Spatial solitons in a semiconductor microresonator

V.B.Taranenko, I.Ganne,* R.J.Kuszelewicz,* C.O.Weiss
Physikalisch-Technische Bundesanstalt 38116 Braunschweig/Germany
**Centre National d'Etudes de Telecommunication, Bagneux/France*

We show experimentally the existence of bright and dark spatial solitons in a passive quantum-well-semiconductor resonator of large Fresnel number. For the wavelength of observation the nonlinearity is mixed absorptive/defocusing. Bright solitons appear more stable than dark ones.

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The possibility of the existence of spatial solitons in semiconductor resonators has recently been investigated in some detail theoretically [1,2] motivated, among others, by possible usefulness of such structures in new types of optical information processing. Bright and dark solitons have been predicted. The majority of the papers treated bright solitons [1]. We have recently reported on experiments concerning the switching space-time dynamics of quantum-well semiconductor resonators [3]. In these experiments we showed the existence of hexagonal patterns, some "robustness" of small switched domains and the possibility of switching of individual elements of ensembles of bright spots; thus giving first evidence for stable localized structures. In this letter we show directly the existence of bright and dark solitons.

The semiconductor resonator used for the measurements consists of flat Bragg mirrors of about 99.7 % reflectivity with 18 $GaAs/Ga_{0.5}Al_{0.5}As$ quantum wells between them [4]. The optical resonator length is approximately 3 μm, the area about 2 cm^2. Across this area the resonator wavelength varies, so that one can work from the dispersive range (wavelength longer than the gap wavelength) to well within the absorption band. The resonator was optimized for dispersive optical bistability, for which reason the absorption of the semiconductor material is too high for absorptive bistability at the bandgap wavelength (the most stable solitons are predicted for absorptive bistability, i.e. for wavelengths near band gap).

Our previous experiments in the dispersive bistability region [3] had shown linear structure formation in the form of somewhat irregular clusters of bright spots. These are simply the result of filtering of light scattered in the material, by the high Fresnel number, high finesse resonator [5]. This structured background field prohibits the formation of pure unperturbed, independent solitons. We attempted therefore to work closer to the band gap wavelength, where the absorption of the nonlinear quantum-well material is larger and thus the resonator finesse smaller, in order to avoid the linear structuring of the field.

The experimental set up is conceptually simple: light is generated by a $Ti{:}Al_2 0_3$-laser tunable to desired wavelengths. It irradiates in a spot about 40 μm diameter the semiconductor sample, with intensities of order of kW/cm^2 as required for saturating the semiconductor material. As the substrate of the semiconductor resonator is GaAs, which is opaque in the wavelength range in question, the light reflected from the sample is observed.

Observations are done either by a CCD camera for recording 2D images or by a small detector which can record the time variation e.g. on a cross-section of the illuminated area ("streak-camera" - images). In order to avoid as much as possible thermal nonlinearities, the measurements are done during a time of a few microseconds. For this purpose the light is admitted to the sample for about 5 μs, repeated every ms, using a mechanical chopper. For recording 2D images with good time resolution, in front of the CCD camera an electro-optical modulator is placed as a fast shutter, permitting recording with exposure times of down to 10 ns. The shutter is triggered after a variable delay with respect to the beginning of the sample illumination. Thus the evolution of the reflected light field can be followed in 2D when varying the trigger delay.

Optical "objects" (e.g. spatial intensity variations) in the light field move according to the field gradients in phase and intensity [6]. Thus, as long as there are well-defined gradients in the field, the time evolution of the 2D field is completely reproducible in each successive illumination. Consequently, averaging over several illuminations is possible to increase signal/noise ratio. The CCD camera in the usual TV-format reads out a frame every 40 ms i.e. it averages 40 illuminations. For the finite extinction ratio of the electro-optical modulator (300) we used a shutter aperture time of 50 ns. The latter can be chosen by the length of a Blumlein line driving the electro-optical modulator.

Fig. 1 shows the structures observed at $\lambda = 860$ nm, i.e. ≈ 10 nm in wavelength above the band gap and 5 nm above the exciton line center. Fig. 1b) shows a bright soliton (dark in reflection) on an unswitched background, 1c) shows a dark soliton (bright in reflection) on a switched background. For clarity 1a) shows a switched area without soliton.

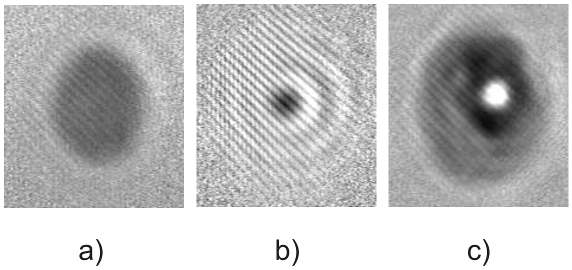

FIG. 1. Switched structures: reflectivity (reflected light/incident light) of the sample: a) switched domain (limited by a contour of Maxwellian intensity) at $\delta\lambda$ = -0.45 nm, power 75 mW; b) bright soliton (dark spot in reflection) at $\delta\lambda$ = -0.75 nm, power 160 mW; c) dark soliton (bright spot in reflection) at $\delta\lambda$ = -0.60 nm, power 360 mW;
Parameters are: λ = 860 nm, size of illuminated area 40 μm.

This switched area is surrounded by a switching front which (when raising the intensity of the illumination with a Gaussian laser beam) initially travels outward from the center of the beam until it stops at an intensity contour given by the Maxwellian intensity [7].

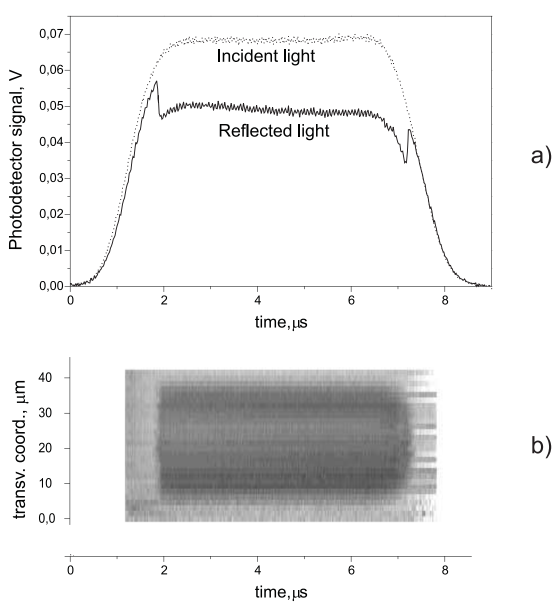

FIG. 2. Development of switched domain corresponding to Fig. 1a: a) incident (dashed) and reflected (solid) light intensity measured at the center of the Gaussian beam, b) evolution of switching front (transverse coordinate vs. time). Parameters as in Fig.1a.

The bright soliton exists on a background corresponding to the lower branch of the (plane-wave) bistability characteristic and the dark soliton on a background corresponding to the upper branch. The solitons Fig. 1b),c) develop above the illumination intensity which switches to the upper branch.
Figs 2,3,4 give "streak-camera" recordings of the formation of the structures Fig. 1. Formation of the switched domain 1a) is shown in Fig. 2. At time t $\approx$ 2 μs the resonator switches in the center of the laser beam and a switching front travels rapidly outward. It stops, because it reaches the Maxwellian intensity contour and the domain retains its size until the reduction of illumination shrinks the domain size and finally switches the resonator back to the lower branch.
The development of the bright soliton Fig. 1b) is given in Fig. 3. The resonator switches at t $\approx$ 1.5 μs and the switched-up domain develops as in Fig. 2. The incident light intensity here reaches a higher value than in Fig. 2, which apparently makes switched-up state modulationally unstable. The consequence is a subsequent shrinking of the switched-up domain to a small size which is stable.

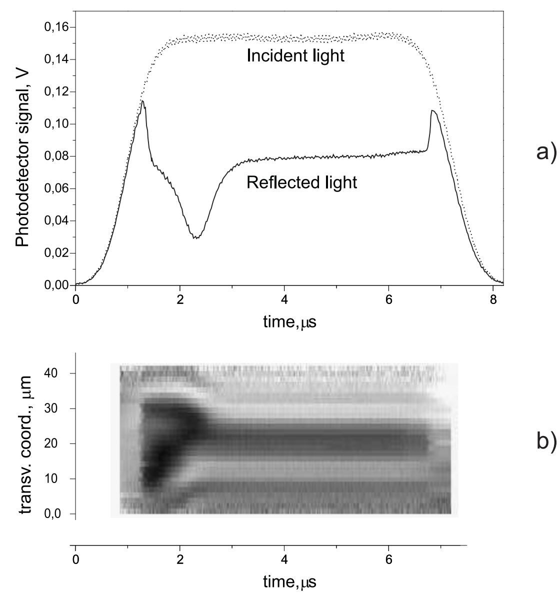

FIG. 3. Formation of bright soliton corresponding to Fig. 1b: a) incident (dashed) and reflected (solid) light intensity measured at the center of the Gaussian beam, b) evolution of switched structure (transverse coordinate vs. time).
Parameters as in Fig.1b.

We note several features of the stable structure which show its soliton properties:
1) Stable diameter in time;
2) Size of 10 μm as expected from model calculations [1,2];
3) Surrounded by characteristic rings due to the "oscillating tails" of the switching front [8];
4) Robustness: From t = 6.3 μs the incident light intensity drops , until the structure switches off at t = 6.8 μs. In spite of this change of illumination, the brightness of the structure remains constant. Such immunity against external parameter variation would seem characteristic for a nonlinearly stabilized structure;

5) We note the fast switch-off of the structure at t = 6.8 μs. The structure disappears abruptly at a certain intensity, in a manner suggesting a subcritical process. This allows to conclude that the nonlinearity is "fast" (electronic). A slow (e.g. thermal) nonlinearity would not allow such abrupt disappearance of the structure.
Due to the properties 1) to 5) we can identify the structure with a bright soliton based on a fast nonlinearity.

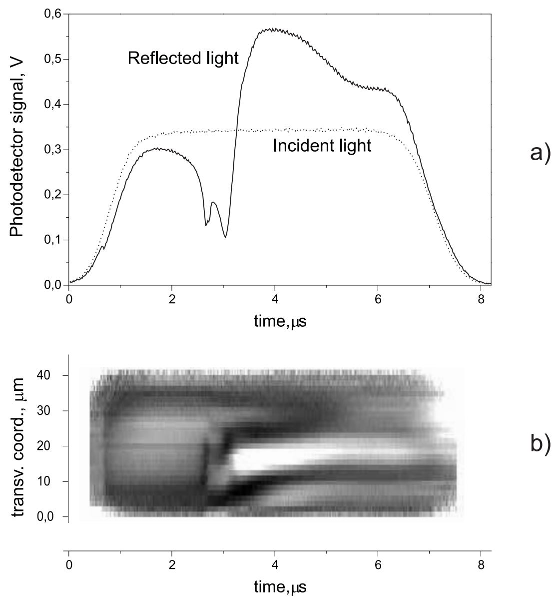

FIG. 4. Formation of dark soliton corresponding to Fig. 1c: a) incident (dashed) and reflected (solid) light intensity measured at the center of the Gaussian beam, b) evolution of switched structure (transverse coordinate vs. time). Parameters as in Fig.1c.

The development of the dark soliton structure (Fig. 1c)) is shown in Fig. 4. The resonator switches at t $\approx$ 0.7 μs, after which the illumination intensity is further substantially increased. Again, after a long transient the bright structure forms slightly off the beam center (compare Fig. 1c)). Surprisingly the reflected light intensity of the structure is almost two times higher than the incident light intensity, indicating that this structure collects light from its surrounding (see the dark surrounding of the bright spot in Fig. 1c)), as one might expect for a nonlinear structure.
The reduction of the brightness of the structure apparent in Fig. 4a),b) in the time 3.5 μs to 6.5 μs does not show a damping or disappearance of the structure but is rather due to a motion of the soliton in a plane perpendicular to the paper plane. Fig. 5 shows three 2D snapshots within the time 3.5 μs to 6.5 μs clearly showing this motion. This bright structure on a switched background which moves like a stable particle and is thus a dark soliton [2].

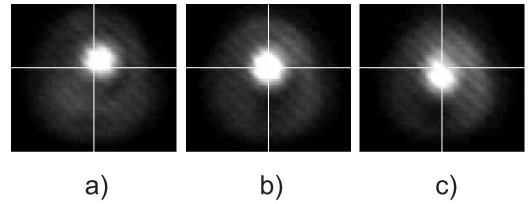

FIG. 5. Motion of dark soliton. Recording time 3.5 μs (a), 5 μs (b), 6.5 μs (c) after start of illumination.

The long formation time of these solitons appears related to "critical slowing". We found that the formation time for the solitons is reduced by a factor of 10 upon increase of the illuminating intensity by only 10 %.

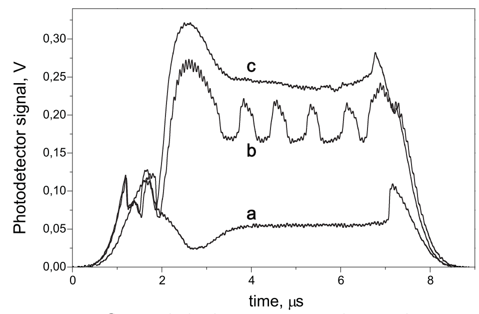

FIG. 6. Reflected light measured at the center of the Gaussian beam. Parameters are: $\delta\lambda$ = -0.8 nm, power 130 mW (a), 245 mW (b) and 270 mW (c).

Fig. 6 gives the field dynamics for fixed detuning $\delta\lambda$ of the laser frequency from the resonator resonance frequency and increasing light intensities. Fig. 6a) corresponds to the bright soliton Fig. 1b) for small intensity. Fig. 6b) shows an unstable (pulsing) dark soliton at medium intensity and 6c) gives the case of the stable dark soliton as in Fig. 1c) for high intensity. Note that the transient period between switching of the resonator (t = 1.3 μs for 6b), 6c)) and the onset of the dark soliton is here reduced compared to Figs 3,4 due to the higher intensity (critical slowing). The two minima of the reflected light before the onset of the soliton in Fig. 4 a) which are related to spatial structure (Fig. 4b)) also appear in Fig. 6b),c).

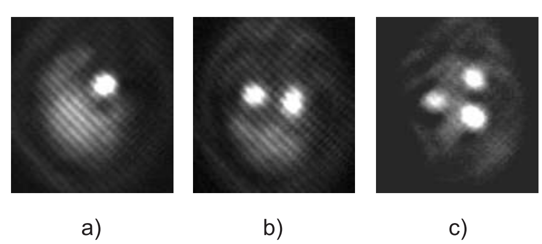

FIG. 7. Dark solitons observed in the switched area (intensity).

In the Figs 1-6 we have shown the cases where only one soliton exists. In general, at higher intensities / at later times in the illumination, several solitons can exist. Fig. 7 shows as an illustration 1, 2, 3 solitons existing simultaneously. We have observed up to 5 simultaneous solitons.

Concluding, we find at wavelengths corresponding to a wavelength detuning of about one exciton linewidth above the exciton line center and at high (negative) resonator detuning the existence of bright and dark resonator solitons as predicted in [1] and [2] respectively. The bright solitons appear stable, while the dark solitons are observed to move in space and to pulse, which makes them appear as less stable objects than the bright solitons.

Acknowledgements
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