Self-Trapping of Optical Beams: Spatial Solitons

Beams of light, prevented from diverging by nonlinear media, exhibit particle-like behavior, as do waves in many other nonlinear systems in nature.

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Although people have always been fascinated by visual manifestations of nonlinear wave phenomena, such as tsunamis and tidal waves, the first scientifically documented report of a self-trapped wave did not come until 1834, when a Scottish scientist, John S. Russell, observed a "rounded smooth and well defined heap of water" propagating in a narrow and shallow canal "without change of form or diminution of speed." The water was calm on both sides of this unusual wave, and Russell noted that it had the form of a "solitary elevation."

Fifty years later, two Dutchmen, Diederik Johannes Korteweg and Gustave de Vries, realized that this phenomenon required an unusually large amplitude and that the medium must behave in a fundamentally different manner to waves of different amplitudes—that is, its behavior must be nonlinear. In 1965, Norman Zabusky and Martin Kruskal realized that such localized pulses, or "wavepackets," maintain their identities even when they undergo collisions with each other, and that they conserve power and linear momentum. Zabusky and Kruskal concluded that these pulses behave like particles and named them solitons.[1] An immense amount of research soon followed, and solitons were observed in many different branches of science. This article concentrates on one particular type of soliton, which has experienced a minirevolution in the last few years: the optical spatial soliton.

In nature, pulses have a tendency to broaden during propagation in a dispersive linear medium. In optics, a wavepacket localized in space (that is, a narrow optical beam) or in time (a short pulse) will, in general, broaden. In temporal pulses, this broadening is due to chromatic dispersion: The pulse's frequency components have different velocities. The narrowest pulse forms when the relative phase among all components is zero. However, as the pulse propagates, the frequency components acquire different phases and the pulse broadens.

For "pulses" in space (beams), the broadening is caused by diffraction. A quasi-monochromatic light beam propagating in a medium of refractive index n in an arbitrary direction z can be viewed as a linear superposition of plane waves, all having the same wavenumber $k = n\omega/c$ but with different angles α with respect to z. Therefore, each component propagates at a different phase velocity with respect to z. As for temporal pulses, each plane-wave component acquires a different phase and the beam broadens (diffracts). In general, the narrower the initial beam, the more it diverges.

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Spatial spreading can be eliminated by waveguiding. In a dielectric waveguide, a beam propagating in a high-index medium undergoes total internal reflection from boundaries with lower index media. When these reflections constructively interfere, the beam becomes trapped between the boundaries and forms what is called a guided mode. A planar dielectric waveguide is called a (1+1)D waveguide because propagation occurs along one coordinate (z), diffraction along a single transverse coordinate (y) and guidance along the third coordinate (x). An optical fiber is a (2+1)D waveguide with spatial guidance in both transverse dimensions.

In a manner similar to Russell's observation, the broadening of pulses can be eliminated with nonlinearity, in which material properties change in the presence of light and can counteract dispersion or diffraction by what is termed light-induced lensing. This process eliminates the accumulated phase differences between the components composing the "pulse," thus allowing a nondiffracting, nondispersing beam to propagate. Short temporal pulses that do not change shape as they propagate in a dispersive material such as an optical fiber are called optical temporal solitons. They were predicted in 1973 by Akira Hasegawa and Frederick Tappert, and first observed in 1980 by Linn Molenhauer, Roger Stolen and Jim Gordon. An optical nonlinearity can be also be used to confine a "pulse in space" (a narrow beam) if a beam modifies the refractive index to generate an effective positive lens—that is, if the refractive index in the center of the beam becomes larger than that at the beam's margins, thus resembling a waveguide. When the beam that has induced the waveguide is a guided mode of the induced waveguide, the beam becomes "self-trapped" with a very narrow diameter. Figure 1 includes a top view photograph of a 10 μm wide spatial soliton propagating in a photorefractive crystal. The beam is visible because of stray scattering in the crystal.

Kerr-type spatial solitons

The mathematical foundations of solitons pose a difficult theoretical challenge. However, the problem is soluble exactly in (1+1)D waveguides when the nonlinearity is

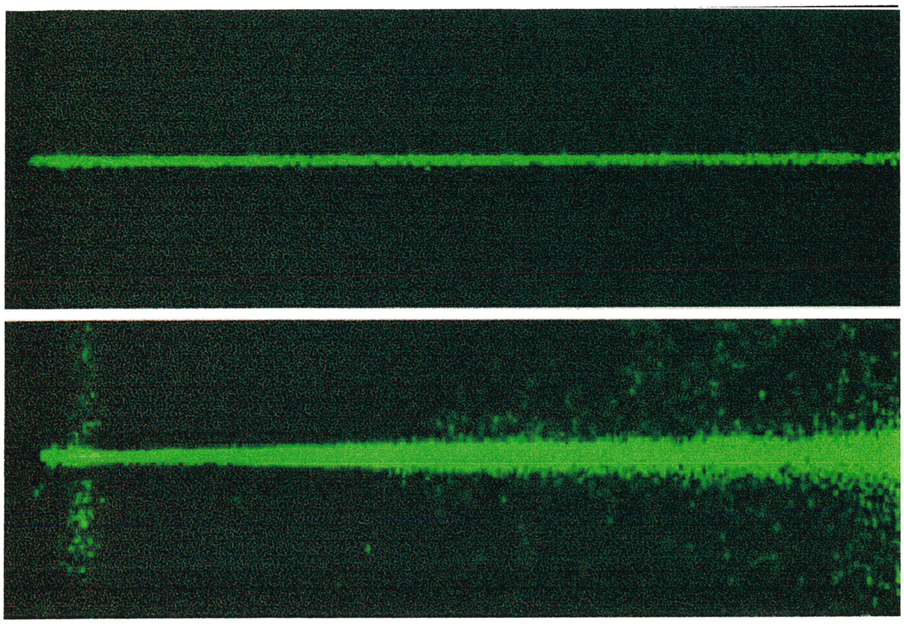


FIGURE 1. SPATIAL SOLITON and ordinary beam. Top: Photograph of a 10 μm wide spatial soliton propagating in a photorefractive crystal. Bottom: Beam in the same crystal diffracting naturally when the nonlinearity is turned off. (From M. Shih *et al.*, ref. 8, second paper.)

due to weak symmetric anharmonicity in the polarization response of a medium to an applied optical field, a common nonlinearity. This situation leads to a refractive index of the form $n = n_0 + n_2 I$, where n_0 is the background refractive index and $I(\mathbf{r},t)$ is the intensity of the electromagnetic wave. This behavior is the optical Kerr effect, and it produces the self-lensing needed for spatial solitons. Following Michael Hercher's 1964 observation of the self-focusing of laser light, Raymond Chiao, Elsa Garmire and Charles Townes theorized that the nonlinear Schrödinger equation with a cubic potential governs the phenomenon and that a beam propagating in a (1+1)D Kerr medium can self-trap. Several years later, Vladimir E. Zakharov and Alexei Borisovich Shabat solved the full (1+1)D problem analytically, using a method called inverse scattering. These nonlinear Schrödinger equation soliton solutions have properties that are unique in nonlinear dynamic systems. For example, upon collision, these solitons conserve power, velocity and their number, and interactions among solitons are fully elastic.

In 1965, Paul Kelley argued that when a circular beam is launched into a Kerr medium it undergoes "catastrophic self-focusing" and eventually breaks up—that is, no stable three-dimensional solitons exist. Self-trapping requires a robust cancellation between the beam's diffraction length and the focal length of the self-induced lens. A stable soliton can be formed when fluctuations in power are compensated by corresponding changes in beam width and vice versa. However, for (2+1)D solitons, stationary propagation occurs at only one peak power, and fluctuations lead to catastrophic self-focusing in a runaway process that results in material damage, as observed in early experiments. Beams that are narrow in one dimension, uniform in the other and propagate along the third direction are also unstable: The "stripe" beam disintegrates into many filaments and becomes "transversely unstable," as Zakharov and Alexander Rubenchik showed in 1974. The end result is that Kerr solitons are stable only in (1+1)D waveguides—that is, in waveguides but not in bulk media, typical of all Kerr solitons in nature. Such solitons were observed first in liquid carbon disulfide (for which an interference grating introduced the necessary transverse stability in the dimension normal to the plane of diffraction) and later they were observed in a glass waveguide. Soon thereafter, interactions between spatial solitons (collisions) were demonstrated by both groups of observers, confirming the elastic collision properties of Kerr solitons.[2] At that point, it seemed as if Kerr solitons were well understood and that other kinds of self-trapped beams—especially (2+1)D solitons—were less likely to exist.

Saturable media

One experiment contradicted the consensus that (2+1)D solitons are unstable. In 1974, John E. Bjorkholm and Arthur Ashkin at AT&T Bell Laboratories demonstrated self-trapping of a laser beam of circular cross section in sodium vapor in the close spectral vicinity of a resonant transition.[3] They conjectured that the effects were due to the saturable nature of the optical nonlinearity.

As early as 1969, Eddie Daws and John H. Marburger at the University of Southern California had found numerically that saturable nonlinearities are able to arrest the catastrophic collapse and lead to stable (2+1)D solitons. Other researchers reached similar conclusions for other forms of saturable nonlinearities in plasmas. Saturable nonlinearities typically arise because resonances give rise to a maximum change in the optical susceptibility and thus higher-order (than n_2) nonlinearities are included to describe the arrest in the increase in index. However, saturable nonlinearities lead to nonintegrable equations, making analytical predictions impossible. As a result, experimental groups focused on temporal solitons. With the exception of Kerr solitons,[2] spatial soliton experiments were deserted until 1990.

The 1990s have witnessed a resurgence of interest in the theoretical aspects of spatial solitons. In 1991, Allan W. Snyder's group at the Australian National University in Canberra expanded upon a 1962 idea by Gurgen Ashotovich Askar'yan of the Institute of General Physics in Moscow. Askar'yan had suggested that a soliton forms when an optical beam induces a waveguide (by way of the nonlinearity) and at the same time is a guided mode of the waveguide it induces. Snyder's group developed this idea into a "self-consistency" methodology[4] that offers much insight into the dynamics of spatial solitons, their stability and interactions. It provides a simple explanation of why self-trapped circular beams are stable in a saturable nonlinear medium. Saturation of the nonlinearity implies that there is a maximum value for the change in the refractive index—for example, of the form $\Delta n(I) = \Delta n_{sat}\, I/(I + I_{sat})$, so that as $I \gg I_{sat}$, $\Delta n(I)$ approaches Δn_{sat} asymptotically. Just like a Kerr medium, a saturable medium acts as a focusing lens at high intensities. However, because the index change cannot exceed Δn_{sat}, the induced lens (waveguide) eventually becomes wider instead of stronger and has less focusing power at its center. Thus, the runaway process that leads to catastrophic collapse in Kerr media can be arrested. Another implication of the progressive broadening of the waveguide with increasing intensity is an increase in the numerical aperture, which leads to a multimode waveguide. The induced potential well becomes broader and more bound solutions exist.

In the early 1990s, the discovery of two new types of solitons, each in a nonlinearity of a saturable nature, rekindled experimental interest in spatial solitons. Photorefractive solitons and quadratic solitons exist in both (1+1) and (2+1) dimensions, and give rise to a whole new family of soliton interactions in three dimensions and a variety of other rich phenomena.

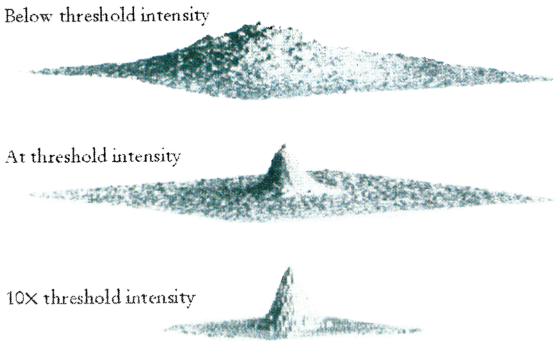


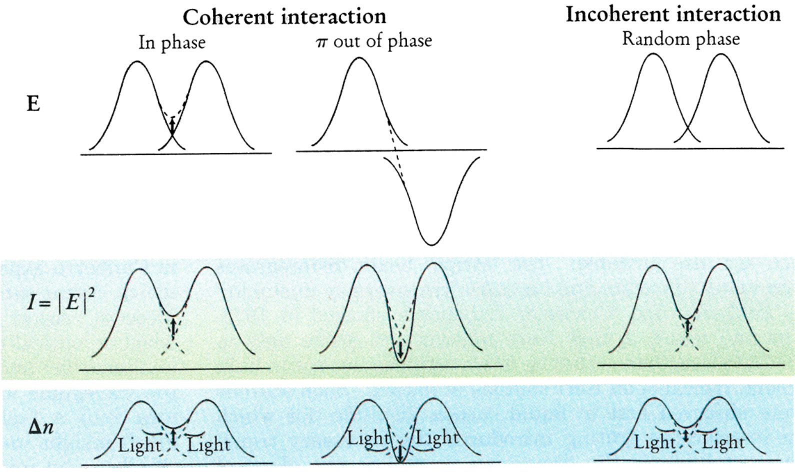
FIGURE 2. QUADRATIC SOLITONS form at intensities above a threshold. Plotted here are the intensity distributions of the fundamental (ω) beam at the output plane, for three different input intensities. (From W. E. Torruellas *et al.*, in ref. 10.)

Photorefractive solitons. Photorefractive materials typically are dielectric noncentrosymmetric single crystals with second-order nonlinearities. Through the electro-optic effect, a DC electric field E modifies the refractive index as $\Delta n \propto E$. Photorefractive materials have "foreign" atoms (dopants) hosted in the crystal, with energy levels inside the lattice's "forbidden gap," which is the range of energies not available to electrons in the undoped crystal. Upon illumination, these dopants contribute free charges, which redistribute following the spatial dependence of the optical intensity. In the usual context, photorefractives are used to record volume holograms for applications such as optical data storage and phase conjugate mirrors. A soliton is a different animal: It entails self-action of a beam and is unrelated to holography.

The existence of photorefractive solitons was predicted by Segev, Bruno Crosignani and their coworkers in 1992 and demonstrated a year later by Greg Salamo and his coworkers.[5] Over the last five years, several different types of photorefractive solitons have been discovered, each resulting from a different nonlinear mechanism that is inherently saturable, and each exhibiting a different dependence of Δn on the optical intensity. Here we focus on one type: the photorefractive screening soliton. It is created when a narrow beam of light is directed into a photorefractive crystal across which a voltage has been applied transversely. In the illuminated region, the density of free electrons increases, which means that the conductivity increases and the resistivity decreases. Because the resistivity is not uniform across the crystal, the voltage drops primarily in the dark regions, leading to a large space-charge field E_{sc} in those regions and to a lower field in the illuminated region. The refractive index changes by $\Delta n \propto E_{sc}$ by means of the electro-optic effect. If $\Delta n < 0$, the large negative index change in the dark regions creates a "graded index waveguide" that guides the beam that has generated it, thereby eliminating diffraction. The actual dependence of Δn on the optical intensity for (1+1)D screening solitons is $\Delta n \propto 1/(I + I_{dark})$, where I_{dark} is the dark irradiance—a material parameter proportional to the conductivity of the crystal in the dark.

The subsequent evolution of the photorefractive soliton family has been meteoric. Screening solitons were predicted in 1994,[6] following a report from researchers at the Instituto Nacional de Astrofísica, Optica y Electrónica, in Puebla, Mexico, of steady-state self-focusing effects in biased photorefractive media,[7] and a soliton observation followed soon.[8] Several other types of photorefractive solitons have also been found. Quasi-steady-state solitons exist during the finite time in which an externally applied field is slowly being screened by the space-charge field.[5] Photovoltaic solitons rely on the bulk photovoltaic effect

FIGURE 3. INTERACTIONS BETWEEN SOLITONS can be coherent or incoherent. These profiles of electric field, intensity and index of refraction illustrate these two types of interaction, which are discussed in the text on page 46. Note that the sum of the intensities of the overlapping soliton tails is not as great in the case of incoherent interactions as in the case of constructive interference of in-phase coherent interactions.



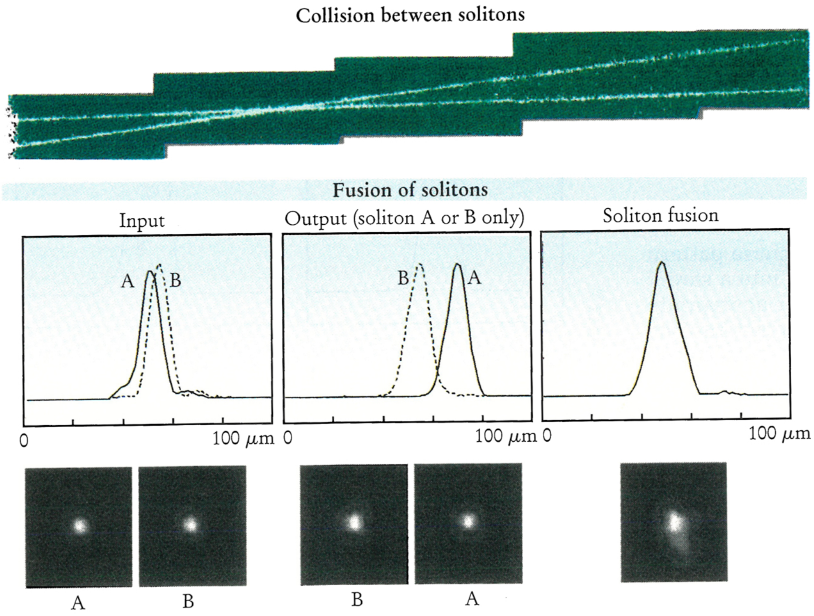


FIGURE 4. SOLITON COLLISIONS. Top: Photograph of an (attractive) incoherent collision between two photorefractive screening solitons in which the solitons pass through each other at a large angle. Bottom: Fusion between the same solitons when the collision occurs at a shallow angle. Shown are the intensity profiles and photographs of beams A and B at the entrance plane (left); beams A and B at the exit plane, each measured when the other is absent (middle); and the fused beam at the exit plane (right). (From ref. 14.)

to create the space-charge field. They were predicted in 1994 and observed a year later. A fourth type of photorefractive soliton was demonstrated in 1996 in semiconductors such as indium phosphide, in which both electrons and holes help form the space-charge field. Finally, solitons in centrosymmetric photorefractive media, in which $\Delta n \propto 1/(I + I_{\text{dark}})^2$, were predicted and demonstrated.

Two additional noteworthy properties are common to all photorefractive solitons. Solitons can be generated with optical power levels of less than a microwatt, because Δn depends on the ratio I/I_{dark} and not on the absolute value of the optical intensity I, and because I_{dark} is very low in photorefractive materials. The drawback is that the response time scales as $1/(I + I_{\text{dark}})$ and can be as long as seconds at these power levels with 10 μm wide solitons. Also, because the material's response is wavelength dependent, solitons generated with microwatt powers can be used to guide and steer powerful (watts) beams at wavelengths in which the material is less photosensitive.

Quadratic solitons. There are three basic differences between quadratic solitons and all other spatial solitons. First, in quadratic solitons, the optical fields do not modify the medium's refractive index or other properties. Second, these solitons rely solely on second-order nonlinearities. Third, self-trapping exists by virtue of the strong interaction and energy exchange between two or more beams at different frequencies. The nonlinear polarizations induced are the product of two or more interacting beams. Hence the fields generated are narrowed in space, and the result offsets diffraction. In addition, they are unique in that they consist of all of the beams strongly coupled by the second-order nonlinearity. For second-harmonic generation, this unique feature means at least one fundamental field and the harmonic field. Furthermore, the properties of quadratic solitons depend on the detuning from phase matching (momentum conservation among the interacting beams). Thus, quadratic solitons require media in which phase matching is possible and thus exist only at reasonable powers over a narrow range of parameters. Although such solitons exist for any second-order process and indeed have been observed in optical parametric generators and amplifiers, they have been studied primarily during second-harmonic generation.

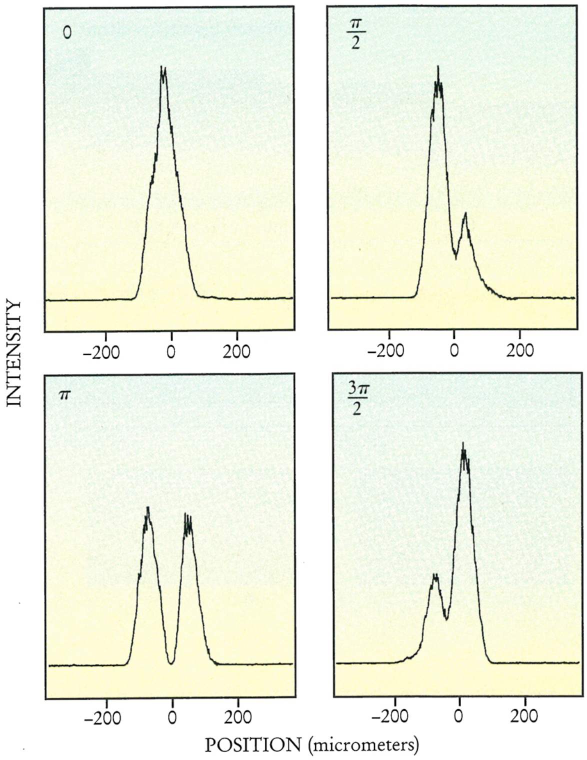
Quadratic solitons were first predicted in the mid-1970s by Yuri Karamzin and Anatoly Sukhorukov. Twenty years passed before their stability was shown[9] and they were observed experimentally in (2+1)D and (1+1)D waveguides.[10] In those first (2+1)D experiments, both the output fundamental and harmonic beams above a threshold intensity collapsed from their diffracted beam sizes to diameters less than the fundamental input diameter, as shown in figure 2. The experiments showed a key point—that the second harmonic required for a soliton could be generated within the crystal, thus forming the soliton. Further experiments by Russell Fuerst and his coworkers have shown that three-wave-mixing quadratic solitons (produced with two input beams) exist over a wide range of relative compositions of the three waves. Another interesting feature is the locking in space of the soliton's components to defeat beam "walk-off," which occurs when the fundamental and harmonic beams have different energy propagation directions (Poynting vectors). This locking was observed at the Center for Research and Education in Optics and Lasers at the University of Central Florida in Orlando, and explained by Lluis Torner and his coworkers at the Polytechnic University of Catalonia in Barcelona, Spain.[10]

Incoherent solitons

Soliton physics appears to be evolving in a new direction, toward a focus on what are termed incoherent solitons. Until 1995, all soliton experiments employed a coherent "pulse,"—that is, the phases were correlated across the beam. However, pulses (wavepackets) do not necessarily need to be coherent. For example, one can focus into a spot a beam from a natural source such as the Sun or an incandescent light bulb. Can such a beam self-trap in a nonlinear medium?

In 1996, Mordechai Segev's group at Princeton University demonstrated self-trapping of beams in which the phase varied randomly in time and space across any plane intersecting the beam.[11] The first experiment employed a quasi-monochromatic light beam that was partially spatially incoherent: A laser beam was sent through a rotat-

FIGURE 5. COLLISION OF PARALLEL SOLITONS. Plotted is the output from a collision between two (1+1)D quadratic solitons launched in parallel at the input. The relative phase angles for the four cases are shown. (From ref. 15.)



ing diffuser that introduced a new, random phase pattern every microsecond. The beam was launched into a slowly responding photorefractive crystal and, under appropriate conditions, the envelope of this beam self-trapped into one narrow filament. In a later experiment, Matthew Mitchell and Segev demonstrated that an incoherent beam of white light—that is, a "pulse" that is both temporally and spatially incoherent—can self-trap in the same medium.[12] In that experiment, the self-trapped beam originated from an incandescent light bulb that emitted light with wavelengths between 380 and 720 nm. Another experiment demonstrated self-trapping of dark incoherent "beams"—that is, one- or two-dimensional voids nested in a spatially incoherent beam.[11]

To understand incoherent solitons, one must understand some aspects of incoherent light. A spatially incoherent beam consists of both bright and dark patches, or speckles, caused by a random phase distribution that varies randomly with time. The envelope of this beam is defined by the time-averaged intensity. Because every small bright speckle contributes to the diffraction, in the limiting case of speckles much smaller than the beam size, diffraction is dominated by the degree of coherence—that is, the speckle size rather than the diameter of the beam's envelope. Such an incoherent beam cannot self-trap in an instantaneous nonlinearity because each speckle forms a small lens and captures a small fraction of the beam, thus completely fragmenting the beam's envelope. On the other hand, in media with nonlinear response times much longer than the phase fluctuation time across the beam, the nonlinearity responds to the time-averaged envelope and not to the instantaneous speckles. In such media, the beam's envelope induces a multimode waveguide, which guides incoherent solitons.

The theory of incoherent solitons has been presented in recent papers by Demetri Christodoulides's group of Lehigh University and Segev's Princeton group.[12] It is now apparent that self-trapping reshapes the statistics of the incoherent beam making it possible to engineer the beam's coherence properties. The rapid progress in this direction brings about many interesting fundamental ideas (such as coherence control) and possible applications for reconfigurable optical interconnects and beam steering. Such applications could use self-trapped beams from incoherent sources such as light-emitting diodes.

Soliton interactions

Among all soliton properties, perhaps the most fascinating are the interactions, or "collisions," between solitons, because solitons interact like particles in many respects. The interactions occur when the tails of the soliton fields overlap in the space between them. Solitons can interact in two ways: coherently or incoherently. (See figure 3.)

Coherent interactions occur when the nonlinear medium responds instantaneously to interference effects between the overlapping beams, through, for example, the optical Kerr effect or a quadratic nonlinearity. For slow nonlinearities, such as photorefractive or thermal ones, the relative phase between the interacting beams must be kept stationary for times longer than the medium's response time. For in-phase beams, the intensity and hence the refractive index between the beams' induced waveguides are increased. This development attracts more light to the center, moving the solitons toward it, and so the solitons appear to attract each other. When the interacting beams are π out of phase, they interfere destructively, reducing the index in the central region, and the solitons "repel."

Incoherent interactions occur when the relative phase between the beams varies much faster than the response time of the medium. In this case, the medium responds only to the time-averaged (over a time longer than the response time) intensity. Therefore, irrespective of the solitons' relative phase, the intensity in the central region between the solitons is increased. In a self-focusing medium, more light is "attracted" toward the center and the solitons "attract" each other.

Collisions in Kerr media exhibit several important differences in their outcome vis-à-vis collision processes in saturable nonlinear media. First, in Kerr media, all solitons are (1+1)D, the collisions occur in a single plane and they are fully elastic. This situation implies that the number of solitons is conserved and that no energy is lost to radiation waves. In addition, the propagation velocities of the solitons recover to their initial values after each collision. This equivalence between solitons and particles is the reason for the term "soliton." Furthermore, if the input soliton trajectories are separated by some angle, the solitons simply go through each other and remain unaffected by the collision, apart from a tiny lateral displacement and a small change in absolute phase. For an attractive collision of parallel launched solitons with small lateral separation, the solitons move toward each other, combine and separate periodically. On the other hand, in a repulsive Kerr collision, the solitons always move away from each other.[2]

Collisions in saturable nonlinear media are much

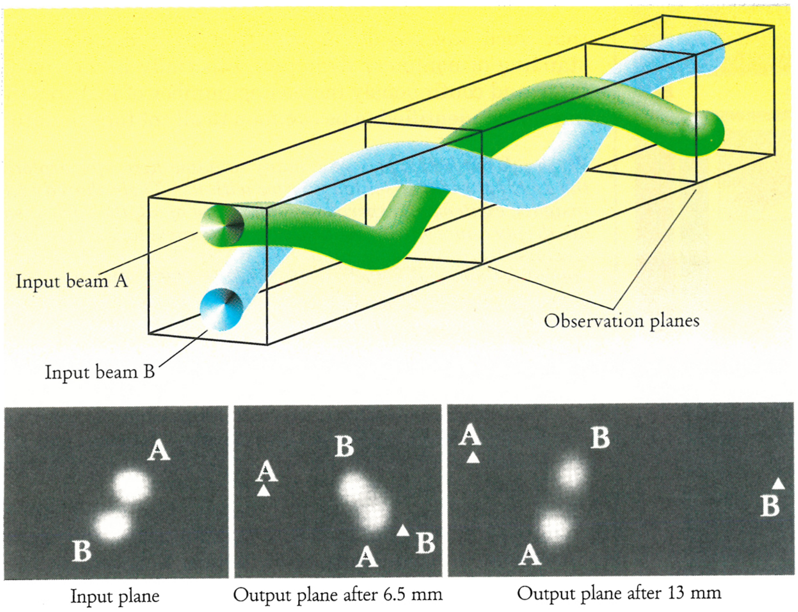


FIGURE 6. SPIRALING of two colliding photorefractive screening solitons with initial trajectories that do not lie in the same plane. Shown are photographs of the optical beams. Left: Beams A and B about 14 μm apart at the input plane. Middle: The spiraling soliton pair after 6.5 mm of propagation. Right: The spiraling pair after 13 mm of propagation. The triangles indicate the centers of the corresponding diffracting beams. After 6.5 mm the solitons have spiraled about each other by 270°; after 13 mm the spiraling angle doubles to 540°. Note that the spiraling is in elliptical orbits (From ref. 18.)

richer than those in Kerr media and consequently are more interesting, primarily for two reasons. First, saturable nonlinear media can support (2+1)D solitons and therefore collisions can occur in a full three dimensions, giving rise to new effects that cannot exist in Kerr media. Second, the self-induced waveguides in saturable nonlinear media can guide more than one mode, giving rise to phenomena such as soliton fusion, fission and annihilation. In 1992 S. Gatz and Joachim Herrmann at the Max Born Institute for Nonlinear Optics in Berlin found that solitons colliding coherently at shallow relative angles in a saturable nonlinearity can fuse together. Theorists Snyder and Adrian Sheppard subsequently showed that colliding solitons can undergo fission—that is, generate additional solitons—or annihilate each other.[4] Their explanation was elegant: One needs to compare the collision angle to the complementary critical angle above which total internal reflection and guiding occur. For a collision angle larger than that critical angle, the solitons simply go through each other. For "shallow" angle collisions, the beams couple light into each other's induced waveguide.

Experimentally, soliton collisions leading to fusion have been observed in all kinds of saturable nonlinear media: atomic vapor,[13] photorefractive[14] and quadratic.[15] The experimental results in figure 4 show an attractive incoherent collision between photorefractive solitons at large angles (top), and fusion (bottom) for small collision angles. Snyder and Sheppard also predicted that two colliding solitons may give birth to a new soliton and that three solitons can emerge after the collision—as has recently been observed.[16] Figure 5 shows an example of coherent soliton collisions in (1+1)D waveguides for quadratic solitons. Phase differences intermediate between 0 and π lead to energy exchange between solitons. The energy flow reverses in going from a phase difference of $\pi/2$ to $3\pi/2$. Similar effects have been seen in saturable media such as carbon disulfide and photorefractives.

Solitons in (2+1) dimensions in saturable nonlinear media offer an opportunity to examine collisions of solitons with three-dimensional trajectories. Solitons launched individually move in their initial trajectories. If they are launched simultaneously so that their attraction balances the centrifugal force due to rotation, the solitons can capture each other into orbit and spiral about each other, like celestial objects or moving charged particles do. This effect, suggested first in the context of coherent collisions,[17] has recently been demonstrated (figure 6) by employing an incoherent collision between photorefractive solitons.[18] When the initial distance between the solitons is increased, the solitons' trajectories bend slightly toward each other, but their relative velocity is too large to form a bound pair. Conversely, if their separation is too small, they spiral in a converging orbit and eventually fuse. Spiraling–fusion effects have also been observed by Barry Luther-Davies and his coworkers at the Australian National University.[13] These observations lead to the interesting question: Do interacting spatial solitons conserve angular momentum?

Variety of features

Space limitations prevent us from discussing the many other interesting features of optical spatial solitons, but we will close by at least identifying a few of the key issues associated with them. In self-defocusing media, for example, solitons take on the form of vortices in (2+1) dimensions or dark stripes in (1+1) dimensions.[1] (2+1)D waveguides feature vortices and (1+1)D waveguides carry dark solitons, which are linear voids borne on uniform beams. Another important topic consists of multicomponent solitons, in which several electric-field components participate in the self-trapping process, by jointly creating an induced waveguide and guiding themselves in it. Yet another issue is the connection between stable solitons in one dimension and instabilities in a higher dimension. Different origins for the instabilities (such as transverse, longitudinal and azimuthal instabilities) have been investigated recently and the results have shed new light on nonlinear dynamics.

Although the propagation distances involved in optical spatial solitons are certainly not on the scale of the temporal solitons in optical fibers, which have pioneered solitons in optics, the variety of nonlinearities accessible is far broader and the physical phenomena are much richer. Here we have glanced at some of the rapid progress, excitement and new physics that are emerging from investigations of optical spatial solitons. One can expect that such investigations will lead to a deeper understanding of nonlinear dynamics, especially in view of the large and continuously increasing number of features that have been identified to be common to all solitons in nature.

We thank our colleagues—too many to name here—for exploring the exciting world of soliton physics with us. Their shared ideas, insights, excitement, experiments and, most of all, their friendship are deeply appreciated. We dedicate this article to our late friend, Gustavo Torres-Cisneros, a talented young Mexican researcher on optical solitons, who died on 25 January 1998. Our research is supported by the Army Research Office, the Air Force Office of Scientific Research and the National Science Foundation.

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