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Solitary beam formation with partially coherent light in an anisotropic photorefractive medium

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Abstract
We report on the stable self-focusing of light for various degrees of spatial coherence. Since the diffraction of a partially spatial coherent light beam is mainly governed by the transverse correlation width, its self-focusing is generally non-trivial. Here, we systematically demonstrate that partially coherent solitons can be generated in a non-instantaneous nonlinear material when the external parameters are properly adapted to the degree of coherence of the light beam.

Keywords: Spatial solitons, incoherent light, photorefractive optics, nonlinear optics

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

1. Introduction

The phenomenon of stable self-focusing of a light beam—commonly denoted as a spatial optical soliton—has attracted considerable attention throughout the last two decades (see [1–3] for an overview). Solitons are known to exist in many nonlinear systems among which nonlinear optics provides an ideal platform for detailed investigations and promising implementations. They can evolve when the inherent wave broadening due to diffraction is compensated for by a nonlinear effect induced by the wave itself. For the case of a Kerr-like nonlinear medium, a light beam may induce a refractive index modulation resembling a waveguiding structure. Consequently, a soliton forms when the transverse profile of the light wave matches an eigenmode of this optically-induced waveguide. In this case, the wave ideally propagates in a diffraction-less way, i.e. it propagates without attenuation while simultaneously maintaining its transverse profile.

A significant feature of spatial solitons is their capability to serve as an all-optical guiding and steering device for other light beams. For example a soliton induced by a light beam in the green wavelength region is capable of guiding an otherwise diffracting beam of red light, to which the nonlinear medium is insensitive [4, 5]. Therefore, (2 + 1)-dimensional solitons in saturable nonlinear media, such as a photorefractive crystal, have become a very promising and versatile tool for the implementation of all-optical coupling and steering devices [6].

So-called scalar solitons display a single-mode internal structure in the sense that only the particular light beam inducing the waveguiding structure can self-trap. Multi-mode solitons in contrast are much more attractive for applications in waveguiding. They obviously provide a larger bandwidth and enhanced loss-less guiding capabilities. We were able to show recently that by shifting or changing the angle of the incoming beam slightly, a limited number of higher-order modes can be excited in a waveguide induced by a scalar soliton [5]. However, a more efficient approach for producing a multi-mode self-trapped beam is by making use of partially spatial coherent light, leading to the formation of incoherent solitary beams. As described by the modal theory for partially incoherent solitons [7] incoherent light can be interpreted as an incoherent superposition of numerous coherent modes all displaying a different transverse profile. Increasing the number of the participating modes reduces the overall degree of coherence of the total light distribution. Therefore, incoherent solitons intrinsically represent multi-mode waveguides that can guide a large number of different transverse optical modes (see [8] for an overview). Another approach postulates the existence of big incoherent solitons [9], with a large transverse diameter. In contrast to that, the transverse size of coherent solitary waves is limited by the diffusion length of the charge carriers involved in the refractive index modulation. Typically, a large coherent beam becomes subject to small-scale self-focusing and disintegrates into a number of small segments [10]. This intrinsic modulation instability might be prevented by means of partially coherent light.

The guiding of light by means of incoherent dark solitons has been successfully demonstrated by Chen *et al* [11, 12]. Furthermore the guiding of light by bright incoherent solitons has been reported lately [13] as well as the transmission of complex transverse light structures through a highly nonlinear medium by gradient-index waveguides formed by incoherent solitons [14].

Moreover, the utilization of light sources with a low degree of spatial coherence in soliton-driven photonics is very attractive by itself. A coherent but quite costly laser light source could be replaced by a low-cost light source such as a light emitting diode (LED) typically featuring a poor transverse coherence radius.

Self-focusing of partially spatial coherent light differs drastically from that of a coherent light source. Its propagation characteristics are not only governed by linear diffraction but also by the correlation distance determining its degree of coherence. The smaller the correlation distance, the larger the angular spreading of the light beam upon propagation.

In 1997 Mitchell and Segev [15] demonstrated the self-trapping of incoherent white light which is partially coherent in the spatial as well as in the temporal domain. The spectrum of the light beam derived from an incandescent source ranged from 380 to 520 nm. In this distinct case, Mitchell and Segev made use of a photorefractive nonlinear crystal featuring an extremely high sensitivity over the entire spectral range of the light source. In order to trap temporally incoherent light, the medium only has to fulfil the prerequisite that its response time is far above the characteristic fluctuation time of the light beam. In another experiment Mitchell *et al* [16] demonstrated the successful self-trapping of a monochromatic beam with a reduced spatial correlation distance. In this paper, Mitchell *et al* only investigated a single particular degree of spatial coherence. They showed that a partially coherent beam featuring a stronger divergence compared to a coherent beam can self-trap in a saturable nonlinear medium.

Stable self-focusing can only be achieved when the divergence of the incident light beam, and hence the diffraction, is exactly counterbalanced by the nonlinearity of the medium. Since a partially coherent beam experiences a larger diffraction than its coherent counterpart, the nonlinearity of the medium has to be properly adapted. In the present publication we focus on the specific dependence between the degree of coherence and the appropriate nonlinearity that is necessary in order to achieve stable self-trapping of a partially coherent light beam. We especially focus on how far external boundary conditions have to be adapted when the degree of coherence of a light beam is modified. Furthermore, and in contrast to previous work [16], we take into account aspects of anisotropy of the nonlinear medium of choice, a DC-electric field biased

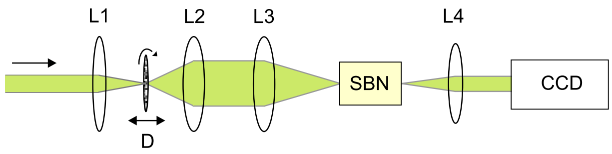

Figure 1. Experimental setup for the generation of quasi-homogeneous spatially incoherent light. With the help of lens L1 the coherent laser beam is focused onto a rotating diffuser D. Depending on its transverse size and the granularity of the diffuser, a speckled light structure evolves, which is collimated and focused into the crystal by the system of lenses L2 and L3. By shifting the diffuser, various degrees of coherence can be generated.

photorefractive strontium barium niobate (SBN) crystal. This specific medium features a saturable nonlinear response, with an upper threshold for the induced refractive index modulation. Due to this property a lower threshold for the degree of coherence beneath which stable self-focusing no longer occurs might also be observable. Since the material features an anisotropic nonlinear response [17, 18] we especially take into account the transverse shape of the evolving light structures. Moreover it is an open question, whether a reduced degree of spatial coherence has an impact on the ellipticity of the incoherent soliton.

2. Experimental Setup

Incoherent light, such as light from an incandescent source, can be represented as the time-averaged intensity of a large ensemble of uncorrelated light emitters on a microscopic scale. Suppose the duration τ of a single light emitting process is much smaller than the relevant material's response time τ_r, i.e. the statistic fluctuations of the source are on a timescale much shorter than the material's response time. In this case, only a time-averaged and hence quasi-homogeneous intensity would have an impact on the nonlinear medium and would lead to an optically-induced refractive index modulation. The non-instantaneous response of the nonlinear optical material is a general prerequisite for the generation of incoherent solitons [8].

In our experimental system we make use of a photorefractive cerium-doped (0.002% by weight) strontium barium niobate crystal (SBN:60), for several reasons. First of all, and as required, the medium's response time is in the range of several seconds, which is far beyond the typical fluctuation time of the light source. Second, the strength of the nonlinearity can be controlled by an externally applied electric field and arbitrarily modified.

We derive partially spatial coherent light by passing a laser beam through the system of lenses L1 and L2 and a rapidly rotating diffuser D as depicted by figure 1. Subsequently the beam is focused with the help of the lens L3 on the front face of the SBN crystal. Depending of the degree of coherence, the focal spot size varies between 21 and 44 μm and the beam linearly diffracts to a size between 36 and 180 μm after propagating through the 13.5 mm long crystal sample. Lens L4 projects the crystal's exit face onto a charge-coupled device (CCD) camera and the self-focusing process can directly be monitored when an external voltage of 2–5 kV cm^{-1} is applied across the 5 mm long crystallographic c-axis thus making use

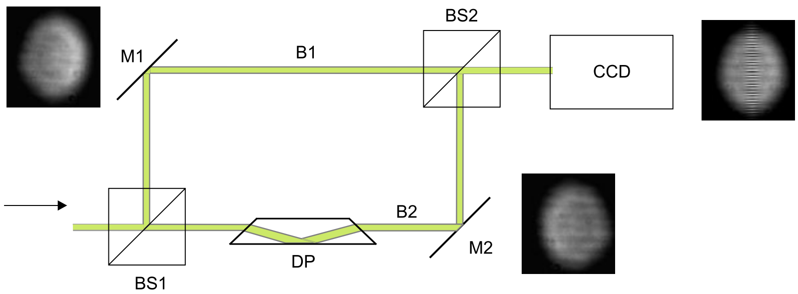

Figure 2. Sketch of the interferometer, inserted between imaging lens L4 and CCD camera. The dove prism, DP, inverts the geometry of beam B2 vertically and, after superimposing B1 and B2 with the beam splitter BS2, the evolving interference pattern indicates the transverse correlation lengths which determine the coherence of the beam. The grey-scale pictures illustrate the intensity distribution of the two separate beams, and the corresponding interference pattern.

of the electro-optic coefficient $r_{33} = 180$ pm V^{-1} of our crystal sample. Additionally the crystal is illuminated with incoherent white light to tune its degree of saturation. The intensity of the white light was measured in a separate two-beam coupling experiment. We finally ensure that the ratio between the total power of the beam and the background illumination is in the range of unity, allowing for the generation of stable photorefractive solitons [17].

The diffuser D destroys the initially homogeneous phase front of the light beam. It introduces a random speckled pattern onto the light beam, which becomes quasi-homogeneous when the device rotates with such a speed that the single speckles fluctuate on a timescale τ which is far beneath the detector's or the material's response time τ_r. Lens L1 focuses the coherent light beam on the diffusive device. Depending on the position of the diffuser, the beam is segmented into a number of fragments. When the diffuser is placed outside the focal plane, the number of fragments increases and the degree of coherence of the light beam decreases. With this technique we are able to artificially generate various degrees of spatial coherence. But in order to gather quantitative results, we still have to determine the light's degree of coherence. Since both the beam radius as well as the correlation distance (or speckle size) increase upon propagation, a measurement of the correlation distance always depends on the distance to the light source. However, for propagation in free space, the ratio between the transverse correlation distance and the width of the beam is a constant of propagation. This ratio is well-known as global degree of coherence q [19] and can therefore be utilized to sufficiently characterize the degree of coherence irrespective of the distance to the source. Since the beam size is directly accessible, the experimental task of determining the light's degree of coherence now reduces to measuring the transverse correlation distance across the beam.

Whereas in previous studies [16] the correlation distance was estimated from the size of the speckles when the diffuser is turned off, we make use of an interferometric arrangement that provides a more accurate access to this relevant parameter. An additional interferometer of Mach–Zehnder type (depicted by figure 2) is inserted in the setup (figure 1) between the imaging lens L4 and the CCD camera. In the lower interferometer arm, the dove prism vertically flips the transverse geometry of beam B2. When B2 and B1 are superimposed, the length of the resulting interference fringes gives a direct access to the transverse correlation length of the partially coherent light

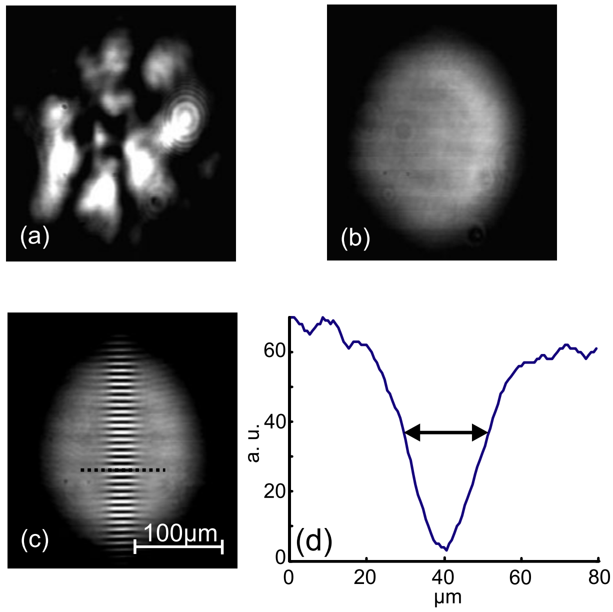

Figure 3. A diffracting light beam for $q = 0.18$ when the diffuser is in a stationary state (a) or in the rotating mode (b). The interference fringes that evolve from the superposition of the vertically flipped beam B2 with beam B1 are illustrated in (c). The dotted horizontal line indicates a cross-section whose intensity profile is illustrated in (d).

beam. By shifting the imaging lens L4, both the crystal's front and exit face, can be projected onto the CCD camera for the case when the bias voltage is turned off and the crystal operates in its linear regime. For the given granularity of the diffuser and the specific system of lenses the resulting degree of global coherence q ranges from $q = 0.37$ to 0.12. A further reduction of the degree of coherence was not possible due to the fact that for lower degrees of coherence the transverse size of the light beam exceeds the aperture of the lens L2.

Figure 3(a) depicts the crystal's exit face for a non-rotating diffuser and a spatial coherence of $q = 0.18$. In this case, the transverse phase structure is non-uniform as can be seen from the numerous light patches that are imprinted on the beam by the diffusive element. When the diffuser is set in motion and rotates at high speed as depicted in figure 3(b), the crystal as well as the camera only detect a smooth quasi-homogeneous intensity distribution. The dotted line in figure 3(c) indicates a cross-section whose intensity profile is given in the plot in figure 3(d). Since the interference fringes cease smoothly in the horizontal direction we always refer to the full width at half maximum (FWHM) of the depicted intensity profile in order to determine the correlation radius of the light beam. In this case, it is measured to be 25 μm as indicated by the arrows.

3. Experimental results

With the help of the setup depicted by figure 1, we generate four different degrees of coherence $q = 0.37$, 0.31, 0.18 and 0.12. These light beams are subsequently focused into the biased photorefractive medium. Recording the evolving transverse light structure at the exit face of the crystal generally reveals a remarkable self-trapping effect when the crystal is appropriately biased. Moreover, for each different degree of coherence the beam self-traps to a transverse size which is in the range of its initial diameter. By gradually decreasing the coherence of the light beam, the external voltage has to be raised constantly.

The entire scenario is illustrated in figure 4 for the four different degrees of partially coherent light in the four rows (b)–(e), and the coherent case in (a). The single frames in each row of figure 4 illustrate the incident light beam at the crystal's front face and its diffracted profile after a linear propagation of 13.5 mm through the crystal when the external voltage is turned off. The third frame reflects the correlation distance which is obtained by the interference experiment described by figure 2 and the last frame shows the most effective self-focused light structure for the appropriate voltage.

Figure 4(a) depicts the coherent scenario when the diffuser is absent. The incident beam has a focal spot size of 21 μm and diffracts to 36 μm in the linear case. The interference fringes in the third frame indicate that the phase front of the beam is homogeneous as required for a coherent beam. Applying a voltage of 1 kV, the well-known photorefractive screening soliton evolves, which displays an elliptical shape of 18 μm in the horizontal and 30 μm in the vertical direction. Effective self-trapping already occurs at this low voltage because the beam is not subject to strong diffraction. Its focal spot size is fairly large—consequently its diffraction is small—compared to typical experiments of screening soliton formation [3].

For the partially coherent scenarios depicted in figures 4(b)–(e) this changes dramatically. With decreasing coherence, the focal spot size as well as the width of the diffracting beam increases. For an otherwise coherent beam, diffraction would gradually decrease for a larger incident light beam. Therefore, the larger diffraction is mainly governed by the succeeding decrease of the light beam's degree of coherence. By introducing the rotating diffuser, the minimum spot size of the beam increases to 28 μm. It diffracts to 85 μm (FWHM) at the crystal's exit face as depicted in figure 4(b). The correlation distance is determined to be 32 μm and consequently $q = 0.37$. When an appreciably higher voltage of 2.1 kV is applied, the entire beam becomes tightly focused and displays a remarkable elliptical shape of 15 μm in the horizontal and 40 μm in the vertical direction.

Comparing the external voltage of $V = 2.1$ kV that has to be applied in order to trap the partially coherent beam in figure 4(b) with the voltage of $V = 1$ kV necessary for self-trapping in the coherent case, illustrated in figure 4(a), it is obvious that self-focusing of a partially coherent beam can only be produced when the external voltage is appreciably raised. The two intermediate scenarios for $q = 0.31$ and 0.18 are illustrated in figures 4(c) and (d). In both cases, a stable self-focusing can be generated when the external voltage is increased to values of 2.1 and 2.3 kV, respectively.

Finally, for the lowest degree of spatial coherence of $q = 0.12$, the focal spot size measures only 44 μm and the beam broadens to more than 180 μm in the linear regime. Optimized self-trapping can be obtained when the external voltage is raised to 2.5 kV (see figure 4(e)). In this case the general self-trapping effect weakens and the structure features a large ellipticity. In the horizontal direction the solitary beam measures 40 μm which is in the range of its incident profile, but the structure remarkably stretches vertically to about 77 μm.

As a general result, the self-trapping of partially coherent light has been successively demonstrated for various degrees of coherence up to a correlation distance which is about eight times smaller than the beam's transverse size ($q = 0.12$). In comparison to previous studies [16] and to the case of a coherent beam, the bias voltage has to be increased by at least a factor of 2–2.5 to compensate for the larger diffraction of the light beam due to the partial coherence.

In order to analyse this behaviour in a more detailed way and taking into account the anisotropic nature of the refractive index change, we illustrate the dependence of the beam diameters on the applied voltage for various degrees of coherence in figure 5. The beam power of 4.5 μW, as well as the background illumination which is in the same order of magnitude, are kept constant. The curves connecting the data points in the plots of figure 5 are guides to the eye. Both graphs reflect the generic behaviour that the beam size decreases with increasing voltage, but their horizontal and vertical diameters display a slightly different course, hence the ellipticity of the self-trapped beams changes with increasing voltage. This might be attributed to the anisotropy of the soliton formation process induced by the applied external voltage along a preferred transverse direction. As can be seen from figure 5(a), the vertical size d_y of the beams remains almost unaffected until the applied voltage reaches values of 750–1250 V. With increasing voltage, the beam radius drops down remarkably and reaches its minimum size, which is at higher voltages when the spatial degree of coherence is lower. Whereas the minimum vertical width for $q = 0.37$ and 0.31 is reached for a voltage of 1700 V, it shifts to values of 2100 and 2500 V for $q = 0.18$ and 0.12, respectively. For $q = 0.37$ and 0.31, the transverse size increases again, when the applied voltage is raised above the value for the minimum beam size. This indicates that the parameters tend towards a region which is outside the existence domain for stable self-trapping. A similar behaviour can be observed (figure 5(b)) for the dependence of the horizontal size of the beam on the applied voltage. Here also, by increasing the voltage, the vertical diameter gradually reduces. But in contrast to the characteristics observed for the vertical diameter (figure 5(a)), the single curves display an almost constant slope.

In figure 6 the effect of a varying ellipticity d_y/d_x of the beams is illustrated for $q = 0.31$ and 0.18 in the solid and dotted curves, respectively. Both beams initially feature

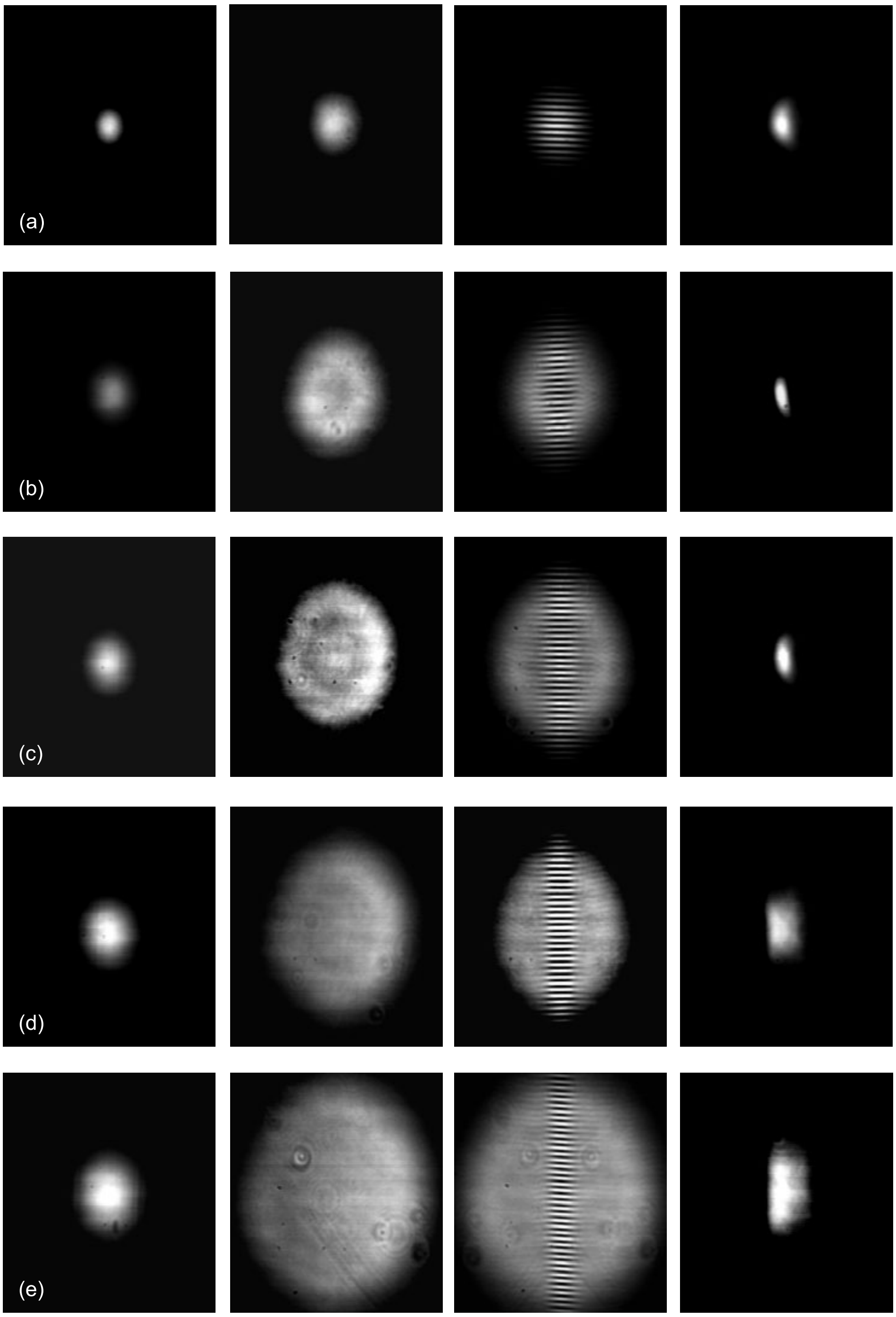

Figure 4. Self-trapping in the biased crystal for various degrees of spatial coherence. For (a) the fully coherent beam $q = 1$, the single frames depict initial beam size $w_i = 21$ μm, diffracting beam $w_d = 36$ μm, the transverse correlation and the self-focused profile for $V = 1$ kV. Similarly for (b): $w_i = 28$ μm, $w_d = 85$ μm, $q = 0.37$, $V = 2.1$ kV, (c): $w_i = 31$ μm, $w_d = 120$ μm, $q = 0.31$, $V = 2.1$ kV, (d): $w_i = 41$ μm, $w_d = 130$ μm, $q = 0.18$, $V = 2.3$ kV and (e): $w_i = 44$ μm, $w_d = 180$ μm, $q = 0.12$, $V = 2.5$ kV.

a small ellipticity of $d_y/d_x \approx 1.2$–1.4, which is due to a slight astigmatism in the optical imaging system focusing the incoherent beam on to the crystal's front face. This is even considered to be beneficial for the generation of solitons, because such an initial intensity profile is certainly closer to the expected solution of an elliptic photorefractive soliton than a circular symmetric one. In both cases depicted in figure 6, the ellipticity of the self-trapped beams rises up to values of 3–3.5 for voltages of 1200 and 1700 V. For an increasing external voltage it quickly drops down to its initial value near 1, which is reached at 1700 and 2500 V for $q = 0.31$ and 0.18, respectively. The shape of the two curves is similar and they appear to be shifted horizontally by about 450 V. This justifies the statement that for self-trapping to occur a decrease of coherence can effectively be compensated for by sufficiently raising the external voltage.

Comparing the above-mentioned behaviour with the self-trapping of a coherent optical beam in a photorefractive

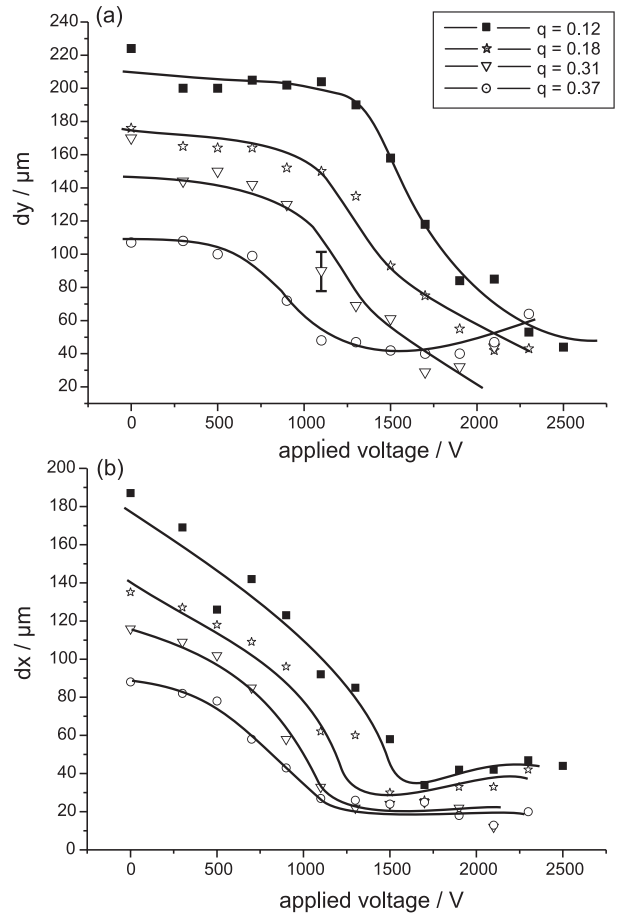

Figure 5. Dependence of vertical (a) and horizontal diameter (b) on the applied voltage. In both cases the minimal horizontal width is reached at 1.7 kV, but with decreasing coherence an effective self-trapping effect in the vertical direction only occurs for higher voltages. The curves are guides to the eye.

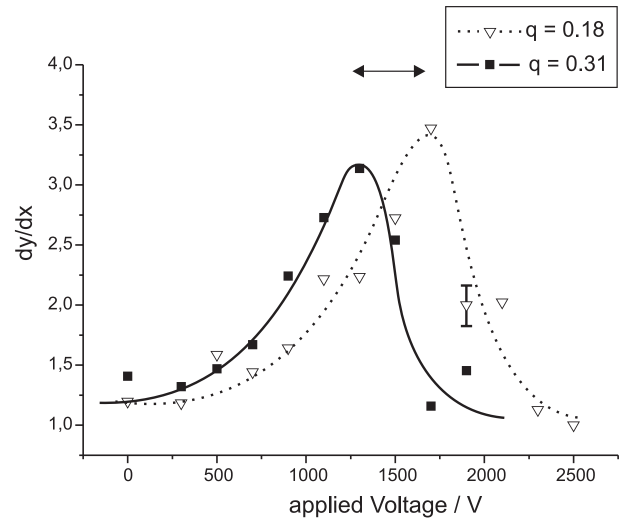

Figure 6. Dependence of the beam diameter ratio d_y/d_x on the external voltage, for $q = 0.18$ (dotted curve) and $q = 0.31$ (solid curve). The characteristic curve shifts to larger values of applied voltage as the coherence decreases (indicated by the arrow). The curves are guides to the eye.

medium [17], a general similarity can be observed. By monitoring both transverse diameters as a function of the externally applied voltage in the moderate saturation regime ($I_{\mathrm{sat}} \approx I$), the ellipticity also increases to a value of 2, before the minimum transverse diameter featuring an ellipticity of $d_y/d_x \approx 1.3$ is reached at 1 kV. The remarkable property that the ellipticity is always larger than unity is apparent in [17] as well as in our experiment on partially coherent self-trapping. Since the graphs depicted in figure 5 reflect the same generic characteristics as a coherent beam in an anisotropic medium [17], we assume that the degree of incoherence has only a minor influence on the ellipticity of the solitary beams.

The most important conclusion to be drawn from the above experiments on the generation of incoherent solitary beams is the fact that a gradual reduction of the degree of coherence can be compensated for by increasing the nonlinearity of the medium. No other parameters like the ratio between beam intensity and background illumination have to be altered. We further conclude that the observed elliptical shape of the solitary light structures are solely due to the inherent anisotropy of the photorefractive medium. Therefore we believe that the degree of coherence of a light beam does not influence the ellipticity of the evolving self-focused light structure.

Apart from the self-trapping of partially coherent light we observe that the transverse size of the solitary light beams gradually increases with decreasing degree of coherence. Considering the two scenarios featuring a low degree of coherence in figures 4(d) and (e), the initial as well as the self-focused transverse width roughly ranges from 30 to 40 μm. A coherent beam featuring such a transverse size initially would inevitably be subject to filamentation in a self-focusing medium [10]. In this case, the transverse optical field is larger than the characteristic screening length of the charge carriers in the photorefractive material, and the beam typically exhibits small-scale self-focusing due to inherent modulation instability. This behaviour clearly differs when the light's degree of coherence is reduced. The modulation instability which is responsible for the filamentation and the succeeding disintegration of the beam, is shifted to larger values of the nonlinearity. Therefore self-focused optical beams with a diameter larger than the typical diffusion length can indeed be generated.

This aspect has been subject to a series of recent studies [20–22] demonstrating that modulation instability arises for higher levels of nonlinearity when the light is only weakly correlated. Remarkably, the modulation instability of incoherent light even displays threshold characteristics. With increasing nonlinearity, a pattern forming effect only arises above a certain threshold, which shifts towards a higher level of nonlinearity when the degree of coherence of the light is reduced.

4. Conclusions

According to our experimental results we conclude that a partially coherent light beam can self-trap for a large range of the light's global degree of coherence of $q = 1$–0.12 when the nonlinearity of the material is appropriately adapted. The smallest correlation distance applied in our experiments corresponds to the distinct degree of coherence that was formerly investigated by Mitchell *et al* in [16]. Additionally, we investigated the relationship between the degree of coherence and the externally applied voltage in a quantitative way. Furthermore, our investigations include aspects of anisotropy that were carefully taken into account in our analysis. By comparing these results with the coherent counterpart, we calculated that the reduction of spatial coherence has no significant influence on the transverse shape of the solitary beams. Furthermore, we demonstrated that the reduction of the degree of coherence inevitably leads to an increase in the transverse size of the evolving solitons. Such an optical beam is inherently of multi-mode type and the undistorted propagation of a large number of transverse optical modes should principally be supported. Especially in an anisotropic waveguide, such as in photorefractive crystals, guidance of a TEM_{10} mode is only possible when the waveguide's transverse size is fairly large [5]. In this case, a large but partially coherent solitary beam may be capable of guiding such a transverse mode. The first experiments guiding three distinct light pixels on the basis of an incoherent bright soliton have already been conducted [14]. For further progress of guiding even more complicated light structures with the help of partially coherent solitons, fundamental investigations of the waveguide's properties and its transfer function are essential and might be subject to future investigations.

Acknowledgments

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