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REVIEW ARTICLE

Experiments on partially coherent photorefractive solitons

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Abstract
We provide an overview of experimental studies on partially coherent spatial solitons in photorefractive materials, including the first experimental demonstration of bright and dark incoherent solitons, incoherent vortex solitons, Y-junction dark solitons and anti-dark solitons, and pixel-like incoherent soliton arrays. These solitons are created with partially spatially incoherent light beams by using the non-instantaneous photorefractive screening nonlinearity. Experimental results on waveguides induced by incoherent solitons are also presented and their potential applications for soliton-driven photonics are discussed. In particular, these experiments introduce the possibility of controlling high-power laser beams with low-power incoherent light sources in waveguide arrays as well as in planar, circular and beam-splitting waveguides optically induced in bulk photorefractive materials.

Keywords: Incoherent solitons, photorefractive nonlinear optics, guided waves

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Solitons are localized wave entities that propagate in nonlinear media while maintaining a constant shape. They exist ubiquitously in many branches of physics such as hydrodynamics, plasma physics, condensed matter physics, and nonlinear optics. In optics, an optical beam (or pulse) propagating in a nonlinear medium will, in general, broaden due to diffraction (or dispersion). When the natural broadening is balanced by a nonlinear effect, in which light-induced lensing counteracts diffraction (or dispersion), the wavepacket forms an optical spatial (or temporal) soliton [1]. Optical spatial solitons have become the subject of active research in the early 1990s, following the discoveries of several classes of solitons in saturable nonlinear media [2]. More specifically, the discovery of photorefractive solitons made optical spatial solitons easy to observe in experiment, even with low power levels of just microwatts or so, and also offered a rich diversity of effects in a large family of versatile nonlinear materials [3]. Consequently, the study of photorefractive solitons had a major impact on soliton science at large, as many fascinating features of solitons were demonstrated first with photorefractive solitons, including interactions of three-dimensional (3D) solitons (such as spiralling, fusion and fission), multi-mode and composite solitons, random-phase solitons, etc. Equally important, optical spatial solitons provide a means for controlling light by light in a confined setting. In particular, recent work on self-trapping and light guiding in various 3D saturable nonlinear materials has opened up several avenues for possible applications of spatial solitons in optical interconnects, optical communications and other areas. For instance, nonlinear directional couplers [4], tunable frequency conversion [5] and optical parameter oscillations [6] based on photorefractive soliton-induced waveguides have been demonstrated successfully. In addition to waveguides induced by a single soliton, waveguides resulting from multiple spatial solitons and soliton arrays have been proposed for applications in optical beam steering [7].

However, before 1996, all experimental studies of solitons in optics as well as in fields beyond optics were based on coherent waves. In fact, for decades, solitons have been considered exclusively to be coherent entities. Yet, nature is full of incoherent (or partially coherent) radiation sources. One can simply focus a light beam from a natural radiation source such as the sun or an incandescent light bulb into a narrow spot, thereby creating a partially coherent light beam. Can incoherent light also self-trap and form optical solitons? More generally, can an ensemble of weakly correlated particles such as those representing partially coherent wavefronts form a self-trapped entity? This intriguing and challenging question has motivated several earlier experiments on self-trapping of incoherent light. By now, a series of experimental demonstrations [8–10] along with theoretical studies [11, 12] has provided clear evidence that incoherent bright [8, 9, 11] and dark [10, 12] spatial solitons are indeed possible in nonlinear materials, provided that these materials have non-instantaneous self-focusing/defocusing nonlinearity. This brings about the interesting possibility of using low-power incoherent light beams to form solitons, which in turn can guide and control other high-power coherent laser beams.

In this paper, we provide an overview of the experimental studies on partially coherent spatial solitons, all carried out in photorefractive materials [13]. We revisit the first experimental demonstration of bright and dark incoherent solitons, incoherent vortex solitons, incoherent Y-junction dark solitons, incoherent anti-dark solitons, and incoherent pixel-like soliton arrays. (For a comprehensive review of incoherent solitons, including also the theoretical aspects of these random-phase weakly correlated entities, see [14].) These solitons are created with partially spatially incoherent light beams, thanks to the non-instantaneous screening nonlinearity in photorefractive materials [15]. In addition, we will discuss the results of experiments on waveguides induced by incoherent solitons. These soliton-induced waveguides allow optical guidance of other beams, which may be coherent as well as incoherent. We will present 2D waveguide arrays induced by 2D arrays of pixel-like incoherent spatial solitons. Generally speaking, it has always been a challenge to create or fabricate 2D or 3D waveguide arrays in bulk media, hence our experiments pave the way for generation of nonlinear waveguide arrays in bulk materials by optical induction techniques. Optical waveguiding and optical control among waveguide channels in the arrays are readily realized experimentally. Furthermore, these stable, robust, pixel-like spatial solitons are in fact light-induced photonic lattices created in real-time. The interaction of a light beam with such a light-induced photonic lattice leads to a host of new phenomena, including lattice solitons, lattice dislocation, lattice deformation, and the creation of optical structures that are analogous to polarons in solid-state physics. Thus, 2D waveguide lattices optically induced in photorefractive materials may be of particular interest to applications as well as to fundamental research related to nonlinear periodic structures or nonlinear partially coherent systems.

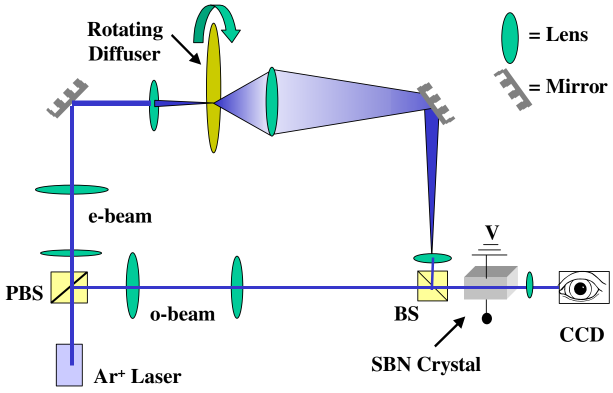

Figure 1. A typical experimental set-up for incoherent solitons. An argon ion laser beam is split into the o-beam and e-beam by a polarizing beam-splitter. The e-beam is sent through a rotating diffuser before recombining with the o-beam at the input face of an SBN crystal. Amplitude and phase masks (not shown) are used, as needed.

2. Experimental arrangement

The typical experimental set-up used for the observation of partially coherent solitons is illustrated in figure 1. An argon ion laser beam ($\lambda = 488$ nm) is split into two beams with orthogonal polarization, one being the extraordinarily polarized beam (e-beam) and the other the ordinarily polarized beam (o-beam). The e-beam is first collimated, then focused by a lens onto a rotating diffuser, thus converting into a quasi-monochromatic incoherent light source [8, 10]. The scattered light from the diffuser is collected by another lens. The rotating diffuser provides random phase fluctuations, thus turning the beam into partially spatially incoherent light. The degree of spatial coherence of the beam is determined by the ratio between the beam width and the size of the scatters upon the diffuser. One can visualize the (spatial) correlation distance and estimate it by measuring the average size of the speckles superimposed on the scattered light, as the speckle size is roughly equal to the correlation distance (the maximum distance within which any two points on the wavefront are phase correlated). One can actually trace the temporally varying speckles with a fast camera or, as we do in various experiments, monitor the speckled beam when the diffuser is stationary. The photorefractive crystal used in our experiments is typically SBN, whose crystalline c-axis is oriented perpendicular to the propagation direction of the beam. An external electric field is applied across the crystal along the c-axis. For the observation of incoherent bright solitons, the speckled beam is focused onto the input face of the crystal directly (as shown in

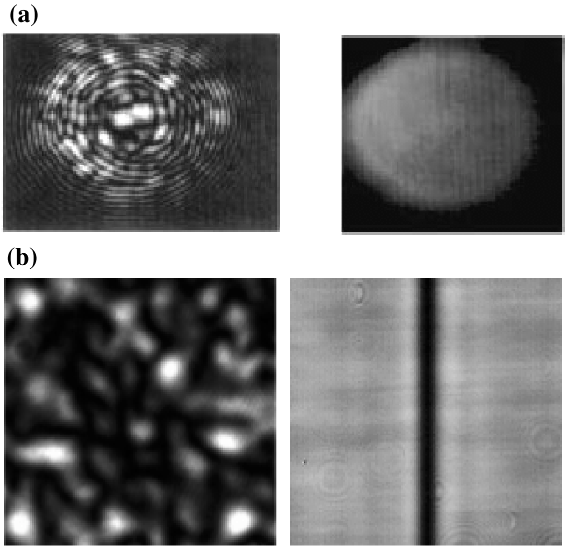

Figure 2. Photographs showing the non-instantaneous response of the photorefractive crystal: (a) interference patterns of a speckled beam and a uniform background beam; (b) intensity patterns of a speckled beam bearing a dark notch (left, diffuser stationary; right, diffuser rotating.

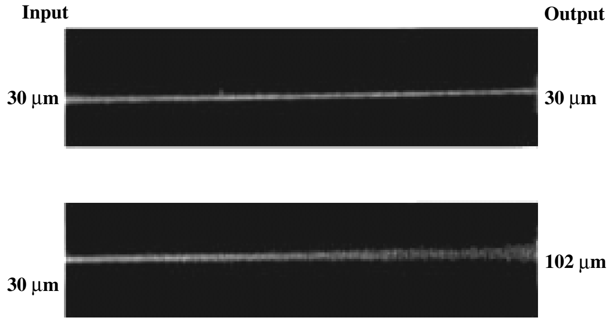

Figure 3. Self-trapping of a bright partially coherent beam. Shown are top-view photographs of the self-trapped (top) and normally diffracting (bottom) bright beams propagating inside the crystal.

figure 1). For the observation of incoherent dark solitons or soliton arrays, the speckled beam is passed through a phase (or an amplitude) mask, which is then imaged onto the crystal input face [10]. The o-beam is also collimated before entering the crystal and propagates collinearly with the incoherent soliton-forming beam. Similarly to earlier experiments on coherent photorefractive screening solitons [16–18], the o-beam is used as the background illumination necessary for steady-state self-trapping and also facilitates fine-tuning of the magnitude of the photorefractive nonlinearity (by acting as the saturation intensity in this saturable nonlinearity) [15–18]. In addition, a coherent Gaussian beam from a He–Ne laser (not shown in the figure) is used as a probe beam, when necessary, to test the waveguides induced by the incoherent solitons. The input and output faces of the crystal are monitored with an imaging lens and a CCD camera. Another CCD camera is available for top-view imaging, when needed, to monitor the beam as it propagates throughout the crystal.

The key ingredient for the generation of incoherent solitons is the non-instantaneous nature of the nonlinearity. That is, for incoherent solitons to exist, the nonlinearity must have a temporal response much slower than the characteristic time of the random fluctuation that makes the beam incoherent. Photorefractives indeed have a non-instantaneous response and their response time can be controlled by the intensity of the beam. This fact, combined with the fairly large nonlinearities offered by photorefractive crystals, makes them a convenient choice for experiments with incoherent solitons. The rotating diffuser creates random phase fluctuations on a timescale much faster than the response time of the crystal, so the crystal can only respond to a time-averaged intensity pattern. The outcome of such a non-instantaneous response can be observed clearly in figure 2. When a speckled beam from the diffuser is sent to interfere with a plane wave (a broad uniform beam), one can see interference fringes superimposed upon a speckle pattern only when the diffuser is stopped (figure 2(a)). When the diffuser is rotating and the interference pattern is monitored with a camera whose response time is much faster than that of the photorefractive crystal, no interference or speckles can be observed since all the phase information is washed out. The photorefractive medium responds only to the time-averaged intensity pattern, thus it 'sees' a smooth time-averaged pattern rather than the rapidly varying speckled pattern [8]. Interestingly enough, this non-instantaneous response can be also employed for the generation of dark solitons that typically have non-uniform phase across the beam. In figure 2(b), a speckled beam is launched onto a phase mask (a $\tilde{\lambda}/4$ step mirror, as used previously for coherent dark screening solitons [17]) and then the reflected beam is redirected to the photorefractive crystal. When the diffuser is stationary, what the crystal 'sees' is the speckled pattern, without 'noticing' the phase jump created by the step mirror in the midst of the random phase fluctuations. However, as the diffuser rotates on a timescale much faster than the response time of the crystal, the crystal 'sees' a dark stripe superimposed on a smooth intensity profile [10]. This illustrates again that our photorefractive crystal responds to the time-averaged envelope and not to the instantaneous speckles.

3. The first experiment on bright incoherent solitons

The first experiment on the self-trapping of a bright partially incoherent optical beam was performed in a photorefractive SBN:75 crystal, which had an electro-optic coefficient of $r_{33} = 1022$ pm V^{-1}. Self-focusing occurred with the application of an appropriate bias electric field (magnitude and polarity). The self-trapping experiments were performed using input beams with a ratio of diameter to speckle size of roughly 8. The size of the beam at the crystal input face was 30 μm (FWHM) which diffracted, in the absence of self-trapping, to 102 μm (FWHM) after 6 mm of propagation through the crystal. (The large diffraction of this spatially incoherent beam exemplifies the difference from a spatially coherent beam, which would have diffracted to 35.75 μm for the same distance.) The application of 550 V between the electrodes, separated by 6 mm, resulted in self-trapping of the beam, which maintained a constant width of 30 μm. Figure 3 shows top-view photographs of the self-trapped (top) and the normally diffracting (bottom) beams. The input widths of both beams in these photographs appear larger than in reality due to the limited dynamic range of the camera and the need to view the beam throughout the slightly absorbing crystal, which causes some saturation near the input, making it appear somewhat wider. A series of similar experiments with other quasi-homogeneous spatially incoherent beams was performed. It was found that self-focusing and self-trapping of incoherent beams in photorefractive media are dominated by several factors, including the beam diameter, the speckle size on the beam, the applied field across the crystal, and the ratio of the beam peak intensity to the intensity of the background o-beam. Compared to earlier experiments on coherent photorefractive screening solitons [16–18], a new feature, i.e. the coherence of the beam, came to play roles for incoherent solitons. This has no counterpart whatsoever in all the coherent solitons studied previously.

This first demonstration of optical spatial solitons from partially coherent light was soon followed by experimental demonstrations of self-trapping of a 'fully' incoherent white-light beam from a simple incandescent light bulb [9] as well as self-trapping of a 'dark' incoherent light beam [10]. These experimental observations surely motivated the theoretical studies towards understanding incoherent solitons. Soon thereafter, several theoretical approaches were developed, including the coherent density theory, the modal theory, the theory describing the propagation of mutual coherence, and the simplified ray-optics approach [11]. The real success of the theories explaining incoherent solitons was in their ability to come up with exciting new predictions, some of which suggest truly fascinating phenomena. It became very clear right from the start that incoherent solitons are not some esoteric creatures specifically related to photorefractives, but rather form a general and rich new class of solitons, whose existence is relevant to diverse fields even beyond nonlinear optics [14]. Indeed, in a number of subsequent experiments, novel phenomena arising from incoherent self-trapping and incoherent modulation instability (MI) [19] were observed, including incoherent anti-dark solitons [20], incoherent pattern formation [21, 22], soliton clustering in weakly correlated wavefronts [23], and photonic lattices induced by partially coherent light [24]. The underlying physics of the observed phenomena may relate to other weakly correlated wave systems which have a non-instantaneous nonlinearity.

4. The first experiment on dark incoherent solitons

'Dark beams' are non-uniform optical beams that contain either a one-dimensional dark stripe or a two-dimensional dark hole resulting from a phase singularity or an amplitude depression in their optical field. For decades, self-trapped dark beams (dark solitons) have been observed using coherent light only. The first experimental demonstration of self-trapped dark incoherent light beams (self-trapped dark incoherent wavepackets) came in 1998 [10]. Both dark stripes and dark holes nested in a broad partially spatially incoherent wavefront were self-trapped to form dark solitons in a host photorefractive medium, which in turn created refractive-index changes akin to planar and circular dielectric waveguides.

Based on the knowledge of coherent dark solitons [25], one may speculate that the transverse phase also plays a crucial role for incoherent solitons. Fundamental 1D coherent dark solitons require a transverse π phase shift at the centre of the dark stripe, whereas an initially uniform transverse phase leads to a Y-junction soliton. Furthermore, 2D coherent dark solitons (vortex solitons) require a helical $2m\pi$ transverse phase structure. Extending the idea of dark coherent solitons to dark incoherent solitons raises several questions. If dark incoherent solitons were to exist, is their phase structure important (as for coherent dark solitons) or irrelevant (as 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? Altogether, even though the bright incoherent solitons have been demonstrated experimentally [8, 9], the possibility for dark incoherent solitons to exist was not at all clear. Motivated by these questions, the coherent density approach was employed first for studying the propagation of an incoherent dark beam in biased photorefractives [12]. Surprisingly, it was found that, although an arbitrary dark stripe-bearing incoherent beam experienced considerable evolution during propagation, it eventually stabilized around a self-trapped solution. Such a self-trapped dark incoherent soliton required an initial transverse π phase jump and, after self-trapping, it was always 'grey' (instead of 'black', as expected for a coherent dark soliton with a π phase jump [25]). This theoretical work, although not providing clear answers to the questions raised above, did suggest that dark incoherent solitons should exist. Indeed, almost in parallel with this work came the first experimental demonstration of the self-trapping of a dark incoherent light beam [10]. Shortly thereafter, the modal theory of incoherent dark solitons was developed [13], which revealed the underlying mechanism of such solitons. It was found that incoherent dark solitons were actually associated with self-induced waveguides involving both bound states (guided modes) and the continuous belt of radiation modes. This 1D theory of incoherent dark solitons provided a qualitative explanation of the experimental observations, such as why a π phase jump was needed to initiate the dark incoherent solitons and why the observed dark incoherent solitons were always grey [13, 14].

The first experiment on dark incoherent solitons [10] was performed with a diffused laser source, as described above. The scattered beam from the rotating diffuser was reflected from a $\lambda/4$ step mirror or a helicodial phase mask before entering a SBN:60 ($r_{33} = 250$ pm V^{-1}) crystal. A dark notch or a vortex hole nested on an otherwise smooth 'speckle-free' spatially incoherent beam was created due to the non-instantaneous response of the crystal (figure 2(b)). Typical experimental results of self-trapping of a dark incoherent beam are shown in figure 4, where the top row is for a 1D dark incoherent soliton and the middle and bottom rows are for a 2D vortex incoherent soliton. At the crystal input face the dark notch was 18 μm (FWHM) wide and it diffracted to 38 μm after the 11.7 mm of propagation when nonlinearity was not present. By applying a field of 850 V cm^{-1}, self-trapping of the dark notch to its initial size was achieved. As explained earlier, such incoherent trapping could occur only in non-instantaneous nonlinear media. When the rotation of the diffuser was stopped, the self-defocusing medium responded to the 'instantaneous' speckles, which fragmented the beam and prohibited self-trapping of the dark notch. Compared with coherent dark solitons, it was observed

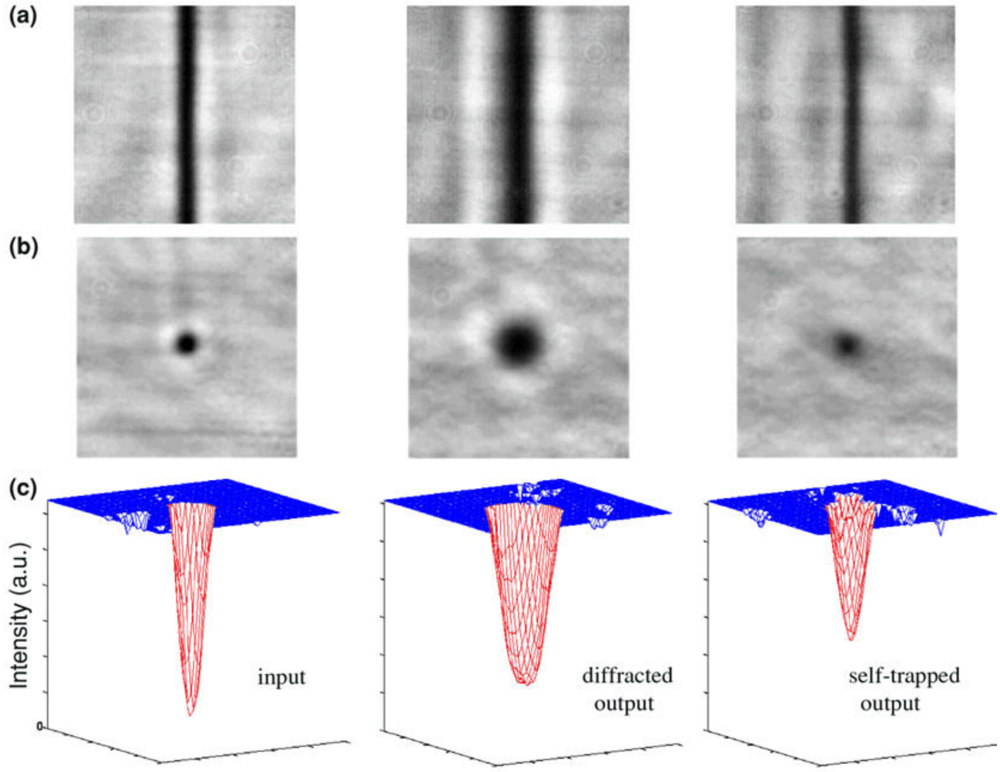

Figure 4. The self-trapping of a dark partially coherent beam. Shown are photographs of the transverse intensity patterns from (a) a dark stripe beam and (b) and (c) from a dark vortex beam taken at the crystal input face (left), the output face with linear diffraction (middle), and the output face with nonlinearity (right).

that incoherent dark solitons were always grey (with their greyness depending on the beam coherence). This observed behaviour was confirmed by numerical simulations, and was also in agreement with theoretical predictions. Figures 4(b) and (c) display experimental results obtained using a 2D incoherent dark soliton (a 2D dark 'hole' on a uniform intensity background). The self-trapped 'hole' was again grey, and it became less visible when the beam was made more incoherent. However, even when the greyness was large and the self-trapped 'hole' was almost invisible, one could still monitor its presence via its induced waveguide [10].

Following this first experiment, a few other experiments were performed for the study of dark incoherent solitons. In particular, dark incoherent soliton Y-splitting and associated 'phase-memory' effects were investigated, and it was found that dark incoherent solitons are characterized by strong 'phase-memory' effects that are otherwise absent in the linear region [26]. Using an amplitude mask (which provides the 'even' input conditions for Y-junction dark solitons [25]), a dark incoherent Y-splitting soliton was observed experimentally. Interestingly enough, as the coherence of the dark beam decreases, the greyness of the soliton increases, but the spacing between the branches of the soliton Y-splitting at the crystal output remains the same as discussed in [26]. In separate experiments, such a dark incoherent Y-junction soliton was shown to be able to induce a Y-splitting waveguide that could be used for guiding other beams [27]. Typical experimental results for beam-splitting waveguides are shown in figure 5. Although we employed a quasi-monochromatic spatially incoherent light source, our experiments suggest that spatial solitons formed from 'fully' (temporally and spatially) incoherent light sources (e.g. incoherent white light) might also be able to induce waveguides capable of guiding other coherent and incoherent beams.

5. Anti-dark incoherent solitons

Anti-dark solitons are self-trapped 'bright' (localized) wavepackets that reside on a non-zero background [28]. Because these solitons are bright-like, they exist only in self-focusing media. In the coherent limit, anti-dark solitons tend to rapidly disintegrate during propagation since the non-zero background suffers from MI [29]. Thus, coherent anti-dark solitons have never been realized in experiment due to inevitable coherent MI that breaks the broad background beam apart.

On the other hand, if the background nesting the bright soliton is made sufficiently incoherent, the resulting anti-dark soliton as a whole can be stable, as demonstrated in [20]. This is because of the unique properties of incoherent MI, which were first investigated theoretically in [19]. According to the theoretical prediction, incoherent MI occurs only when the value of the nonlinearity exceeds a threshold imposed by the degree of spatial coherence. Below the threshold, incoherent MI could be entirely eliminated. Thus, by using a partially incoherent background beam with a varying degree of spatial coherence, one can make the anti-dark soliton stable or unstable in a self-focusing nonlinear medium.

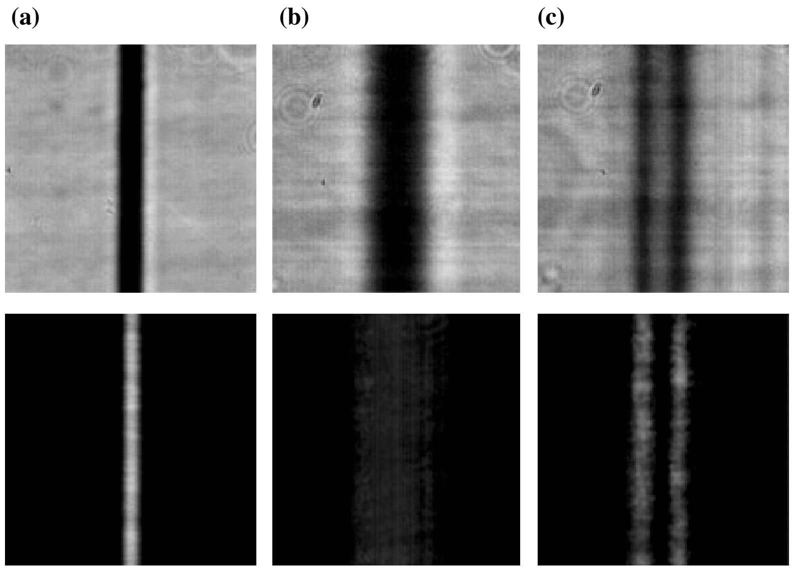

Figure 5. Photographs showing the self-trapping of a Y-splitting incoherent soliton (top) and the guidance of a probe beam (bottom) by the soliton-induced Y-splitting waveguide: (a) input, (b) output with linear diffraction, and (c) output with nonlinearity.

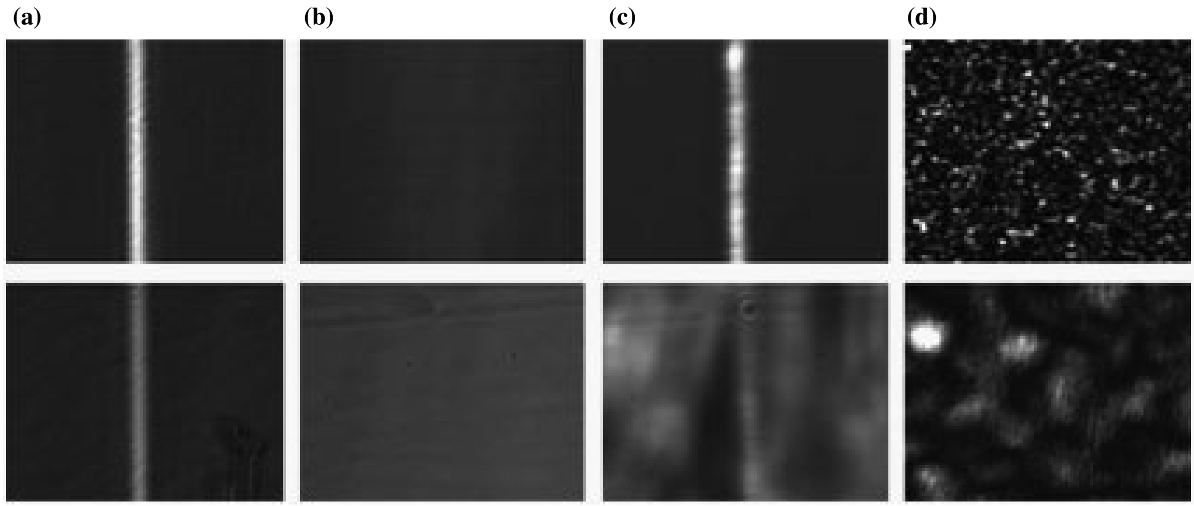

Figure 6. Experimental observation of a stable (top) and unstable (bottom) anti-dark soliton on a partially coherent background beam. Shown are photographs of (a) input beam, (b) output diffracted beam, (c) output self-trapped beam, and (d) speckled background beam.

The incoherent anti-dark soliton experiment was performed in a 20 mm-long biased photorefractive SBN:60 crystal. The experimental set-up was similar to that shown in figure 1, except that the background beam was extraordinarily polarized and partially incoherent. Typical experimental results are presented in figure 6 for two different degrees of spatial coherence. When the background beam was made sufficiently incoherent (with a correlation distance of about 5 μm or less), stable trapping of anti-dark solitons was achieved (figure 6, top). However, when the background beam was made more coherent (with a correlation distance of about 20 μm or more), stable trapping of the anti-dark beam could not be realized (figure 6, bottom) because, for a beam with such a degree of coherence, the nonlinearity was well above the threshold for incoherent MI to occur. In both cases, the trapping voltage was set to 1320 V over the 5.6 mm-wide crystal. The application of a higher voltage while keeping the coherence of the beam fixed led to MI. That experiment was the first demonstration of stable anti-dark spatial solitons in any nonlinear media. It also provided a proof of concept that incoherent MI occurs only when the nonlinearity exceeds a certain threshold value imposed by the beam coherence [19].

Following a similar approach, an incoherent two-component soliton of anti-dark shape was generated, in which a broad incoherent dark beam was coupled with a focused coherent bright beam, forming a stable coherent–incoherent vector–soliton pair [30]. Such a bi-modal soliton structure cannot be stable due to MI in a self-focusing medium if both beams are coherent, as was shown both in theory [31] and in experiment [32]. With spatially incoherent light, however, the MI can be greatly reduced or eliminated, provided that the nonlinearity is below the threshold for incoherent MI to occur. In fact, the possibility of suppressing MI via coherence control has opened up new avenues for investigating soliton structures

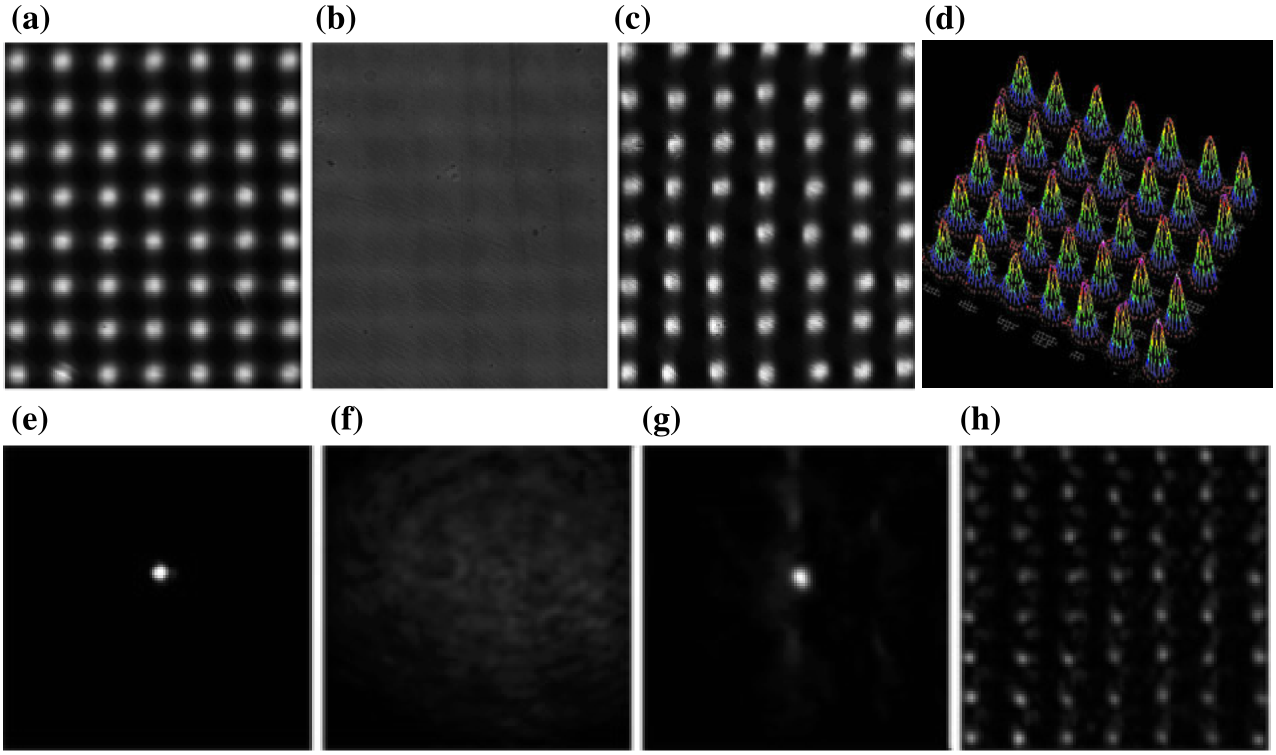

Figure 7. Spatial soliton pixels of partially incoherent light. Shown are intensity patterns from (a) the input, (b) output with linear diffraction, (c) output with nonlinearity, and (d) output 3D-intensity plot of (c). The bottom row shows a Gaussian-like probe beam at (e) the input, (f) linear output, (g) output with soliton-induced waveguides, along with (h) a plane-wave probe beam guided into waveguide arrays.

that would otherwise have been impossible to observe with coherent light. Such entities include, in addition to anti-dark solitons, stable incoherent 1D bright solitons in bulk Kerr-type media [33], incoherent ring-shaped solitons [34], and incoherent pixel-like spatial solitons [24].

6. Pixel-like incoherent solitons

Pixel-like spatial solitons and soliton-based waveguide arrays are of particular interest because of their potential applications in signal processing and information technology [35]. Yet, it has always been a challenge to create (or fabricate) a closely spaced two-dimensional soliton array or a 2D waveguide array. Recently, pixel-like spatial solitons were studied in a semiconductor microcavity [36] and in a cavityless optical parametric amplifier [37]. In all those previous studies, spatial soliton arrays were generated with coherent light waves.

Very recently, pixel-like spatial solitons from partially coherent light were demonstrated successfully [24]. These soliton pixels were created under critical experimental conditions (e.g. the degree of beam coherence, the strength of nonlinearity, and the spacing between nearby pixels) which relate to the growth of the induced incoherent MI [38]. For example, when a spatially coherent e-beam was used instead, even at a much lower strength of nonlinearity, the beam tends to break up into many disordered filaments rather than ordered soliton arrays due to strong coherent MI. This experiment brings about the possibility of optically inducing reconfigurable photonic lattices with low-power incoherent light.

The incoherent soliton-pixel experiment was performed in a 20 mm-long biased photorefractive SBN:60 crystal ($r_{33} = 280$ pm V^{-1}). An array of as many as 32×32 soliton pixels was established. Nonlinear propagation of a spatially modulated partially coherent beam led to the formation of stable soliton pixels, provided that the coherence of the beam and the strength of nonlinearity were set at appropriate values. In general, a broad, uniform and partially coherent e-beam tends to break up into many disordered filaments due to incoherent MI [19]. However, under certain conditions, ordered patterns as well as clusters of quasi-solitons in incoherent (weakly correlated) wavefronts were observed [21–23]. When the incoherent beam was periodically modulated initially, robust 2D pixel-like spatial solitons were observed [24]. Such pixel-like solitons created a 2D waveguide lattice in steady state, as tested by a probe beam. Figure 7 shows a typical example. At the input to the crystal, the incoherent beam (whose correlation distance was 20 μm) had a grid-like intensity pattern, as spatially modulated by an amplitude mask. Without the bias field, each incoherent intensity spot diffracted dramatically, and the diffraction washed out the fine structures in the beam after 20 mm of propagation through the crystal. When an electric field of 2400 V cm^{-1} was applied and the crystal reached a steady state, the output intensity pattern became almost identical to the input pattern, forming a niche array of spatial solitons. For this experiment, each soliton had a FWHM of about 30 μm and the spacing between solitons was 70 μm. In separate experiments, a 56×56 lattice with a much smaller spacing was also generated. Once the 2D array of spatial solitons was created, a probe beam of a longer wavelength was launched, either as a focused beam into one of the solitons or as a broad beam illuminating the entire 2D soliton lattice. Strong guidance of the probe beam within the waveguide channels induced by the incoherent soliton lattice was observed (figure 7(h)). In addition, local coupling in the waveguide lattice was demonstrated successfully by introducing an additional ‘control’ beam between adjacent solitons [24].

Pixel-like solitons and nonlinear waveguide arrays are of particular interest, apart from their potential applications. This is because their collective behaviour as an array of self-localized nonlinear waves exhibits many intriguing phenomena, such as discrete self-focusing and discrete solitons, that are also found in other nonlinear discrete systems [39, 40]. Recently, it has been suggested that discrete solitons could be created in a waveguide array optically induced in photorefractive materials [41]. Indeed, such discrete solitons were observed in waveguide lattices induced by coherent multi-beam interference in a SBN:75 crystal [42, 43]. In those experiments, the interfering beams are ordinarily polarized, hence these ‘array-forming beams’ propagate linearly while inducing a stationary (distance-independent) 2D array of waveguides that maintains its form even at high bias fields. If the arrays are induced with partially coherent light, the waveguide arrays could be made either linear or nonlinear and stable in both regimes. Many fascinating behaviours of light in such partially coherent light-induced photonic lattices could be studied. In fact, very recently, 2D discrete solitons as well as lattice dislocation, lattice deformation and the creation of structures akin to optical polarons have been demonstrated successfully with a stable partially coherent lattice [44].

7. Summary

We have provided a brief overview of experimental studies on partially coherent spatial solitons in photorefractive materials. For a more complete review, including theoretical studies of incoherent solitons along with other aspects of incoherent solitons and incoherent MI, we refer the reader to [14]. The rapid progress in this new area of incoherent solitons brings about many interesting fundamental ideas as well as possible applications. For example, the exciting ability to obtain self-trapped light beams from incoherent sources such as LEDs for reconfigurable waveguides may find applications in optical interconnects and beam steering. Self-trapping of incoherent wavepackets brings about interesting nonlinear phenomena which are related to many other nonlinear systems of weakly correlated particles, in which nonlinearities, stochastic behaviour and statistical (ensemble) averaging are involved. The closest immediate example is in cooled atomic gases, where the nonlinearity results from interactions between atoms (an ensemble average of head-on collisions) [45]. Already, many studies on coherent solitons in nonlinear optics have had a large impact on research in Bose–Einstein condensates. We believe that the studies on incoherent solitons will prove to be relevant to many other nonlinear weakly correlated systems as well.

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