We show experimentally the existence of bright and dark spatial solitons in semiconductor resonators for excitation above the band gap energy. These solitons can be switched on, both spontaneously and with address pulses, without the thermal delay found for solitons below the band gap which is unfavorable for applications. The differences between soliton properties above and below gap energy are discussed.

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We have recently shown that spatial solitons of various characteristics can exist in nonlinear optical resonators [1], confirming various theoretical predictions [2]. Our motivation for such investigations is the common property of bistability and mobility of all such optical spatial solitons, possibly useful in optical parallel information processing. For such applications semiconductor resonators are best suited. Technically the resonator structures needed are rather precisely the structures used today for vertical-cavity surface-emitting lasers (VCSEL), i.e. a stack of quantum wells between Bragg mirrors.

For such structures in the dispersive limit we found the hexagonal structure formation [3] theoretically predicted for nonlinear dispersive resonators [4] and demonstrated local switching of individual spots of the structure with address pulses [5]. Closer to the band gap of the quantum well material we were recently able to show the existence of bright and dark spatial solitons [5]. The dynamics of formation of these solitons [5] observed during experiments for switching bright solitons on and off by local addressing [6] was, however, found dominated by dissipation and occurs thus with characteristic times of $\sim 1$ $\mu$s, somewhat slow for most applications. We find here that when working inside the absorption band, i.e. above the band gap energy, (i) bright and dark solitons do also exist and (ii) can be switched on apparently without the delay due to thermal dissipation.

For the experiments on structures and solitons below or near band gap we had used a resonator structure originally grown for experiments on dispersive optical bistability. The resonance wavelength of the resonator varies over the sample area from 30 nm longer than, to close to the band gap wavelength.

For the experiments inside the absorption band we use a structure originally grown for use as an optically pumped picosecond VCSEL [7]. For this sample the resonator resonance lies 10 nm shorter than the band gap (exciton-) wavelength. The reflectivity of the Bragg mirrors is 99.5 % and consequently, due to the high linear absorption of the QW-material the resonance can not be detected linearly. We found the resonance wavelength for a particular point of the sample by applying a high laser field and observing the (nonlinear) response.

For the measurements a set-up was used as described in [3]. It consists briefly of a $cw$ tunable Ti:Al$_2$O$_3$-laser of a few hundred mW power, permitting to illuminate an area of 50 to 100 $\mu$m diameter on the sample, and detection equipment for time-resolved recording of the light reflected from the sample. This is a camera allowing to take snapshot pictures with a time resolution of 10 ns, and a small area photodiode with 1 ns response, which could be imaged into particular points of the illuminated area, thus allowing to record the reflected intensity as a function of time, locally. Mostly this photodiode is used to construct "streak"-images of the intensity on a diameter across the illuminated area as described in [3], to visualize the soliton formation dynamics. A tightly focused "address"-beam (of spot diameter 8 $\mu$m) split off from the illumination beam is used to apply locally short switching pulses (20 ns). As the polarisation of the address beam is perpendicular to that of the illumination beam, the switching is incoherent (i.e. by local carrier generation, and not by interference of light). Although the sample used was designed as a laser, it showed bistability readily, as can be expected for the parameters of the structure [7].

FIG. 1. 3D representation of reflectivity. Bright soliton above band gap (a, b). Due to observation in reflection the bright soliton appears dark. a): view from above, b): from below, c): dark soliton.

Analogously to the excitation below/near band gap [5] at smaller illumination bright solitons form and at higher intensity dark solitons. Fig. 1 (a,b) shows the bright solitons as observed in the reflected light with their charac-
teristic concentric rings \[8\] with the same appearance as the bright solitons below band gap. Dark solitons (Fig. 1 c) also look similar to the excitation below band gap \[5\]. As to be expected the laser field had to be blue-detuned with respect to the resonator to permit structure formation by "tilted waves" \[9\].

**FIG. 2.** Comparison of bright soliton formation above band gap (left) and below band gap (right). b), d) reflectivity on a diameter of the illuminated area as a function of time. a) c) intensity of incident (dotted) and reflected (solid) light, at the center of the soliton as a function of time. Arrows mark the switch-on and -off.

Fig. 2 compares the dynamics of the bright soliton formation for excitation above band gap (left) and below band gap (right). For the latter case the solitons form (spontaneously) in the following way: When the illumination intensity is increased, a larger area of the resonator is switched rapidly. This switched area contracts subsequently slowly to form the stable soliton. When the intensity is reduced, the soliton is switched-off, as one would expect.

This relatively slow soliton formation can be understood using a simple model (similar to \[10\]) for the intracavity optical field \(E\) and carrier density \(N\):

\[
\begin{align*}
\frac{\partial E}{\partial t} &= E_{in} - E[1 + 2C\text{Im}(\alpha)(1 - N)] - iE[\theta - 2C\text{Re}(\alpha)N - \nabla^2 N], \\
\frac{\partial N}{\partial t} &= -\gamma[N - |E|^2(1 - N) - d\nabla^2 N],
\end{align*}
\]

where \(\text{Re}(\alpha)N\) is used to describe the reactive nonlinearity. All other notations as in \[10\]. From (1) we obtain the reflected intensity as a function of incident intensity for wavelengths above \((\text{Re}(\alpha)>0)\), as well as below the band gap \((\text{Re}(\alpha)<0)\), for plane waves (Fig. 3). One sees that the bistability range is large below and small above the band gap. Solving (1) numerically the typical bright soliton (top of Fig. 3) is found coexisting with homogeneous intensity solutions in the shaded regions of Fig. 3 a,b.

After switching on the resonator below band gap (Fig. 3b), the intensity in the resonator is high and with it the thermal dissipation. The temperature consequently rises, which shifts the band gap \[11\] and with it the bistability characteristic, so that the switch-off intensity, close to which the stable solitons exist, becomes close to the incident intensity. Then the resonator is in the basin of attraction for the solitons and the soliton forms as observed in Fig. 2 c,d.

**FIG. 3.** Steady-state plane wave solution of Eq.(1) above band gap a): \(\text{Re}(\alpha) = 0.05\); and below band gap b): \(\text{Re}(\alpha) = -0.05\). Other parameters: \(C = 15\), \(\text{Im}(\alpha) = 0.99\), \(\theta = -3\), \(d = 0.1\). The soliton solution shown exists for incident intensities corresponding to the shaded areas, in co-existence with homogeneous solutions. For a temperature increase the characteristics together with soliton existence ranges shift to higher incident intensities. Reflected and incident intensities normalized to the same value.

**FIG. 4.** Bistability characteristics (reflected light intensity versus incident light intensity) measured at the center of an illuminated area of 100 \(\mu\)m diameter, for above band gap (a)) and below band gap (b)) excitation.

Above the band gap Fig. 2 a,b show that the soliton is switched on immediately without the slow thermal process. Fig. 3a shows why. The plane wave characteristic of the resonator above band gap is either bistable but very narrow, or even monostable (due to the contribution of the self-focusing reactive nonlinearity \[12\]) but still with bistability between the soliton state (not plane wave) and the unswitched state. In this case the electronic switching leads directly into the basin of attraction for solitons and the switch-on of the soliton is purely electronic and fast. The width of the bistability characteristics observed
experimentally (Fig. 4) scale in agreement with Fig. 3.

Nonetheless, also above band gap there is strong dissipation after the switch-on. The associated temperature rise influences and can even destabilize the soliton. The effect can be seen in Fig. 2a. Over a time of a few µs after the soliton switch-on the soliton weakens (reflectivity increases slowly) presumably by the rise of temperature and the associated shift of the band gap. At 6.5 µs the soliton switches off although the illumination has not yet dropped.

**FIG. 5.** Spontaneous repeated switching on and off of a bright soliton due to thermal dissipation.

**FIG. 6.** Switching on an above band gap soliton with an address pulse. Arrow marks application of the pulse. Incident light at soliton center, dotted; reflected light intensity at soliton center, solid.

Thus, while the dissipation does not hinder the fast switch-on of the soliton, it finally destabilizes the soliton. After the soliton is switched off, the material cools and the band gap shifts back so that the soliton could switch on again. Fig. 5 confirms this by observing for a longer time.

**FIG. 7.** Spontaneous direct switch-on of above band gap soliton which remains stable in the presence of heating. The initial switch-on of soliton (t = 1.8 µs) is fast. The further decrease of reflected intensity (i.e. increase of intracavity soliton field) follows adiabatically the incident intensity.

In summary, we find that for excitation above the semiconductor material band gap spatial resonator solitons exist and can be directly switched on without the delay due to thermal dissipation, as it is found for excitation below the band gap. Conditions can be found where this direct switch-on is not accompanied by destabilization of the solitons due to the heating. Thus, fast switching of spatial solitons as required for applications is compatible with stable solitons even with strong heat dissipation. We understand the different soliton formation dynamics above and below band gap in terms of the different widths of the resonator plane wave bistability characteristics. The structure used for the observation of above band gap solitons was a vertical cavity laser.

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