Optical Spatial Solitons: Historical Perspectives

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Invited Paper

***Abstract*—Optical spatial solitons are self-trapped optical beams that exist by virtue of the balance between diffraction and nonlinearity. They propagate and interact with one another while displaying properties that are normally associated with real particles. Solitons, in general, manifest themselves in a large variety of wave/particle systems in nature: practically in any system that possesses both dispersion (in time or space) and nonlinearity. Solitons have been identified in optics, plasmas, fluids, condensed matter, particle physics, and astrophysics. Yet over the past decade, the forefront of soliton research has shifted to optics. In this paper, we describe the historical evolution of spatial solitons from speculative creatures to one of the most fascinating features optics has to offer.**

***Index Terms*—Beam self-trapping, bright solitons, coherence, dark solitons, discrete solitons, discrete systems, Kerr solitons, modulational instability, nonlinear optics, nonlinear optics in cavities, nonlinear waves, optical bullets, photorefractives, photorefractivity, second harmonic generation, solitons, soliton collisions, soliton interactions, spatial solitons.**

I. Introduction

THE best-known characteristic of wave propagation is that beams that are finite in space tend to broaden due to diffraction effects. In fact, such diffraction effects are fully equivalent to the broadening of temporal pulses propagating in media that possess chromatic dispersion. That this paradigm can be broken is perhaps one of the most fascinating features of nonlinear optics. For this to occur, it requires a strong nonlinear interaction between the wave and the medium through which the beam is propagating. As a result, a self-trapped beam or a spatial soliton can form [1], [2]. Spatial solitons are optical beams that propagate in a nonlinear medium without diffraction, i.e., their beam diameter remains invariant during propagation. Intuitively, a spatial soliton represents an exact balance between diffraction and nonlinearly induced self-lensing or self-focusing effects, as shown schematically in Fig. 1. An actual picture of the contrast between soliton propagation and normal diffraction for a beam in a photorefractive material is shown in Fig. 2. Such spatial solitons belong to the same family of phenomena as their better known relative, the temporal soliton. Again, in a way fully analogous to the spatial case, a temporal soliton forms when group velocity dispersion is totally counteracted by temporal self-focusing or self-phase modulation effects [3], [4].

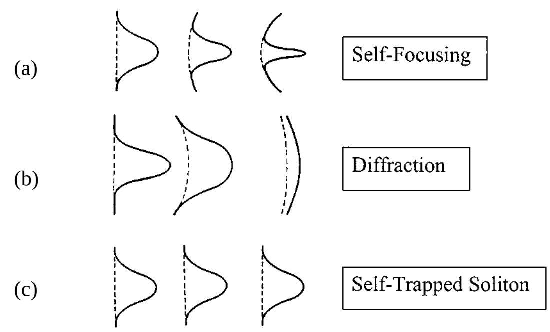

Fig. 1. Schematic showing the spatial beam profiles (solid line) and phase fronts (dashed line) for (a) beam self-focusing, (b) normal beam diffraction, and (c) soliton propagation.

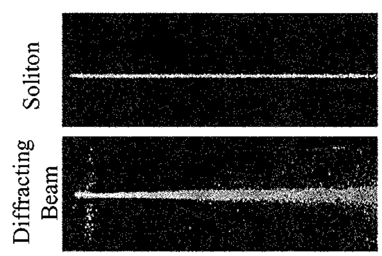

Fig. 2. Top view photograph of a 10-μm-wide spatial soliton propagating in a strontium barium niobate photorefractive crystal (top), and for comparison, the same beam diffracting when the nonlinearity is "turned off" (bottom).

All solitons require that a strong enough nonlinear interaction takes place between themselves and the material in which they propagate. This interaction typically requires that the so-called diffraction length for the spatial case or the dispersion length for the temporal (fiber) case is comparable to a nonlinear length that characterizes self-focusing in the medium. In fibers, low losses allow propagation distances of kilometers, and as a result, the very weak glass nonlinearity becomes cumulatively sufficient for soliton formation. In the spatial case, however, the sample sizes are typically limited to only centimeters, and thus, either the nonlinearities and/or operating powers need to be larger. What sets spatial solitons apart from their fiber counterparts is their dimensionality. Fiber solitons are described by a (1+1)-dimensional [(1+1)-D] space-time evolution equation, whereas spatial solitons are by nature (2+1)-dimensional creatures (two transverse dimensions plus one propagation coordinate). The fact that the spatial domain exhibits a higher dimen-

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sionality leads to a host of interesting phenomena and processes, which have no analog whatsoever in the temporal case. These include for example, full three-dimensional (3-D) interaction between solitons and soliton spiraling, vortex solitons, angular momentum effects, rotating dipole vector solitons, etc. These are a direct consequence of the fact that the number of different nonlinear mechanisms that can support spatial solitons is to date much larger than for their temporal counterparts. Solitons in fibers exist as a result of the glass Kerr nonlinearity. In pure Kerr media, the index change Δn is linearly proportional to the optical intensity I, i.e., $\Delta n(I) = n_2 I$, where n_2 is the Kerr coefficient. In the spatial case, however, optical solitons have been observed based on several other nonlinear processes. In addition to the Kerr nonlinearity, various photorefractive effects, parametric $\chi^{(2)}$ mixing phenomena, nonlinearities in liquid crystals and polymers, and the saturable nonlinearities of two-level systems were found to support spatial solitons.

Over the years, there has been some discussion as to which self-trapped optical beams should actually be called solitons. Historically, the concept of solitons emerged in the mathematics literature and was reserved for optical self-trapped beams/wavepackets obeying integrable nonlinear partial differential equations. In nonlinear optics, the so-called nonlinear Schroedinger equation represents such an example. This equation, which is known to describe (1+1)-D wave propagation in pure Kerr nonlinear media, can be fully solved (or integrated) using the "inverse scattering theory" [5]. Because of this "royal" property of integrability, solitons remain unchanged (apart from a phase factor) during a collision event. In reality, however, most nonlinear physical systems of importance (involving other types of nonlinearity) are described by nonintegrable evolution equations. Nevertheless, even in this latter case, self-trapped solutions exist and display important features and conserved quantities that relate solitons to real particles. Initially, such self-trapped entities in nonintegrable systems were referred to as "solitary waves." In general, solitons and solitary waves have some specific interaction and collision properties that differ from one another. Solitons do not couple to radiation on collision, and the number of solitons is conserved [5]. This is not the case for solitary waves. Yet, in spite of their "humble" roots, solitary waves, like solitons, still exhibit particle-like properties. As a result, in today's literature this distinction is, in general, no longer used (except maybe in mathematics papers), and all self-trapped beams are loosely called solitons.

The number of papers dealing with spatial solitons has risen meteorically in the 1990s, still dominated by theoretical work. As in any other area, there have been certain key ideas and experiments that have defined this field and the directions that it has taken. In this paper, we discuss a selection of such papers and their significance. This overview is by no means all-inclusive, nor was it meant to be.

II. Early Experiments on Spatial Solitons

Although the history of the temporal fiber soliton has been widely publicized and its 25th birthday celebrated, in fact, both the theory and experimental discovery of the spatial soliton actually preceded those of its temporal counterpart. The idea that an optical beam can induce a waveguide and guide itself in it was first suggested by Askar'yan as early as 1962 [6]. On the experimental side, one of the earliest observations (1964) in the field of nonlinear optics key to the evolution of soliton ideas was the self-focusing of optical beams due to third-order nonlinearities [7]. In order to investigate this effect, the wave equation in nonlinear Kerr media was analyzed in both one and two transverse dimensions [8], [9]. In 1964, Chiao, Garmire, and Townes [8] and Talanov [9], independently discussed the spatial trapping of optical beams in Kerr media via the nonlinear wave equation. A year later, Kelley showed [10] that the two-dimensional [(2+1)-D] self-trapped solutions to the nonlinear wave equation undergo catastrophic collapse, and thus, they are unstable. In fact, as it turns out, one-dimensional (1-D) solitons in a bulk 3-D nonlinear medium are also unstable. They break up into multiple filaments due to transverse instabilities [11]. Thus, spatial solitons in Kerr media can only exist (in terms of stability) in configurations where one of the two transverse dimensions is redundant, i.e., where diffraction is arrested in one dimension by some other means, for example, in a slab waveguide. Just a few years after Kelley's paper, Dawes and Marburger found numerically that saturable nonlinearities are able to "arrest" the catastrophic collapse and can lead to stable 2-D spatial solitons [12]. These ideas formed the basis for experimental developments for the next 20 years. Furthermore, the concept of a "saturable nonlinearity," i.e., materials in which the magnitude of the index change has an upper bound (and thus ceases to increase with increasing intensity), has turned out to be a key to many of the new families of solitons discovered in the 1990s.

The first experiment on spatial optical solitons was reported in 1974 by Ashkin and Bjorkholm [13]. They used a circularly symmetric beam in a 2-D medium, namely, a cell filled with sodium vapor and operated their input laser near the famous sodium yellow line. At low powers, their laser beam diverged (diffracted) in the gas cell, whereas at higher powers, the beam diameter self-stabilized and propagated without diffraction. This is the classical signature of a spatial soliton. The nonlinearity employed in these first experiments was not the classical Kerr nonlinearity, but rather the saturable nonlinearity that exists near an electronic resonance in a two-level system. Near any such active transition between a ground state and an excited state, the transition gives rise either to gain or to loss, and the loss (or gain) are interlinked through the Kramers–Kronig relations to a dispersive resonant contribution to the index of refraction. The probability for the absorption of a photon depends on the population difference between the excited upper level and the lower energy level. This population difference can be reduced by a strong laser beam that creates a significant population in the excited state. This reduces both the absorption coefficient (hence leading to saturation of the absorption) and the resonant contribution to the refractive index at and near the "saturating laser" wavelength for an inhomogeneously broadened transition and over the full dispersion curve for a homogeneously broadened transition. In such two-level, absorbing systems, $\Delta n(I) > 0$ for $\lambda < \lambda_{\max}$ and $\Delta n(I) < 0$ for $\lambda > \lambda_{\max}$. Ashkin and Bjorkholm used a cw dye laser tuned to the short wavelength side of the sodium yellow line, and hence, their beam experienced self-focusing. The nonlinearity is commonly referred to as "saturable" because an intense enough field can reduce the difference between populations of the energy levels, and hence, no additional change in the index will occur with further increase in intensity. This distinction between Kerr and saturating nonlinearities is important because 2-D spatial solitons are only stable in saturable nonlinear media.

This was the first experiment demonstrating self-trapping in a medium with a self-focusing nonlinearity, i.e., the refractive index increases with intensity. The index was thus largest at the peak of the beam intensity and decreases to the background value of the index in the tails of the beam. Therefore, the phase velocity is lowest at the beam maximum and increases toward the tails. This results in a bending of the phase fronts as shown previously in Fig. 1 and consequently leads to beam focusing. Counteracting this focusing is diffraction, and this interplay leads to the formation of a robust spatial soliton.

Because of the dynamics of the field of nonlinear optics at that time, this turned out to be the classical case of an experiment before its time. It was more than another ten years before this field was revisited in a pair of experiments by researchers at Limoge University [14]. They essentially performed the first 1-D soliton experiments in waveguides using the reorientational nonlinearity of liquid carbon disulphide-CS_2. Although the nonlinearity of CS_2 is inherently of the saturable type, in the regime in which it was used in these experiments, it behaved in a Kerr-like fashion. Two approaches to achieving confinement in one dimension were used. First, by producing an interference pattern in 1-D, effectively, a parallel series of 1-D waveguides was formed orthogonal to that dimension. Thus, light could not diffract across the dark zone of the interference pattern. Although clever in concept, this approach was not widely adopted. Their second experiment consisted of liquid CS_2 sandwiched between two glass plates. In this 1-D planar waveguide, classical 1-D self-trapping was observed. This was the first observation of a 1-D Kerr spatial soliton. These solitons can be analyzed by inverse scattering theory, and their collision properties are special within the soliton family. These experiments opened the way to subsequent 1-D bright soliton demonstrations in glass [15], semiconductors [16], polymers [17], etc.

III. 2-D Interactions Between Kerr Solitons

One of the precepts of nonlinear optics is that waves interact and so it should be no surprise that spatial solitons affect each other. These interactions can all be understood in terms of the wave-mixing properties associated with nonlinear optics. However, the fact that the number of solitons into and out of a collision differs by an integer number is indicative of the particle nature of solitons.

Interactions between solitons are perhaps the most fascinating features of all soliton phenomena. They are sufficiently complex that it is frequently necessary to resort to detailed numerical calculations for predictions. However, in the simplest case of 1-D Kerr solitons, interactions can be treated analytically using the inverse scattering theory [5]. First, because Kerr solitons are (1+1)-D, their collisions occur in a single plane. Second, all collisions between Kerr solitons are fully elastic so that the number of solitons is always conserved. Third, the system is integrable, and therefore, no energy is lost (to radiation waves). Finally, the directions and propagation velocities of the solitons remain the same even after each collision. This equivalence between solitons and particles was actually first suggested in 1965 and led to the term soliton [18]. The real surprise was, however, that solitons survive the collision event as self-trapped entities, even though the solitons themselves are highly nonlinear creatures. Furthermore, the collision between solitons involves "forces": Solitons interact like real particles, exerting attraction and repulsion on one another [19]. (For a detailed review on soliton interactions, see [1] and [2]).

The first experiments demonstrating soliton collisions in 1-D glass waveguides were performed back in 1991 by Aitchison *et al.* [20], [21]. They found that in-phase Kerr solitons attracted, whereas out-of-phase solitons repelled one another. This is simply a manifestation of the well-known concept of linear optics that light is bent toward regions of higher index and away from regions of lower index. For the in-phase case, the index increases in the overlap region due to constructive interference between the soliton fields and, hence, the attraction toward the centroid of the system. Conversely, out-of-phase solitons result in destructive interference between the fields which leads to repulsion. The situation is more complex at other relative phase angles. The first experiment to demonstrate the importance of the four-wave mixing term of nonlinear optics for coherent solitons was reported by Shalaby *et al.* [22]. They showed that for a $\pi/2$ phase difference, one soliton gained energy at the expense of the other soliton. The energy exchange direction is switched when the phase is increased to $3\pi/2$. These effects can be viewed as the consequence of the well-known four-wave mixing term in nonlinear optics.

These two experiments demonstrated the basic collision properties of coherent Kerr solitons. The number of solitons at the output, after a collision, equals the number at the input. Furthermore, if there is a quadrature component to the interaction, i.e., relative phases of neither 0 nor π, there is energy exchange between the solitons in addition to attraction and repulsion which are manifestation of the in-phase component. Yet, up until that point in time, true solitons were believed to exist only in a 1-D form in a plane, and all interaction features were restricted to planar interactions (conservation of "effective mass" or power and linear momentum, i.e., velocities and trajectories). As we will see below, this situation has dramatically changed following the discoveries of photorefractive and quadratic solitons and with pioneering collision experiments in atomic vapors.

IV. Dark Solitons

It was shown theoretically in 1973 that as the converse to an optical bright soliton, the dark soliton should also exist in 1-D when the nonlinearity is of the self-defocusing type [23]. This soliton is a dark "hole" in an otherwise bright background, or more accurately, a dark line of finite width along the propagation axis (z). It is further characterized by a π phase shift right where the field is zero. This soliton requires a self-defocusing environment, that is, $n_2 < 0$ in a Kerr medium.

The first experiments on dark solitons were clustered around 1990 and 1991 and were actually performed in bulk media, i.e., in 2-D [25], [26]. Strictly speaking, the dark lines with a phase shift of π across the light minimum correspond to 1-D dark solitons. However, as is frequently the case for spatial solitons, there are regions of parameter space in which soliton solutions valid for a lower-dimensional system, 1-D in this case, are for all practical purposes stable over the typical sample lengths available in a higher dimension, i.e., 2-D. These experiments employed a variety of media, including those with thermal and semiconductor nonlinearities, all of the saturable type. In the early work of Schwartzlander *et al.*, a mask provided two orthogonal boundaries across which a phase discontinuity of π could be obtained. This led to the two orthogonal nondiffracting dark lines observed in their experiment. Blocking the incident light with a single or multiple absorbing stripes led to the generation of diverging pairs of dark solitons with equal but opposite π phase shifts across their intensity minima. Phase masks in which a π phase discontinuity was introduced (by inserting an extra optical path into one half of the incident beam) have proved to be very effective in generating single clean dark solitons.

Soon thereafter, the stable propagation of a (2+1)-D dark soliton (optical vortex soliton) was observed for the first time in self-defocusing media with thermal nonlinearities [27]. This type of soliton consists of a circularly symmetric dark hole in a bright uniform background. It is a vortex around which there is an angular phase discontinuity of $\pm 2\pi$. The vortex in fact propagates without any change in shape, except for phase rotation, around its center of symmetry, as imposed by its azimuthal phase. Vortex solitons were actually studied earlier in the context of superfluidity [28] and later predicted to occur in optics [29]. The experimental observations have confirmed the phase singularity by interfering the field from a vortex with a plane wave showing that two dark fringes coalesce at the center of the vortex.

Dark solitons have a unique place in nonlinear optics. The fact that plane waves are unstable in self-focusing media and therefore can disintegrate into solitons (with self-focusing being balanced against diffraction) is perhaps not surprising. However, plane waves are stable in self-defocusing media. Therefore, an extra "ingredient" is needed to form solitons, and that ingredient is the phase jump of $m\pi$ which leads to beam localization in both 1-D and 2-D.

By the end of the early 1990s, spatial solitons in both 1-D and 2-D, and their interactions, had been demonstrated. These solitons were all an extension of the Kerr nonlinearity approach to soliton generation. The Kerr solitons turned out to be the exact analog to the temporal case in the 1-D case. At that point in time, except for the Bjorkholm and Ashkin experiment, solitons seem to behave "by the book," exactly as predicted by theory. The surge of new classes of solitons, which occurred shortly thereafter, was first faced with skepticism, which later on turned into enthusiasm: (2+1)-D solitons and (3+1)-D solitons (the latter being trapped in both transverse dimensions and in time) have completely revolutionized the field of solitons.

V. New Classes of Solitons

The last decade has been characterized by the experimental discovery of new classes of solitons in material systems that are very different from those of the Kerr-type family. These new solitons exhibit many properties that are similar to those of Kerr or Kerr-like solitons. However, the physical mechanism behind their nonlinearity is quite different. As a result, as new discoveries were made, it started to become clear that soliton phenomena are pervasive in nonlinear optics and are not just restricted to Kerr-type nonlinearities. The two new classes of solitons, at least in terms of nonlinear mechanisms, are quadratic solitons and photorefractive solitons. In addition to these solitons in new material systems, other generic families were also discovered; they were not directly related to particular materials. These include, for example, multicomponent vector solitons, incoherent and discrete solitons, and spatio-temporal and cavity solitons. For numerous reasons, the field of photorefractive solitons has proven to be especially fruitful, and many of the key new discoveries have been made with them.

A. Photorefractive Solitons

The discovery of photorefractive solitons [30], [31] was, for many reasons, a radical turning point in the development of the field of spatial solitons. These solitons are formed due to *multiple* physical effects, some of which are nonlocal, and all of which have a noninstantaneous temporal response. The common features are the absorption of light and subsequent charge generation, the motion of charge under the influence of electric fields and the consequent establishment of local fields, and finally, an electro-optic effect in which an index change Δn is created via the local fields. The nonlinear response is *nonlocal* due to the charge migration over macroscopic distances. The time scale is determined by the dielectric relaxation time (the necessary time for charge separation), which is inversely proportional to the intensity of the optical beam and the charge recombination rate. This results in a nonlinear mechanism that is inherently saturable, and hence, many of the soliton's global properties beyond the generation process resemble those of Kerr solitons (in some regimes) or those of solitons in saturable nonlinear media.

The term "photorefractive effect" encompasses many different physical processes on a microscopic level, all of which lead to an index change due to a combination of light absorption and charge migration [32], [33]. In general, the family of photorefractive solitons encompasses several members, each one exhibiting a different $\Delta n(I)$ dependence. Thus, there is no single type of photorefractive soliton but instead, a number of them whose origin depends on the details of the different physical mechanisms. Of these, the photorefractive screening soliton [34]–[36] has had the largest impact. Fig. 2 showed the propagation of a photorefractive soliton made visible by scattering centers in the crystal.

Intuitively, one may view the formation of bright photorefractive screening solitons as follows. Consider a narrow light beam propagating through the center of a photorefractive crystal across which a voltage has been applied in the direction orthogonal to the light propagation. In the illuminated region, the density of free electrons increases due to absorption, which means that the conductivity increases (or the resistivity decreases). Since the resistivity is now not uniform across the crystal, the voltage drops primarily in the dark regions (a simple voltage divider), and this leads to a large space charge field E_{SC}. On the other hand, this same field is much lower in the illuminated region. In practice, the spatial distribution of the field in this intuitive voltage-divider picture is supported by different concentrations of ionized donors on either side of the beam. This leads to an electric field "under" the beam with polarity opposite of that of the applied field, thus resulting in partial screening of the applied field in the region of the optical beam. In turn, the refractive index changes by $\Delta n \propto E_{SC}$ (via the electro-optic effect). The sign of Δn depends on the direction of E_{SC} with respect to the principal axes of the noncentrosymmetric photorefractive crystal and can be reversed by simply changing the voltage polarity. The actual dependence of Δn on the optical intensity I, for 1-D screening solitons, is $\Delta n = -(V/L)(n^3 r_{\rm eff}/2)[1 + (I/I_{\rm dark})]^{-1}$. Here, $r_{\rm eff}$ is the effective electro-optic coefficient, which depends on the direction of the applied field and the polarization of the beam, V is the voltage applied between electrodes separated by distance L ($L \gg$ soliton width). $I_{\rm dark}$ is the so-called "dark irradiance," which is a material parameter that is proportional to the conductivity of the crystal in the dark. Note that the dark irradiance parameter can be artificially increased by illuminating the entire crystal, thus reducing the soliton formation time.

The first photorefractive self-trapped beam, predicted in 1992, was demonstrated a year later in a Strontium Barium Niobate (SBN) crystal [30], [31]. Although, historically, it was the first photorefractive self-trapped beam, it was transient in nature and not a steady-state soliton. It was not until 1994 that the first steady-state photorefractive self-focusing was reported [37] by a group from Mexico lead by Stepanov. At the same year, steady-state "screening solitons" were predicted [34], and experimentally demonstrated soon thereafter, in both (2+1)-D [38], [39] and (1+1)-D [40] realizations. Since then, photorefractive screening solitons have been investigated intensively and have been used to demonstrate many of the interesting features of photorefractive solitons in particular and solitons in general. In addition to screening solitons, many other versions of photorefractive solitons were subsequently reported, based on the rich diversity of photorefractive effects [41].

The discovery of photorefractive solitons was important for many reasons. The power necessary to generate these solitons can be very small, as small as μWs; therefore, spatial soliton experiments can be carried out with CW laser beams and very elementary equipment. Photorefractive solitons are also attractive for waveguide and steering applications. Once the index distribution responsible for the self-trapping is established, beams of much higher power can be guided by these index waveguides, provided that they are at wavelengths where the absorption is small. The waveguides induced by these solitons can be actually impressed into the crystalline lattice and become permanent, yet erasable with large electric fields and/or elevated temperatures. Furthermore, since the photorefractive response time can be in the millisecond to microsecond range, it is relatively straightforward to work with either coherent or incoherent light. Finally, from a credibility point of view, photorefractive solitons were the first to be imaged (due to scattering impurities) during their propagation, as shown in Fig. 2. They made believers of many people that what was claimed to be happening during propagation in the interior of a material was really happening.

B. Quadratic Solitons

The most recent generic class of spatial solitons to be experimentally demonstrated was the quadratic soliton. They were actually predicted back in the early 1970s by Sukhorukov and Karamzin [42] but were demonstrated experimentally only in 1995 [43]. In this case, the beam-trapping mechanism is due to the energy exchange between the fundamental and second harmonic, as described by the usual coupled-mode equations for SHG.

The initial experiment used Type II phase-matching in KTP; i.e., there were two orthogonally polarized fundamental input beams [43], [44]. The crystal geometry was such that the extraordinary fundamental wave and the second harmonic "walk away" from the ordinary fundamental beam. That is, the group velocities of the interacting beams are not collinear. It was shown experimentally on and near phase matching that once the soliton was formed, all three beams not only did not diffract but also propagated in the same direction in space, i.e., their group velocity directions were locked together. Furthermore, although the steady-state quadratic soliton consists of in-phase fundamental and harmonic fields, they can also be generated during the SHG process with the fundamental beam input only.

The importance of this particular type of soliton is that it demonstrated experimentally that, in nonlinear optics, nonlinear wave mixing can lead to soliton formation. Here, we will use a very simple example to illustrate the beam focusing that takes place. Consider the case of a waveguide in which the field distributions along the x-axis are locked in by the waveguide. From the usual expansion of the nonlinear polarization in terms of the products of the interacting fields, the nonlinear polarization term driving the harmonic is of the form $P^{NL}(y, 2\omega) \propto a_1^2(y)$, and the one driving the regenerated fundamental is $P^{NL}(y, \omega) \propto a_2(y) a_1^*(y)$, where $a_1(y)$ and $a_2(y)$ are the fundamental and harmonic field, respectively, and y is the coordinate along which diffraction (or self-trapping) occurs. Again, assume for simplicity that the initial fundamental field distribution is Gaussian of the form $a_1(0)\exp[-y^2/w_0^2]$. Therefore, $P^{NL}(y, 2\omega) \propto \exp[-2y^2/w_o^2]$, and thus, the polarization source and, hence, the harmonic generated by it are both narrower in space than the fundamental. Similarly, $P^{NL}(y, \omega) \propto \exp[-3y^2/w_0^2]$, i.e., the polarization source which regenerates the fundamental is narrower than the original fundamental. Although the actual field distributions for the fields are more complicated than Gaussian, these arguments are valid for all beams of finite width. Therefore, this parametric interaction leads to beam narrowing for both beams. This counteracts diffraction and results in stable solitons. Note that any process involving the product of finite beams will lead to mutual self-focusing and, presumably, spatial solitons.

At the same time, (1+1)-D quadratic solitons were demonstrated in $LiNbO_3$ waveguides [44]. What distinguishes this experiment from previous work is the amount of second harmonic generated. In this case, it was very small, since a geometry far from the phase-matching condition was chosen. This limit is called the cascading or Kerr limit in which only a small amount of second harmonic is needed to impart a nonlinear phase shift to the fundamental beam proportional to its intensity [45]. This now leads to self-focusing of the beam, and quadratic soliton formation can take place similar to that for the Kerr case. The difference, of course, is that some harmonic must be present since the process relies on the second-order nonlinearity.

This 1-D experiment was important because the effective nonlinearity used now depends on the phase-mismatch, i.e., is tunable both in sign and magnitude, and the geometry is flexible because stringent phase-matching conditions need not be imposed. It is these concepts that ultimately led to quadratic solitons in which temporal spreading was also arrested, at least in one dimension.

VI. Multicomponent Vector Solitons

In 1992, Shalaby and Barthelemy demonstrated experimentally that a bright-dark spatial soliton pair can propagate in a nonlinear material such as CS_2 [46]. This was the first experimental observation of a vector (multicomponent) spatial soliton. This composite structure involved two different soliton components (each of different color) which coexisted via symbiosis. In this particular case, the physical mechanism that coupled these two soliton components happened to be the cross-phase modulation between the two wavelengths (1064 and 532 nm). Yet, it was not until 1996 that the experimental field of multicomponent vector solitons actually blossomed. From a theoretical perspective, the existence of a vector soliton was predicted in 1974 by Manakov [47]. Such a Manakov structure involves two coupled degenerate solitons polarized along the two orthogonal axes. Moreover, this vector self-trapped state is possible as long as the polarization self-phase and cross-phase modulation coefficients (which depend on the material system) are equal. It is also interesting to note that the partial differential equation describing the Manakov system are fully integrable via the inverse scattering transform. Therefore, the Manakov states are solitons in the strict sense of the word.

Manakov solitons were first demonstrated in AlGaAs waveguides in 1996 [48]. For electric field vectors polarized parallel to the AlGaAs 110 and 001 crystalline axes, it happens that the self- and cross-phase modulation terms are approximately equal, thus satisfying the requirement for Manakov solitons. In this experiment, the two polarizations were passed through two separate optical systems with different group velocity dispersion to eliminate the temporal coherence between them.

The self-trapping of a vector soliton can perhaps be better understood by considering the properties of the jointly induced waveguide of such a multicomponent structure. Self-consistency requires that each soliton component is exactly a mode of this waveguide [49]. Conceptually, this is an important step since one can view such a multicomponent soliton as a "superposition" of the modes of the commonly induced waveguide. Vector solitons were first suggested in the temporal domain, i.e., in fibers [50]–[52] and later on for spatial solitons [53]. Over the years, two additional methods (other than those relying on orthogonal polarizations) were suggested to realize multicomponent solitons. The first one assumes that the two soliton components are widely separated in the frequency scale [54], whereas the second one considers components which are mutually incoherent with respect to each other [55]. The latter method proves particularly useful in terms of implementing Manakov-type systems of any arbitrary dimensionality N, where N is the number of components involved. This is possible in materials with noninstantaneous nonlinearities (as in photorefractives), even when all the fields share the same wavelength and polarization. This method was employed with photorefractive solitons, first to demonstrate bright-bright, dark-dark, and dark-bright soliton pairs [56], [57], and later on to make the first experimental demonstration of multimode/multihump solitons [58]. In the multimode soliton experiment, the two input field distributions resembled the first and/or second and third modes of a slab waveguide. The beams were made to be mutually incoherent by delaying one of the components beyond the coherence length of the laser. With the nonlinearity, i.e., the voltage turned on, the intensity profile remained invariant during propagation and both "modes" were guided as a composite soliton. Very recently, 2-D dipole vector (or composite) solitons were also demonstrated experimentally. These vector solitons consist of a bell-shaped component and a 2-D dipole mode [59], [60].

The general ideas behind multicomponent vector solitons proved invaluable for later developments and, in particular, to the area of incoherent solitons discussed in the next section.

VII. Incoherent Solitons

Until 1996, the commonly held impression was that all soliton structures are inherently coherent entities. In that year, however, an experiment carried out at Princeton University demonstrated beyond doubt that self-trapping of a partially spatially incoherent light beam [61] is in fact possible in noninstantaneous nonlinear media such as biased photorefractives. In this case, a spatially partially-coherent soliton can form. This same effect was later on observed with white light, i.e., a beam that is both temporally and spatially incoherent [62]. In this experiment, the self-trapped beam originated from a simple incandescent light bulb that emitted light between 380–720 nm. In yet another experiment, self-trapping of dark incoherent "beams," i.e., 1-D or 2-D "voids" nested in a spatially incoherent beam was also demonstrated [63].

For self-trapping of an incoherent beam (an incoherent soliton) to occur, several conditions must be satisfied. First, the nonlinearity must be noninstantaneous with a response time that is much longer than the phase fluctuation time across the optical beam. Such a nonlinearity responds to the time-averaged envelope and not to the instantaneous "speckles" that constitute the incoherent field. Second, the multimode (speckled) beam should be able to induce, via the nonlinearity, a multimode waveguide. Otherwise, if the induced waveguide is able to support only a single-guided mode, the incoherent beam will simply undergo spatial filtering, thus radiating all of its power but 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.

These experiments were the first to show that solitons can exist with both spatial and temporal incoherence. These unexpected observations opened the way for several other important results. These include, for example, the discovery of gray fundamental dark incoherent solitons [64], anti-dark incoherent states, elliptic incoherent solitons, and suppression of transverse modulational instability using anisotropic coherence control. Following this, a number of experiments were carried out demonstrating the effects of partial coherence on various soliton effects.

VIII. Discrete Solitons

Another fascinating class of self-trapped states can arise in discrete nonlinear networks such as large arrays of coupled waveguides. In this case, a discrete soliton can form whose field extends over a limited number of nonlinear waveguides. Unlike other families of spatial solitons, which are known to exist in homogeneous media, discrete solitons result from the collective behavior of the array as a whole. In reality, they represent nonlinear defect modes in a photonic crystal or optical lattice. To understand how such a discrete structure can actually form, it is perhaps useful to take a look at the linear properties of such arrays. Let us first assume that only one waveguide is initially excited under very low power conditions. In this case, power will eventually flow to more and more neighboring waveguides as a result of waveguide coupling due to the overlap of the fields associated with individual waveguides. In essence, this tunneling or coupling process can be considered as some sort of discrete diffraction. On the other hand, as the input power increases, the waveguide becomes eventually detuned from its neighbors (because of nonlinearity), and as a result, the power transfer among waveguides ultimately stops. Thus, the light becomes trapped to a few of the waveguides via the Kerr nonlinearity, and the envelope described by the peaks of the fields of each waveguide takes on a soliton-like envelope. In other words, these states are possible through a careful balance of discrete diffraction effects and waveguide nonlinearity. Discrete solitons were first predicted in 1988 [65] and observed experimentally ten years later by Eisenberg *et al.* in AlGaAs nonlinear waveguide arrays [66].

As mentioned in several studies [67]–[70] discrete solitons differ from their continuous counterparts in fundamental ways. For example, there is no translational or Galilean invariance in waveguide arrays. This in turn can lead to power dependent steering—an effect that has been also observed experimentally [71]. Recently, diffraction management has been successfully demonstrated in such waveguide arrays [72]. The prospect of tailoring at will the diffraction properties of these structures (in some cases even reversing the sign of diffraction) brings about several exciting possibilities. Among them is the possibility of dark spatial solitons in self-focusing environments or bright solitons in materials with de-focusing nonlinearities.

These experiments have opened the way to the exploration of this new class of solitons. The introduction of discreteness adds another degree of freedom, which should allow other novel families of solitons to exist. This is an interesting area that is sure to capture the attention of experimental groups in the near future.

IX. Spatio-Temporal Solitons

It is well known that self-focusing nonlinearities counteract group velocity dispersion (GVD) in optical fibers and, as a result, temporal solitons can form. It has been known for some time that in principle, a wave packet self-trapped in both space and time (an “optical bullet”) should also be possible [73]. The problem in realizing such creatures is to find the right material so that for a given optical pulse width, the dispersion length in time is comparable to the spatial diffraction length and that both are equal to the nonlinear length. In this case, the pulsed beam can be confined in all dimensions (2-D space+1-D time, (3+1)D). The stumbling block has always been that for typical materials, an unusually high GVD is required for centimeter long samples.

The first experimental work reporting a quasi-bullet used a very clever scheme to control the GVD along one spatial axis [74]. In this experiment, self-trapping occurred only along one spatial dimension of a 2-D beam. By reflecting a beam from a diffraction grating, the nonspecular orders have their energy wavefront tilted relative to their phase velocity wavefront with different spectral components having different tilts. Pulse compression in time based on this principle was first demonstrated by DeTrapani *et al.* [75] utilizing the cascaded nonlinearity in second-order nonlinear materials. The experiments of Liu *et al.* utilized quadratic solitons in the cascaded limit in bulk $LiIO_3$ with highly elliptically shaped beams. Along the long axis of the beam cross-section, the diffraction length was longer than the length of the crystal so that no diffraction occurred. Along the short axis, the diffraction length was about one third of the crystal length and it is along this axis that the beam behaved like a spatial soliton. The pulse width of 110 fs was used, with the grating-engineered GVD, to match the dispersion length to the diffraction length. Along that dimension they showed that no spreading occurred in space or in time: a characteristic of an optical bullet.

This was a landmark experiment. Very recently, self-focusing of 2-D beams in both space and time was reported [76], and it seems that the road to full 3-D optical bullets is now open.

X. Cavity Solitons

Cavity solitons are soliton-like structures trapped between reflecting surfaces [77]. This is in contrast to all of the solitons just discussed that are traveling waves. This introduces new properties and greatly widens the class of materials in which solitons may be discovered. Although there have been a number of experiments reported on patterns in resonators, the first experiments in which isolated solitons were observed were only reported very recently [78]. They utilized GaAs in a resonator and studied the spatial structure of the light reflected from the cavity. The shape of the soliton within the cavity is in excellent agreement with theory, right down to the oscillations in the tail of the soliton. By changing the cavity detuning via tuning the input light frequency, these authors were able to show dark solitons as well. They also showed some beautiful examples of collisions between cavity solitons. This was an important first experiment.

Another recent experiment [79] reports stable, controllable spatial solitons in Na vapor with a single feedback mirror. These are also dissipative structures, and many of the properties predicted for cavity solitons have been directly observed in this system, as well as in earlier experiments on feedback systems [80]. This recent progress on cavity solitons, especially in systems that do not support traveling-wave states, e.g., dissipative systems, are expected to offer many more surprises.

XI. Summary

The field of spatial soliton research, which really started back in the mid 1970s, picked up momentum in the late 1980s, and reached some maturity in the 1990s, is now a very active field. It represents a fruitful direction for nonlinear optics in the new millenium. At this point, much remains to be uncovered, and we expect rapid progress on several fronts. Many areas such as those of incoherent and vector solitons, discrete and cavity solitons, and the field of optical bullets remain still largely unexplored. Judging from the current level of activity, it is certain that this area will continue to flourish for years to come.

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