Appl. Phys. B 72, 893–895 (2001) / Digital Object Identifier (DOI) 10.1007/s003400100599

Applied Physics B
Lasers
and Optics

Rapid communication

Incoherent optical switching of semiconductor resonator solitons

V.B. Taranenko*, **C.O. Weiss**

Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany
(Fax: +49-531/592-4423, E-mail: victor.taranenko@ptb.de)

Received: 22 February 2001/Published online: 27 April 2001 –

Abstract. We demonstrate experimentally the bistable nature of the bright resonator solitons in a semiconductor microresonator with mixed absorptive/defocusing nonlinearity and show that they can be written and erased by incoherent local optical injection.

PACS: 42.65.Sf; 42.65.Pc; 47.54.+r

Spatial optical solitons, i.e. light beams propagating without transverse spreading, form when diffraction is balanced by a nonlinear process such as self-focusing in a nonlinear dispersive medium. Light inside an optical resonator filled with a nonlinear medium can also form stable filaments, or resonator solitons, as a result of a more complex balance involving additional resonator detuning. In contrast to propagation solitons, resonator solitons can exist not only for self-focusing but also for self-defocusing and absorptive nonlinear media [1, 2]. The resonator solitons are free to move in the resonator cross-section (or move by themselves [3]), which implies their bistability, and ability to carry information. The mobility of resonator solitons, however, makes them different from fixed binary elements, so that new types of information processing have been considered [4], making use of spatial resonator solitons.

Early observations of localization of resonator structures in slow materials were given in [5, 6]. We investigated in the past spatial resonator solitons of phase-type [7] and intensity-type [8], including experiments demonstrating large simultaneous collections of solitons [9] and their manipulation [8] as required for applications. These experiments were conducted using slow nonlinear materials, for the sake of easy observeability of the complex 2D space–time dynamics. For practical purposes, however, speed is of importance and compatibility with semiconductor technology is desirable. Spatial solitons and their switching in semiconductor microresonators have therefore been predicted theoretically [1, 2, 10]. With the aim of realizing spatial solitons in semiconductor resonators, experiments were conducted recently with passive resonators [11] and with resonators with population inversion [12]. We showed the spontaneous formation of bright and dark spatial semiconductor resonator solitons in [13]. We demonstrate here the bistable nature of the bright spatial semiconductor resonator solitons by local switching experiments and show the incoherent writing and erasing of the bright solitons [14].

The experimental arrangement (Fig. 1) was essentially as described in [11, 13]. The resonator consists of two Bragg mirrors of about 99.5% reflectivity and 18 pairs of $GaAs/Ga_{0.5}Al_{0.5}As$-quantum-wells between them. A Gaussian beam from a $Ti:Al_2O_3$-laser illuminates the semiconductor resonator sample in an area of 40 μm. It provides a reasonably large Fresnel number since the optical resonator length is only about 3 μm. The working wavelength (860 nm) is chosen to be 10-nm red-shifted from the absorption band edge, where nonlinearity is mixed absorptive/defocusing. At the same time the working wavelength is blue-shifted (≈ 0.7 nm) with respect to the resonator resonance as necessary for soliton formation [4]. Observations are done in reflection because the substrate material (GaAs) is opaque at the working wavelength.

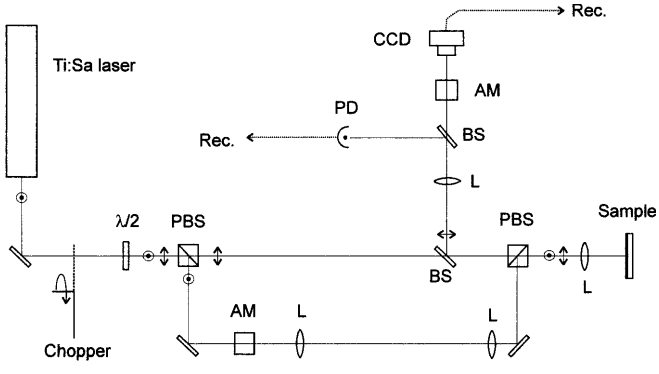

Fig. 1. Optical arrangement: λ/2, halfwave plate; PBS, polarizing beam splitters; AM, electro-optical amplitude modulators; L, lenses; BS, beam splitters; PD, photodiode. Lenses in the lower arm form a telescope, polarizations indicated

*Corresponding author.

The laser light is modulated by a mechanical chopper, limiting illumination to durations of a few μs, in order to minimize thermal nonlinear effects. The repetition rate of the illuminations is 1 kHz, permitting stroboscopic recordings of the dynamics, or signal averaging. Part of the laser light is split away from the main beam for local injection into the illuminated sample area. Polarization of the injection light is perpendicular to that of the main beam to avoid interference, so that intensities, instead of fields, add. The injection is applied in pulses of several tens of nanoseconds duration using an electro-optic modulator (EOM). The light reflected from the sample is imaged onto a CCD camera. For time-resolved observations another EOM in front of the camera (50-ns aperture time) is used, which is opened with a variable delay with respect to the start of the illumination. The 2D intensity can thus be recorded for arbitrary moments during the illumination. Further, the intensity in a particular point can be monitored by a small area photodiode PD. In the observations reported, the intensity of the main beam was chosen so that only one bright soliton (dark in reflection) would appear (at the center of the main beam). The small-area photodiode PD measures the intensity at the beam center.

Figure 2 shows the switch-on of a bright soliton. The illuminating intensity rises initially due to the mechanical chopper opening. The maximum intensity is below the switching intensity for the bistable resonator. At $t \approx 3.9$ μs the injection beam of width 10 μm is opened for 70 ns to switch the resonator. During the switch, initiated by the injection pulse, a switching front travels radially outward [11] and forms a switched area surrounded by the switching front (left inset in Fig. 2). The switching area then collapses into a spot of about 10-μm diameter (right inset in Fig. 2), the expected size of a soliton for this resonator (for details see [13]). This collapse takes place from 4 to 5 μs. After 5 μs a stationary soliton exists, as shown in the right inset of Fig. 2. When the incident illumination (dotted trace) is finally decreased (chopper closes) the soliton switches off.

Figure 2 demonstrates thus that the bright soliton can be switched on by an external control beam, implying the bistability of the soliton. The fast switch on and off indicates that material nonlinearity responsible for switching would be electronic.

The relatively slow collapse of the switched area probably indicates a thermal effect: after the resonator switches on the intracavity intensity increases, heating the material. A rising temperature leads to the well-known red shift of the semiconductor absorption band edge [15]. This in turn leads to a shift of the bistability curve to higher intensity. Thus, the low-intensity switching point, near which solitons are stable [1, 2], comes to lie close to the incident intensity. The soliton formation after injection thus proceeds as for the spontaneous case [13].

Figure 3 shows the switching off of a bright (dark in reflection) soliton. The illumination intensity in Fig. 3a is chosen above the switching intensity of the resonator so that a soliton forms spontaneously as described in [13] during the transient phase from about 2.4 to 3.5 μs. At about 3.5 μs a stationary soliton exists (central inset in Fig. 3). At about 3.9 μs the injection beam (same properties and alignment as for Fig. 2) is opened. This switches the soliton off and returns the whole resonator to the unswitched state (right inset in Fig. 3). In Fig. 3a it is surprising that after the switch off the soliton does not form again spontaneously. This indicates that the switching threshold at 2.5 μs is lower than after the

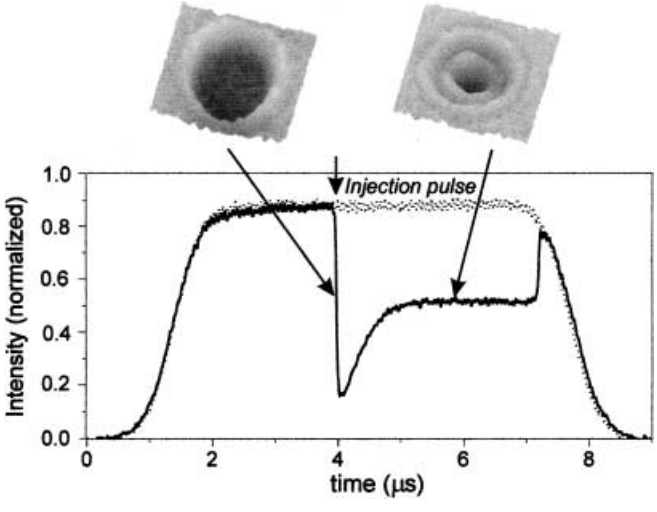

Fig. 2. Recording of the intensity reflected from the sample at the center of the illuminating beam, when switching a soliton on. Snapshot pictures show a circular switched domain (*left*) and a soliton (*right*). *Dotted trace*: incident intensity. The absolute intensity is the same in Figs. 2–4.

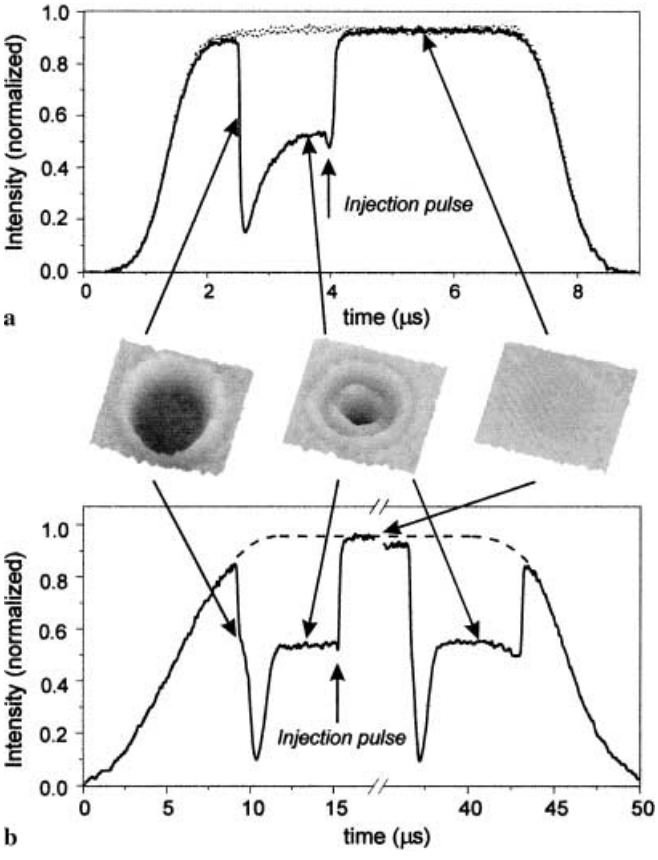

Fig. 3a,b. Recording of the intensity reflected from the sample at the center of the illuminating beam. A soliton is formed spontaneously and then switched off by external injection. The insets *left*, *center*, *right* show intensity snapshots, namely switched domain (as Fig. 2), soliton (as Fig. 2) and unswitched state, respectively. *Dotted trace* (**a**), *dashed trace* (**b**): incident intensity

switch back ($\approx 4.4\,\mu s$). Such an increase is compatible with the above interpretation of the thermal shift of the bistability curve. To prove this, the recording time was extended. Figure 3b shows indeed that after a longer time ($\approx 33\,\mu s$) the soliton switches on again spontaneously.

Apparently during the time from $15\,\mu s$ to $33\,\mu s$ the temperature has decreased, bringing the switching threshold to below the incident intensity.

Figure 4 shows that the switching off of the soliton requires a minimum intensity in the external beam. Here the external beam is opened at $t \approx 3.9\,\mu s$ with an intensity 10% smaller than in Fig. 3. The soliton in this case is transiently perturbed, but remains stably switched on.

In summary, we have shown that bright spatial solitons of a semiconductor resonator can be switched on and off by an external incoherent address beam. Thus, we demonstrate that such solitons are controllable as required for applications. The bistable nature of the solitons is unambiguously demonstrated. The switch-on mechanism observed presently is too slow for fast processing applications. We attribute this to thermal effects and assume that better heat sinking of the sample would directly switch on the bright solitons, without the long transient soliton formation phase.

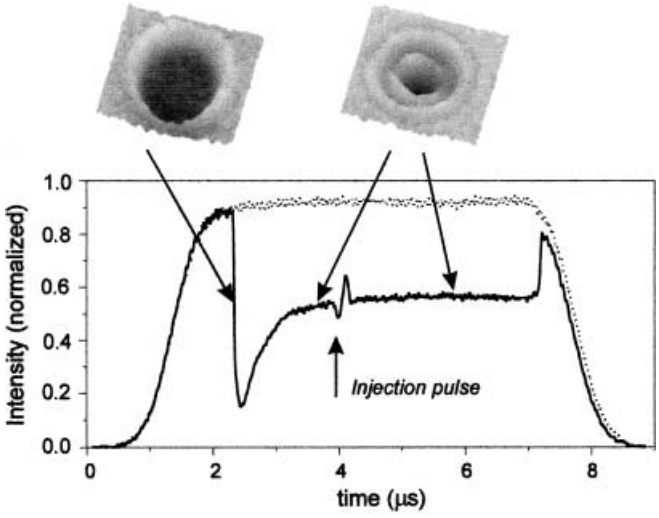

Fig. 4. Failed switch-off of soliton. Intensity of the injected beam too small to switch soliton off. *Dotted trace*: incident intensity

Acknowledgements. This work was supported by the ESPRIT LTR project PIANOS. The quantum-well semiconductor sample was provided by R. Kuszelewicz, CNET, Bagneux, France.

References

1. M. Brambilla, L.A. Lugiato, F. Prati, L. Spinelli, W.J. Firth: Phys. Rev. Lett. **79**, 2042 (1997)
2. D. Michaelis, U. Peschel, F. Lederer: Phys. Rev. A **56**, R3366 (1997)
3. K. Staliunas, V.B. Taranenko, G. Slekis, R. Viselga, C.O. Weiss: Phys. Rev. A **57**, 599 (1998)
4. W.J. Firth, G.K. Harkness: Asian J. Phys. **7**, 665 (1998)
5. M. Kreuzer, H. Gottschling, T. Tschudi, R. Neubecker: Mol. Cryst. Liq. Cryst. **207**, 219 (1991)
6. B. Fischer, O. Werner, M. Horowitz: Appl. Phys. Lett. **58**, 2729 (1991)
7. V.B. Taranenko, K. Staliunas, C.O. Weiss: Phys. Rev. Lett. **81**, 2236 (1998)
8. V.B. Taranenko, K. Staliunas, C.O. Weiss: Phys. Rev. A **56**, 1582 (1997)
9. G. Slekis, K. Staliunas, C.O. Weiss: Opt. Commun. **149**, 113 (1998)
10. D. Michaelis, U. Peschel, F. Lederer: Opt. Lett. **23**, 337 (1998)
11. V.B. Taranenko, I. Ganne, R. Kuszelewicz, C.O. Weiss: Phys. Rev. A **61**, 063818-1 (2000)
12. T. Ackemann, S. Barland, M. Cara, M. Giudici, S. Balle: In *Nonlinear Guided Waves and Their Applications*, OSA Technical Digest (1999) p.53
13. V.B. Taranenko, I. Ganne, R. Kuszelewicz, C.O. Weiss: Appl. Phys. B **72**, 377 (2001)
14. V.B. Taranenko, C.O. Weiss: Los Alamos Preprint Server nlin. PS/0003004
15. T. Rossler, R.A. Indik, G.K. Harkness, J.V. Moloney, C.Z. Ning: Phys. Rev. A **58**, 3279 (1998)