. Coskun, D. N. Christodoulides, M. Mitchell, Z. Chen and M. Segev, Opt. Lett. **23**, 418 (1998).
11. Z. Chen, M. Mitchell, M. Segev, T. Coskun, D. N. Christodoulides, Science **280**, 889 (1998).
12. T. Coskun, D. N. Christodoulides, Z. Chen, and M. Segev, Phys. Rev. E **59**, R4777 (1999).
13. D. N. Christodoulides, T. Coskun, M. Mitchell, Z. Chen and M. Segev, Phys. Rev. Lett. **80**, 5113 (1998).
14. N. N. Akhmediev, W. Krolikowski, and A. W. Snyder, Phys. Rev. Lett. **81**, 4632 (1998)
15. E. D. Eugenieva, D. N. Christodoulides and M. Segev, Opt. Lett. **25**, 972 (2000).
16. T. Coskun, A. G. Grandpierre, D. N. Christodoulides, and M. Segev, Opt. Lett. **25**, 826 (2000).
17. E. M. Dianov, P.V. Mamyshev, A. M. Prokhorov, and S. V. Chernikov, Opt. Lett. **14**, 1008 (1989)
18. P.V. Mamyshev , C. Bosshard, and G. I. Stegeman, J. Opt. Soc. Am. B **11**, 1254 (1994)
19. M. D. Iturbe-Castillo, M. Torres-Cisneros, J. J. Sanchez-Mondragon, S. Chavez-Cerda, S. I. Stepanov, V. A. Vysloukh, and G. E. Torres-Cisneros, Opt. Lett. **20**, 1853 (1995).
20. M. Soljacic, M. Segev, T. Coskun, D. N. Christodoulides, and A. Vishwanath, Phys. Rev. Lett. **84**, 467 (2000).
21. D. Kip, M. Soljacic, M. Segev, E. Eugenieva, and D. N. Christodoulides, Science **290**, 495 (2000); see also *(1+1) Dimensional modulation instability of spatially-incoherent light*, J. Opt. Soc. Am. B, to appear, (2001).
22. J. Klinger, H. Martin, and Z. Chen, Opt. Lett. **26**, 271 (2000).
23. Z. Chen, S. M. Sears, H. Martin, D. N. Christodoulides, and M. Segev, Clustering of solitons in weakly correlated systems, to be published (accepted) in the Proc. Nat. Acad. of Sci. (PNAS), 2002.
24. See, e.g., Th. Busch and J. R. Anglin, Phys. Rev. Lett. **84**, 2298 (2000).
25. M. P. Lilly, K. B. Cooper, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **82**, 394 (1999).
26. A. A. Koulakov, M. M. Fogler, aand B. I. Shklovskii, Phys. Rev. Lett. **76**, 499 (1996).
27. O. Bang, D. Edmundson and W. Krolikowski, Phys. Rev. Lett. **83**, 5479 (1999).
28. C. Anastassiou, M. Soljacic, M. Segev, D. Kip, E. Eugenieva, D. N. Christodoulides, Z. H. Musslimani, and J. P. Torres, Phys. Rev. Lett. **85**, 4888 (2000).
29. M. Peccianti and G. Assanto, Opt. Lett. **26**, 1791 (2001).
30. A. Picozzi and M. Haelterman, Phys. Rev. Lett. **86**, 2010 (2001).

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