Spatial Solitons in Resonators

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We describe experiments testing the existence and investigating the properties of spatial solitons in nonlinear resonators. We investigate the properties of stationary and moving spatial solitons in lasers with saturable absorber, with a subcritical bifurcation, as well as their manipulation. As opposed, spatial solitons relying on a supercritical bifurcation are shown to exist in degenerate 4-wave mixing (DOPO). With a view to technical applications in parallel information processing or communication, experiments on spatial solitons in large area quantum well semiconductor resonators are conducted.

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I. INTRODUCTION

Solitary structures can form in optics when a balance occurs between a linear and a nonlinear optical process. The best known instance of such structures in optics are solitary pulses propagating along optical fibers. Here a balance occurs between the linear mechanism of dispersion, which leads to a broadening of the pulse in the propagation direction, and the nonlinear mechanism of ”self-phase-modulation” or intensity-dependent refractive index, (e.g. Kerr effect) which tends to shorten the pulse. The result is a pulse traveling along the fiber without changing its shape. Such pulses can well be described by the soliton solutions of the 1+1D nonlinear Schrödinger equation (NLSE). In this equation the time co-ordinate may as well be a spatial co-ordinate. It follows that spatial solitons should also exist. The linear broadening mechanism in this case is diffraction. In one spatial dimension such spatial- or propagation solitons do indeed exist. The phenomenon manifests itself in the contraction of a light beam with propagation, until a filament of constant thickness is formed which then propagates without further change ("Self-trapped beam").

Taking, however, a normal laser beam which diffracts or contracts in 2D (the beam cross section), the NLSE has no stable solutions of the form of a beam propagating with a constant diameter, at least in the paraxial optics approximation. The Kerr-nonlinearity is ”stronger” than the diffraction, so that catastrophic collapse of the beam cross section occurs. It was pointed out that such collapse can be avoided if the nonlinearity is ”saturable” i.e. reduces with increased light intensity. In this way a variety of experiments on propagation solitons in 2D has been possible. Technical applications in information routing and field steering with such propagation solitons are under consideration.

A particular situation occurs if such a ”self trapped” beam propagates inside an optical resonator. The finite mirror reflectance acts in this case somewhat similarly to the saturation of the nonlinearity because in each round-trip of the light, to the already self-focused light unfocused light, which irradiates the resonator, is added, thus continually weakening the self-focusing. Consequently, in resonators of finite finesse stable filamentation is possible.

Evidently, the stability of such structures can be enhanced further by a saturability of the nonlinearity of the material filling the resonator. Thus, occurrence of spatial resonator solitons has been predicted for a number of nonlinear materials. The first observations of such solitary structures in optical resonators occurred before the bulk of theoretical work on passive resonator solitons appeared. In such solitary structures were observed using a liquid crystal film inside a resonator and in such a spatial soliton was observed in a resonator made up of two phase-conjugating mirrors which contained a saturable absorber.

Spatial resonator solitons can exist if the characteristic of the resonator shows two coexisting stable steady states (bistability). In such a bistable resonator, if it is of large Fresnel number, domains of the two states can exist, which are then connected by ”switching fronts” (or -waves). Such switching waves move into or out of domains of one of the states depending on the difference of the background field value and the field value corresponding to the unstable steady state solution lying between the two stable steady states. A switching front will move into the state of higher intensity if the background field is larger than that of the unstable steady state, and it will move into the domain of the lower intensity state if the background field is smaller than that of the unstable steady state. Thus in general one kind of domain will shrink and the other expand.

In general the asymptotic state will be that the total resonator cross section is entirely switched to one of the two states. If, however, the system is not far from
a modulational instability, then the switching fronts do not aperiodically connect the two states but can be accompanied by damped spatial oscillations on either side of the fronts. Then as a domain contracts, finally the switching front on one side of the domain will "feel" the spatial oscillations of the field close to the front on the other side of the domain. The spatial field minima can then "trap" the front of the other side of the domain, which case the (small) domain has attained a stability (and is then called a solitary or localized structure). It can be freely moved around the resonator cross section. If the spatial field oscillations on the one side of the domain trap not the front from the other side itself, but the spatial oscillations accompanying it, then a higher order spatial soliton is formed \[9\].

We have found so far, that the solitons of low orders resemble Gauss-Laguerre-Modes with ring nodes (not the flower-like variety). There is no obvious reason why that should be so. Optical resonator modes are the eigenfunctions of a boundary problem with the boundaries given by the mirror surfaces. Conversely, the solitons are the solutions of a self-consistence problem where the "potential", constituted in case of an optical resonator by the resonator mirrors, is created by the light field itself. Thus it is not obvious why these two problems should have similar solutions, and reasons for the similarity of the solutions are an open question. Interestingly it has been found, that the potential created by a fundamental soliton can actually allow besides the existence of the field of the fundamental soliton - the stable additional existence of a \[1st\] order soliton \[10\].

One can, in all cases, picture a spatial soliton as a small domain of one of two coexisting states surrounded by a stationary switching front which has locked into a stable ring. Due to the bistable character of the resonator such spatial solitons are bistable. They can be switched on or off and are thus suitable for carrying information.

II. SOLITONS IN LASER WITH NONLINEAR ABSORBER

The theoretical work on solitons of active resonators dates back to the 80s (see a summary in \[11\]).

It suggested experiments with a repetitively pulsed dye-laser with an internal saturable absorber \[12\]. FIG. 1 shows the output power of the dye laser with an internal Bacterio-Rhodopsine (BR) absorption cell as a function of pump power. The pulse repetition rate is 12 Hz, the acidity of the BR-absorber solution is chosen for an absorber recovery time constant of 300 ms so that the system dynamics is slaved by the absorber and the system can be treated like a continuously emitting system. The bistability of the system is apparent. The upper part of FIG. 1 shows the output beam cross section. Apparently the narrowest beam occurs within the bistable region. It represents a spatial soliton.

FIG. 1. Average output power of laser with BR-absorber as a function of pump power showing bistability. Beam profiles at the positions (a), (b), (c) indicated are given above.

The resonator used is of "self-imaging" type. This kind of resonator is in its transverse mode structure equivalent to a plane resonator of zero length. For the precise self-imaging length, its transverse modes are completely degenerate. The diffraction losses, equally, correspond to a plane resonator of zero length. Thus, this resonator, on the one hand, has the complete transverse mode degeneracy of a plane resonator of zero length as necessary for arbitrary images to resonate, and on the other hand it has sufficient length to house various intracavity elements without the detrimental diffraction losses of a plane resonator of the same length. (It may be noted that such a resonator permits to realize also a negative length as far as the transverse mode structure concerns).

FIG. 2 shows the "writing" of a spatial soliton in this system in various places of the resonator cross section. The absorber cell was locally bleached for a short time (by a He-Ne laser beam). The result is a stationary spatial soliton (which remains after the external bleaching is stopped). FIG. 2 shows on the one hand that the solitons are bistable (i.e. can be switched on and off) and on the other hand that they can exist at any location in the cross section.

The motion of solitons in field gradients was also tested. In a fluid analogy of the laser \[13\] a phase gradient corresponds to flow velocity and an intensity gradient to a density- (or pressure-) gradient. Thus a soliton should move in such gradients. FIG. 3 shows experiments...
with phase gradients. In FIG. 3a a phase gradient across the laser cross section was created by a small tilt of one laser resonator mirror. The snapshots taken at equidistant times show the motion of the soliton induced by the phase gradient. By changing the length of the self-imaging laser resonator away from the precise-self imaging length in FIG. 3b a ”phase trough” was created with its minimum at the center of the resonator. As the snapshots show, the soliton is drawn from all sides towards the center of the phase trough, were it is then trapped. This movement and trapping of solitons would likely be important for uses of resonator solitons in optical information processing [14].

FIG. 2. A soliton can be ”written” at any location in the laser cross section.

In these initial experiments, the laser containing the nonlinear absorber was emitting a larger number of longitudinal modes. Thus the tuning of the resonator was of no importance, as the modes emitted adjust to the resonator length. The resonator tuning does, however, affect the solitons, their motion, and characteristics if emission is restricted to a single longitudinal mode family. The simplest way for such mode selection is an active medium with a very narrow gain spectrum. By far the narrowest ”gain” spectra (if one interprets in a laser-physics concept) have photorefractive gain media [15]. Therefore experiments were conducted using resonators of self-imaging type [16] with photorefractive gain. To picture the effects of a narrow gain line one can think of the self-imaging resonator as a plane-plane resonator. Such a resonator has a (longitudinal) resonance if the length can accommodate an integer number $N$ of (half) wavelengths of radiation generated - whose wavelength is fairly strictly given by the wavelength of the center of the gain line.

Then, if the length of the resonator is between $N\lambda/2$ and $(N-1)\lambda/2$ the emission can adjust to this resonator length by tilting the propagation direction of the radiation with respect to the resonator axis. In this way $N$ half wavelengths can be accommodated in the resonator [17]. Such a ”tilted wave” has a propagation component along the resonator axis and a (small) propagation component lying in the resonator mirror plane. Light will therefore move across the resonator section in a detuned resonator, corresponding to the motion in a phase gradient. We can therefore expect stationary solitons in the case of precise resonator tuning, and moving solitons for detuning.

FIG. 3. A phase gradient (tilt of one resonator mirror) leads to drift of the soliton (a), a soliton drifts from all directions into a phase trough (b).

The stationary solitons, correspond to the stationary solitons described above for the broadband (dye) multi mode laser which can adjust its detuning to zero by choice of different longitudinal modes. For the moving solitons corresponding to detuned (tilted wave-)emission, one can from this picture directly deduce the characteristics of the soliton motion:

1) the direction of the tilt of the wave vector of the light generated is free. Only the decomposition of the wave vector into a longitudinal and a transverse component, in magnitude, is fixed. Thus the direction of motion of the solitons is a priori undetermined. The actual direction of motion is determined by spontaneous symmetry breaking (in the same way as a single mode laser chooses the phase of its field at laser threshold). As for the laser phase, there is here no restoring force for a particular direction. The direction of motion of a soliton can therefore change under external influence. In presence of noise it will change diffusively.

2) Whereas the direction of motion of a soliton, as well as its position in the laser cross section are free, the magnitude of the soliton velocity is fixed and given by the
detuning of the resonator (wave vector tilt is proportional to detuning).

3) Different longitudinal orders can be emitted simultaneously if their wave vectors are tilted by different amounts. Thus in a resonator of length $N\lambda/2$, which emits a stationary soliton, simultaneous emission of moving solitons is possible. According to the different longitudinal orders, the velocities of the moving solitons are quantized for a resonator of given length.

4) If we consider that in the experiment a self-imaging resonator is used, with the nonlinear absorber in the near field (near a plane mirror) and the (photorefractive) gain medium in the far field, a strange type of competition among moving solitons follows. Fields of two solitons overlapping inside the gain medium compete. Only one soliton can then survive. The consequence is a competition of solitons in velocity space. If and only if two solitons have the same vectorial velocity (i.e. velocity direction and magnitude equal), they will compete. Notably, even when they are far apart in the near field plane.

5) For stationary solitons the competition condition is trivially fulfilled. Therefore only one stationary soliton can exist at a time.

6) Moving solitons of different direction of motion and/or different magnitude of velocity can coexist, thus in general a large number of moving solitons can coexist with one stationary soliton.

FIG. 4. Intensity distributions in the near and far field for stationary and moving solitons. A central spot in the far field corresponds to a stationary soliton with arbitrary position in the near field. A spot (elliptical shape) on a resonant ring corresponds to a moving soliton. Simultaneous emission on two rings corresponds to a moving soliton with (stationary) modulation of the soliton intensity ("inch-worm").

FIG. 4 pictures the situation: a stationary soliton corresponds to emission along the resonator axis. Moving solitons correspond to emission at a fixed angle (given by detuning), to the resonator axis, in the far field. Therefore the stationary soliton corresponds to light in the central spot of the Airy rings of the resonator, while the moving solitons correspond to emission on the rings.

The restriction on the wavelength of the light generated is given by the finite widths of the gain line of the active medium. The finite width of this gain line corresponds to the allowed spread of tilt angles of the emitted wave. Therefore the emission of the stationary soliton corresponds to a central disk of finite diameter and that of the moving solitons to finite area sections of a ring. For moving solitons, the wavevector of emitted light changes faster with radial angle than with azimuthal angle. Therefore the light of a moving soliton in the far field occupies an elliptical section of an Airy ring (see FIG. 4). Its Fourier transform (moving soliton in the near field) is of elliptical shape, with the long axis into the direction of motion (suggesting again a fluid picture) FIG. 4.

FIG. 5 shows cases of all these soliton types as recorded on a photorefractive BaTiO$_3$ oscillator with a BR-saturable absorber which uses a self-imaging resonator [16]. Excitation of emission segments on two rings into the same azimuthal angle results in an "inch-worm"-soliton FIG. 5.

FIG. 5. Experimental realisation of the solitons described in FIG. 4 (left: near field, right: far field): a) one stationary soliton 1 and two moving solitons 2, 3; b) one stationary soliton 1 and a moving "inchworm"-soliton 2.

In these experiments the gain elements of the lasers were placed in the conjugate plane of the near field. This leads to competition among certain solitons and, in particular, only one stationary soliton can exist. For applications where such solitons are to serve as binary elements for information storage, however, large numbers of sta-
tionary solitons are desirable.

In order to test whether this is achievable, experiments were conducted with the gain element and the nonlinear absorber both in the near field plane. This case had been extensively treated in [11] in the form of both elements being inside a plane resonator. In the experiments the unsaturated absorption of the nonlinear absorber was so high that, even at the highest pump power available, the laser could not be brought to emit. External bleaching of the absorber (by a green laser) was used for complete saturation of the absorber so that large area laser emission occurred. Reducing then the pump strength, the absorber gradually unsaturates and becomes intensity dependent (nonlinear).

FIG. 6 shows the formation of the solitons in the experiment. To illustrate the development of solitons out of the laser emission, FIG. 7 shows a numerical calculation of the process:

FIG. 6. Transition from 1D to 2D solitary structures.

a) shows the emission typical for a tuned laser: A number of optical vortices exist which are separated by "shocks" [18] ("vortex glass" [19]).

b) as the pump is reduced, the vortices develop into dark areas and the shocks convert to 1-dimensional soliton-structures (see c), d)).

c) Further reduction of the pump leads to shortening of the 1-D solitary structures, which can then be converted to 2-D bright solitons by increasing the pump slightly.

d) This final increase in pump is necessary since the diffraction losses for a 2-D soliton are larger than for a 1-D solitary line. For details see [16]. This can be seen in FIG. 6: in the outer regions where the pump is weak, stripes prevail, while at the higher pump in the center spots dominate.

FIG. 8 finally shows ensembles of 2-D solitons in the final stage, for different pump powers. It appeared that the number of solitons existing in the final state is a monotonic function of the pump power.

FIG. 7. Numerical calculation of the transition from laser-to soliton emission.

FIG. 8. Collections of solitons as experimentally observed corresponding to different pump powers

As the pump beam has a Gaussian intensity profile, gradients existed in the emission, which caused a slow outward motion of the solitons. Thereby some solitons would reach the edge of the emission field and extinguish there. This loss of solitons at constant pump power was accompanied by continual splitting of solitons in the central area of the near field. It appeared that the splitting occurred to balance the loss of solitons at the edges. FIG.
9 shows such soliton splitting.

FIG. 9. Splitting of solitons in a laser with saturable absorber (for details see text).

Time has not yet allowed us to study the interaction of solitons in this system, which must exhibit interesting phenomena. Each of the solitons here is an independent laser whose phase is arbitrary. The interaction between solitons would on the one hand depend on the relative phase, on the other hand two solitons whose phase is free to change can be expected to synchronize their phases. Whether this would be in or out of phase, combined with the initial independence of the phases of the individual solitons should produce a complicated interaction.

III. PARAMETRIC MIXING SOLITONS

Whereas the field of a laser, as used in the experiments described above, can have any phase value, in wave-mixing with phase matching the phase of the generated field is tied to the phase of the pump field. The generated field can therefore be described as a real-valued variable - as opposed to the complex-valued field of a laser.

Spatial resonator solitons require, as has been described in Sec. II, a bistable characteristic of the resonator. Experiments described so far utilize a subcritical bistability with a high- and a low-intensity branch. For degenerate wave mixing such as 4-wave mixing (D4WM) or degenerate parametric mixing (DOPO) a phase bistability of the (real-valued) field occurs [20]. Although this is a symmetric and supercritical bistability, one would expect that also this kind of bistability would support spatial solitons, which we would call phase-solitons. A calculation shows [21] that indeed spatial solitons exist for a finite small detuning.

FIG. 10 gives shapes of such solitons in intensity and phase. Inside the solitons the phase field is opposite to the surrounding so that a dark circular interference fringe forms the switching front connecting the two steady states.

The corresponding experiment was conducted using D4WM in BaTiO$_3$ [22]. FIG. 11 shows the resonator used. Two pump beams together with the generated fields form an index grating in the material which diffracts pump radiation into the generated fields and adjusts self-consistently to the generated field.

FIG. 10. Different stable localized structures calculated for a DOPO or for D4WM. a) fundamental solitons, b) bound states between fundamental solitons, and between fundamental and higher order solitons, c) higher order solitons, d) a complicated bound state of solitons.

FIG. 11. Scheme of the resonator used for observing phase-solitons in degenerate (photorefractive) 4-wave-mixing. M: mirrors, $f$: local length of lenses, $l$: deviation from self-imaging length, D: iris for blocking high resonant rings.

The two counter-propagating generated fields resonate in the same (linear) resonator which forces their degeneracy and with that the bistability and real value of the generated field. A typical intensity distribution of the field generated experimentally is shown in FIG. 12. Small circular domains coexist which larger domains and black domain walls as was expected. FIG. 13 shows a domain wall of complicated shape together with an interferogram proving the opposite phase of the field on either side of the domain wall. We note that the domain walls themselves are extended 1-D solitary structures [23]. They are the switching waves connecting the two steady states of the resonator (field with $+\pi/2$ and $-\pi/2$ phase). In gen-
eral such switching waves move and the domains they surround grow or shrink, the length of the domain walls expanding or contracting. The expansion/contraction can be controlled by resonator detuning [21]. FIG. 14 shows the contraction of a domain wall.

FIG. 12: A typical intensity distribution as observed from a resonator as in FIG. 11. Small circular domains coexist with large, irregularly shaped domains.

Although in the experiment the small domains appeared to be stable, it is necessary to prove their stability more explicitly since stability is hard to distinguish from a slow transient dynamics. Recordings under well-defined resonator tuning conditions were therefore analysed. The resonator length was for this purpose actively stabilized with respect to the pump light frequency in a manner similar to that described in [24].

FIG. 13: A domain boundary of complex shape. Interferogram shows that the fields separated by the boundary have opposite phase (experimental).

FIG. 14: Contraction of a domain boundary (experimental).

FIG. 15 shows three snapshots out of an evolution captured in 20 frames. Fig. 16 shows the change of the length of the boundaries of the domains "1", "2", "3" as a function of time as measured on the 20 recorded frames. The largest domain-"1"-boundary shrinks fastest. The medium sized domain-"2"-boundary shrinks at a slower rate, while the domain-"3"-boundary does not change in time. This is proof that the small circular domain "3" is stable and represents a phase-soliton. The faster shrinking of the larger domain is what is expected theoretically [21].

FIG. 15: Large domains 1, 2 shrink, while the small domain 3 keeps constant size (experimental).

FIG. 16: Lengths of boundaries 1, 2, 3 from FIG. 15 as a function of time (experimental).

Stability of a soliton, under conditions where the shrinking rate of a large domain is even larger, is shown in the four snapshots FIG. 17.

FIG. 17: Length of boundary 2 shrinks rapidly while length of boundary 1 is constant in time (experimental).

Analysing the 20 frames out of which the FIG. 17 snapshots are taken leads to FIG. 18 proving again than the small domain is a phase-soliton.
FIG. 18. Boundary lengths of FIG. 12 as a function of time (experimental).

IV. NONLINEAR SEMICONDUCTOR RESONATORS

An interesting nonlinear material for technical applications is a semiconductor. Solitons in semiconductor resonators were predicted in [25].

FIG. 19. Scheme of a semiconductor microresonator.

We have used a nonlinear semiconductor Fabry Perot for initial experiments on spatial solitons. The nonlinear medium consists of three quantum wells (FIG. 19). These three wells have between them 99.5% Bragg mirrors, spacers to make the space between the mirrors equal to a few \( \lambda/2 \). The thickness of this structure is a few micron while the cross section of the resonator is a few cm. Details about these nonlinear Fabry Perots are given in [24]. The resonance of the Bragg resonator is slightly dependent on the location on the sample, so that by choice of the area to be irradiated the wavelength of excitation of the semiconductor material can be chosen to lie either in the interband transition, between interband transition and exciton line, on the exciton line, or above the exciton line. Typically we work a few 10 nm above the exciton wavelength so that the nonlinearity is largely dispersive and defocusing. The empty resonator finesse is around 500. With the residual absorption of the semiconductor material the resonator finesse is \( \approx 100 \). A cw Ti:Al\(_2\)O\(_3\)-laser is used for the excitation.

To avoid thermal effects the observations are done during radiation pulses of a few microseconds length which are repeated every millisecond. To create the pulses acousto-optic modulators are used. The radiation is focused into a spot size of 50 - 100 \( \mu \)m on the semiconductor resonator surface, the light reflected from the sample is observed by a CCD camera or by a fast (2ns) photodiode.

As has been theoretically predicted for such dispersively nonlinear resonators, under irradiation structure forms. FIG. 20 shows that the structure is a hexagonal lattice as expected [27].

FIG. 20. Hexagonal patterns as observed on the semiconductor nonlinear Fabry-Perot of FIG. 19.

Bistability of the resonator is easily reached (at intensities of a few 100 W/cm\(^2\)). FIG. 21a shows the incident intensity (dashed) and the reflected intensity (solid) as measured by the fast photodiode.

The reduction of reflected light, as the sample is switched on, is clearly seen, as is the increase of reflected light as the sample is switched back off. From the intensities at which the switching "on" and "off" occurs, the width of the bistability loop is apparent. After the resonator was switched "on" at the point of observation (image of detector) we varied the irradiating intensity in order to observe the motion of the switching waves connecting the on- and off-switched regions. By recording curves as in FIG. 21a for different locations across a diameter of the laser irradiation spot on the sample one is able to construct the time history of the resonator dynamics on this diameter. FIG. 21d shows a recording thus obtained.

Brightness in FIG.21d corresponds to reflectivity value. The corresponding irradiation is given in FIG.21b in the form of equi-intensity lines.

As the irradiation intensity is initially increased the switching-on threshold is reached at a certain time in the
center of the laser field. A switching wave travels then outward until it becomes stationary. We call it then "switching zone". As mentioned in Sec. I a switching wave moves into the unswitched region if the background intensity is larger than that corresponding to the unstable steady state solution on the unstable branch of the S-shaped resonator characteristic and vice versa. Thus the switching wave becomes stationary at a particular intensity corresponding to a certain distance from the maximum of the Gaussian laser beam. This is what we observe.

![Image](image1.jpg)

**FIG. 21.** Bistable switching of semiconductor microresonator and spatial behaviour. a) Bistable switching: input intensity: dashed line; reflected intensity: solid line. By initial increase of irradiation the sample is switched "on" and by decrease later "off". In between, intensity is varied to demonstrate width of bistable region and to observe dynamics of switching fronts. b) Equi-intensity lines (input intensity) for a spatial co-ordinate on a diameter of the illuminated region, and time. c) Motion of the switching front. d) Reflectivity of sample.

When the power of the laser field is reduced, one would then expect that the stationary switching wave (switching zone) would move towards the center of the laser beam. Comparing FIG. 21b and FIG. 21d this is confirmed. The switching zone (boundary between on- and off-switched areas) moves precisely on an equi-intensity contour of the input light. FIG. 21c shows for clarity the equi-reflectivity line corresponding to the switching zone, which follows the second lowest intensity contour of the incident light.

If one chooses a location on the sample where the resonator resonance is further from the exciton line, the switching zone becomes accompanied on the lower branch side by fringes. This is an indication that under these conditions the lower branch is close to a modulational instability. This is a requirement for the formation of spatial dark solitons as described in Sec. I.

![Image](image2.jpg)

**FIG. 22.** A small (10 µm) bright structure giving first indication of a soliton.

Suitable choice of parameters appears indeed to lead to a solitary structure. FIG. 22 shows a bright narrow spot of the size the order of the elements of the hexagonal pattern FIG. 20. (FIG. 22 is an average over 20 laser pulses with rectangular intensity-vs-time-form). We can clearly show that this small structure is bistable as predicted for a soliton: FIG. 23 shows the proof. We use a rectangular laser pulse with a constant intensity in the middle of the bistability region. A short increase in intensity beyond the upper intensity of the bistability switches the small localized structure "on". It remains "on" until the intensity is for a short time reduced to below the lower intensity of the bistability.

![Image](image3.jpg)

**FIG. 23.** Test of bistability of the small structure of FIG. 22. a) Equi-intensity lines of input light. b) Sample reflectivity.

This clearly demonstrates that the small structure is
bistable as expected for a spatial soliton. We have tried to record that this structure has a stability of its shape as one would expect for a soliton (or a circularly locked switching zone). This is shown in FIG. 24.

FIG. 24. Test of stability of the small bright structure. a) Equi-intensity lines of input light. b) Motion of the switching front. c) Light intensity reflected from the sample.

FIG. 24a gives the equi-intensity lines of the input field. During a short high intensity period at the beginning, the central part of the beam is switched up (see reflected intensity FIG. 24c). Reducing the intensity lets the switched-up region then contract to the small diameter of FIG. 22.

We test the stability of this structure now by a variation of the light intensity: if the small bright structure is just a circular switching zone (which is not locked and thus is not a soliton) then its diameter should follow a contour of the incident light. FIG. 24b shows the contour corresponding to the switching zone. Evidently it does not follow any of the contours of the incident light (FIG. 24a). This indicates a certain robustness of the narrow structure against changes of system parameters, for which reason FIG. 22 can be taken as the first indication of the existence of localized structures in semiconductor resonators.

A more explicit test on the existence of such independent localized structures was possible by injection of spatially narrow, temporarily short light pulses into the illuminated area. FIG. 25a shows a collection of bright spots resulting from illumination of the area shown. The narrow pulse is first directed at the spot marked "a". As can be seen in FIG. 25b, this switches the bright spot "a" to dark. All other spots remaining unchanged.

Correspondingly, the second pulse was directed at bright spot "b" which is equally switched to dark, all other spots remaining unchanged, as seen in FIG. 25c. As the FIGs 25a to c are time-average-pictures not indicating directly the switching, FIG. 25d gives the intensity at the center of a switched spot as a function of time. The upper trace corresponds to a pulse energy not sufficient for switching and no permanent switch of the bright spot results. With sufficient energy of the pulse, however, permanent switching occurs, i.e. the intensity remains small throughout the illumination (until the reduction of the background intensity near the end of the illumination returns the resonator to monostable.) Thus, in this case, individual bright spots are found which can be independently of the rest of the system, switched. This makes the bright spots observed very "soliton-like".

FIG. 25. Switching of individual bright spots of a bright spot cluster (see text). Nonlinearity is defocusing dispersive.

To experiment with single bright spots, in order to show their soliton nature, was not possible under the largely dispersive conditions used, because the collection of bright spots appears largely as a consequence of linear filtering of the high finesse, high Fresnel number resonator. For details see [28].

In order to suppress this linear ("noise induced") structure, we chose to work at lower resonator finesse i.e. closer to the band edge or the exciton line, where, moreover, the dissipative solitons predicted in [14] could be more likely expected. FIG. 26 shows observations (pictures were taken as snapshots of 50 ns duration) under these conditions.

FIG. 26a shows a switched area (resonator field is high in the dark area because observation is in reflection) surrounded by a switching front. For small intensities such switched area collapses into the structure shown in FIG. 26b, which shows all the characteristic features of a bright soliton (dark due to observation in reflection), particularly, the spatial oscillations around it.

We have recently been able to switch this structure on and off by a narrow pulse similar to what was done to
observe Fig. 25d.

Interestingly, at higher illumination intensity "dark" solitons (bright in reflection) appear. FIG. 26c shows such a soliton; embedded in the upswitched area as to be expected [29]. Such dark solitons were predicted in [30]. As predicted there, we have found that these "dark" solitons are less stable than the bright ones. They appear to move and we find that for smaller intensities they tend to pulse in a regular fashion, somewhat similarly to what was predicted in [30].

![Fig. 26](image1)

FIG. 26. Switched structures: reflectivity (reflected light/incident light) of the sample: a) switched domain (limited by a contour of Maxwellian intensity), b) bright soliton (dark spot in reflection), c) dark soliton (bright spot in reflection).

A hint towards the nonlinear nature of these structures comes from the brightness of the light reflected on the structure. Quantitative intensity measurement [29] shows that the light reflected at the center of the structure is almost twice as high as the illumination intensity. This means a reflectivity higher than one. This has to be interpreted such that the structure collects light from its surrounding and emits it at its center.

![Fig. 27](image2)

FIG. 27. Dark solitons observed in the switched area (intensity).

FIG. 27 finally shows that more than one soliton can exist, even at our conditions which are limited by finite laser power and spatial nonuniformity of the illuminating field [29]. With these solitary structures in semiconductor microresonators, information processing and storage should be possible.

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[1] V.E.Zakharov, A.B.Shabat, Sov. Phys. JEPT 34, 62 (1972).
[2] P.V.Manuyshev, A.Villeneuve, G.I.Stegeman, J.S.Aitchison, El. Lett. 30, 726 (1994).
[3] P.L.Kelley, Phys. Rev. Lett. 15, 1005 (1965).
[4] J.M.Marburger, Theor. Progr. Quantum. Electron 4, 35 (1975).
[5] see e.g. M.Shih, P.Leach, M.Segev, M.Garret, G.Salamo, G.Valley, Opt. Lett. 21, 324 (1996); see also W.Torrueñas, B.Lawrence, G.I.Stegeman, Electr. Lett. 32, 2092 (1996).
[6] M.Tlidi, P.Mandel, R.Lefever, Phys. Rev. Lett. 73, 640 (1994); also W.J.Firth, G.K.Harkness, Asian J. Phys. 7, 665 (1998).
[7] M.Kreuzer, H.Gottsche, T.Tschudi, R.Neubecker, Mol. Cryst. Liq. Cryst. 207, 219 (1991).
[8] B.Fischer, O.Werner, M.Horowitz, Appl. Phys. Lett. 58, 2729 (1991).
[9] A hint towards the nonlinear nature of these structures comes from the brightness of the light reflected on the structure. Quantitative intensity measurement [29] shows that the light reflected at the center of the structure is almost twice as high as the illumination intensity. This means a reflectivity higher than one. This has to be interpreted such that the structure collects light from its surrounding and emits it at its center.

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[1] V.E.Zakharov, A.B.Shabat, Sov. Phys. JEPT 34, 62 (1972).
[2] P.V.Manuyshev, A.Villeneuve, G.I.Stegeman, J.S.Aitchison, El. Lett. 30, 726 (1994).
[3] P.L.Kelley, Phys. Rev. Lett. 15, 1005 (1965).
[4] J.M.Marburger, Theor. Progr. Quantum. Electron 4, 35 (1975).
[5] see e.g. M.Shih, P.Leach, M.Segev, M.Garret, G.Salamo, G.Valley, Opt. Lett. 21, 324 (1996); see also W.Torrueñas, B.Lawrence, G.I.Stegeman, Electr. Lett. 32, 2092 (1996).
[6] M.Tlidi, P.Mandel, R.Lefever, Phys. Rev. Lett. 73, 640 (1994); also W.J.Firth, G.K.Harkness, Asian J. Phys. 7, 665 (1998).
[7] M.Kreuzer, H.Gottsche, T.Tschudi, R.Neubecker, Mol. Cryst. Liq. Cryst. 207, 219 (1991).
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This work was supported by ESPRIT projects PASS and PIANOS. Growth of semiconductor Fabry-Perots by I.Sagnes is gratefully acknowledged.
[28] V.B.Taranenko, R.Kuszelewicz, I.Ganne, C.O.Weiss, subm. Phys. Rev. A 1999; also Los Alamos Preprint Server nlin.PS/0001055.

[29] V.B.Taranenko, R.Kuszelewicz, I.Ganne, C.O.Weiss, subm. Phys. Rev. Lett. 1999; also Los Alamos Preprint Server nlin. PS/0001056.

[30] D.Michaelis, U.Peschel, F.Lederer, Opt. Lett. 23, 1814 (1998).