Observation of gain-pinned spatial dissipative solitons in a microcavity laser

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Solitons are localised, stable waves created when the effects of dispersion or diffraction are compensated by nonlinearity. In the presence of gain and loss in the system, a balance between them has to be achieved to sustain a localised dissipative mode. Dissipative solitons can be generated in semiconductor microcavity lasers that can be used as building blocks in all-optical information processing. However, such implementation requires precise bistability conditions arising from coherent feedback, which are difficult to realise experimentally. Here, we demonstrate an alternative approach: we shape the spatial gain profile of a microcavity laser with a nonresonant optical pump to create spatially localised modes that are stabilised by nonlinear losses and confined in a diffraction-limited volume. Furthermore, the ultrafast formation dynamics of gain-pinned solitons is directly probed, showing their creation on a picosecond timescale, orders of magnitude faster than for the laser cavity solitons. This approach offers novel possibilities for ultrafast all-optical manipulation of light confinement in semiconductor devices.

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The last decades of research in nonlinear optics have brought an immense wealth of systems and material configurations in which solitons can be created\textsuperscript{1}. In conservative optical systems, spatial solitons are supported by nonlinearity compensating for the diffraction of light in the propagating geometry\textsuperscript{2-4}. Real-world photonic devices suffer from intrinsic losses, e.g. via photon escape out of the structure, and it is essential to achieve the balance not only between the diffraction and nonlinearity, but also in the energy flow, i.e. between gain and loss of the system, to support self-sustaining solitary modes. Temporal dissipative Kerr solitons, recently realised in ring microcavity resonators, are considered to be a very promising platform for various applications in miniaturisation of time standards, frequency metrology systems\textsuperscript{5,6} or mode-locked lasers\textsuperscript{7}. Another type of spatially localised dissipative structures has been successfully created in broad area vertical cavity surface emitting lasers (VCSELs)\textsuperscript{8-10}. In this configuration, the device is kept below the lasing threshold, while the use of an additional external coherent holding laser beam, coupled to an external cavity mirror, or to a saturable absorber to set up an optical bistability condition, leads to the creation of stable localised modes. Their control is implemented with an additional external writing laser beam or pulse\textsuperscript{11,12}. These stable, spatially localised structures are called cavity solitons, as they are not created in a propagating geometry in the device, but rather confined within the optical microcavity containing the active medium.

In the opposite regime, when the laser device is driven above the threshold, the spatially uniform gain alone\textsuperscript{13} (without a coherent holding beam) is not capable of sustaining a localised bright mode which becomes unstable due to the action of the gain outside of the bright soliton core. Therefore, another approach has to be implemented to overcome the competition between the coherent holding beam and the gain lasing field. One can imagine modifying the spatial gain profile in the device to overcome this issue. A straightforward way is to contain gain in a small spatial volume, where the loss outside of this ‘hot spot’ can provide a balance between gain and loss around the bright soliton core\textsuperscript{14}, see Fig. 1a. Dissipative solitons pinned by a localised gain have been intensively studied \textit{theoretically}, and their realisations in various systems were proposed\textsuperscript{15}. These so-called \textit{gain-pinned solitons} have been predicted to be robust and stable over a wide range of parameters even in the absence of Kerr nonlinearity in the medium. In particular,
a one-dimensional complex Ginzburg-Landau model with an infinitesimally localised gain in a dissipative medium supports an exact soliton solution\textsuperscript{15,16}:

\begin{equation}
E(x) = A \sinh(\kappa(|x| + \xi))^{1+\mu},
\end{equation}

where \( A \) is the amplitude of the mode, \( \mu \) is the chirp coefficient and \( \kappa, \xi \) determine the shape of the soliton envelope function. It is not a generic solution, as the analytical form is only available under a constraint on the parameters. Nevertheless, it has been shown numerically that this type of solution represents a broader family of modes\textsuperscript{16}. Moreover, the localised dissipative solitons are expected to be stabilized in systems with non-negligible nonlinear losses\textsuperscript{15,16}.

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**Figure 1.** Gain-pinned dissipative soliton and the experimental characterisation of the one-dimensional microcavity laser. a, Schematics of the experimental realisation. The pumping laser beam is focused on a small area of the quasi-one-dimensional microcavity laser supporting a pinned soliton mode. The dimensions of the microlaser stripe are indicated in the figure. b, Dissipative soliton shapes simulated with a constant linear pump of finite width under assumption of linear (black line) and nonlinear loss (green line) in the system (parameters given in Methods section). c, Dispersion of the nonlinear refractive index \( n_2 \) and the two-photon absorption coefficient (2PA) for GaAs (cavity spacer material), calculated after ref. 18. The indication of the spectral position of the cavity mode is given by a shaded area. d, Power dependent input-output series of an investigated microcavity laser showing typical threshold behaviour. Far-field spectra of the lasing mode below - e, and at the lasing threshold - f. Blueshift and narrowing of the lasing mode is observed. Dashed line indicates the cavity photon momentum dispersion. g, Real-space image of the spatial shape of the lasing soliton mode for \( P = 3.3P_{th} \). h, The same as in g but in logarithmic colour scale to enhance visibility of the low intensity signal. Red circle indicates the gain spot.
In a realistic model of an experiment, the gain spot has a finite spatial width convolved with the analytical shape of the solitary mode, see Fig. 1b. In the simplest case of linear losses in the cavity (photon escape rate), without the bulk Kerr nonlinearity, the mode’s profile is trivial and is characterised by exponential decay outside of the gain spot (black line in Fig. 1b)\textsuperscript{14}. However, the shape is considerably changed when a nonlinear loss, i.e. two-photon absorption, is also present (green line in Fig. 1b). In this case, the dissipative nonlinearity focuses the robust solitary mode to the volume limited by the gain spot, which is translated into the modified mode shape.

In this work, we present a proof-of-concept experimental realisation of a gain-pinned spatial dissipative soliton in the experimental configuration schematically shown in Fig. 1a. We create a gain spot with a focused, pulsed, nonresonant laser beam tuned above the bandgap of the cavity material (GaAs), and generate a dynamical spatial soliton. The observed lasing mode is confined to a volume around the area of the resolution-limited gain. Subsequently, we track the ultrafast dynamics of the soliton formation, the evolution of the spatial profile and the profile narrowing, as well as the far-field emission by streak camera measurements. Additionally, we measure the soliton onset times of the order of few picoseconds, which is orders of magnitude faster than the previously reported cavity soliton manipulation dynamics\textsuperscript{10–12}, and comparable to bright exciton-polariton soliton excitation timescales\textsuperscript{17}.

Results

Experiment

Following the existing theoretical proposals, we implement an experimental realisation of one-dimensional spatial dissipative solitons in a semiconductor microcavity laser, as shown in Fig. 1a. The cavity structures were processed by lithography and etching from a planar GaAs-based VCSEL sample in the form of stripes of hundreds of micrometres in length and only a few in width, creating effective one-dimensional confinement of optical modes (see Fig.1a and Methods for details). The localised gain is provided by a pulsed laser source, frequency-tuned above the GaAs bandgap for efficient photo-excitation of electron-hole pairs. The laser spot is focused to a diffraction limited spot on the surface of the cavity stripe. In contrast to typical GaAs-based waveguide designs for optical soliton experiments, where the detrimental effects of
nonlinear losses are kept to a minimum\textsuperscript{3,4}, our sample design places the fundamental cavity mode in the spectral range where the refractive index nonlinearity is small and defocusing, and most importantly, where significant nonlinear losses due to the two-photon absorption are expected to occur\textsuperscript{18}, see Fig. 1c. These material characteristics provide the conditions for the generation of gain-pinned dissipative solitons, as indicated by the theoretical models\textsuperscript{15}. Additionally, the nonlinear loss channel is known to be more pronounced in photonic devices due to a small volume of the confined photon mode\textsuperscript{19–22}, effectively lowering the total power densities at which the nonlinear effects occur. This property makes our system most suitable for exploiting the nonlinear loss in the process of soliton formation.

\textbf{Figure 2. Experimental dynamics of the soliton creation and decay.} \textbf{a, b,} Time-resolved spatial dynamics of the soliton mode emission respectively in linear and logarithmic colour scale at pump power $P=3.3 \, P_{th}$. \textbf{c,} Far-field dynamics of the mode emission, where two distinct momentum wave vectors are visible and indicated with white dotted lines. \textbf{d,} Time dependency of the lasing soliton mode signal intensity and its spatial width (full width at half maximum - FWHM). Three different stages in the time dynamics are indicated in the figure: (I) lasing onset, (II) soliton creation and (III) diffraction and decay at later times. Region with low signal to noise ratio of the spatial width data is depicted with dotted line. \textbf{e, f,} Spatial distributions of the lasing mode at different times indicated in the figure. Red dashed curve is the soliton mode envelope curve fitted to the experimental data $|E|^2$ and the black dotted line indicates the Gaussian laser gain spot. \textbf{g,} Soliton mode compression dynamics under different pumping powers showing decrease of the minimal width with increasing number of photons and carriers. \textbf{h,} Minimal spatial width of the soliton, showing density-dependent narrowing of the lasing mode. Dashed line in \textbf{g,h} indicate the spatial resolution of the setup, simultaneously defining the minimum measurable width of the gain spot.
The power dependent measurements of the device luminescence output intensity reveal a typical lasing threshold (where $P_{th} = 29 \text{ pJ}/\mu \text{m}^2$), see Fig. 1d, being accompanied with the linewidth narrowing and the distinct blueshift of the emission mode energy (by about 3 meV), as seen in the far-field (wave vector space) spectra in Figs. 1e and 1f. This energy shift originates from the local cavity refractive index change due to the free carriers generated in the GaAs spacer of the cavity volume by a nonresonant pump pulse$^{21,23}$. Subsequently, carriers relax to quantum wells, creating an electron-hole plasma providing gain for the lasing mode. Nevertheless, the energy shift does not influence the stability of the observed soliton creation, as the soliton dynamics is weakly affected when the local potential modification is absent (see Supplementary Material). The broad momentum range of the far-field spectrum in Figs. 1e and 1f reflects the strong localisation of the mode observed in real space, Figs. 1g and 1h. The spatial extent of the lasing mode is constrained to the diffraction-limited gain spot ($\sim 1.5 \mu \text{m}$) in the longitudinal direction, and the sample dimensions in the transversal direction (mode width is about 4 $\mu \text{m}$). The mode volume could possibly be confined to an even smaller area by employing narrower microwire cavities or photonic crystal nanocavities$^{20}$.

The pulsed excitation used in the experiment results in a non-stationary, decaying lasing mode owing to the finite lifetime of the carriers and cavity photons in the system. Hence, we performed an analysis of the shape and dynamics of the solitary pulse in the direct time-resolved experiment imaging the emission with a streak camera (see Methods). The dynamics of the near and far-field emission patterns along the microcavity wire above the lasing threshold are presented in Figs. 2a-c with analysis of the spatial width and the signal intensity shown in Fig. 2d. One can distinguish three stages of the soliton laser dynamics. Firstly, the pump pulse creates high-energy electrons and holes in the barrier which relax and form a gain medium within the quantum well states. Then, after about 10 ps, the lasing occurs with a rapid narrowing of the mode’s spatial width down to the optical resolution limit of the setup (approx. 1.5 $\mu \text{m}$). Subsequently, the soliton pulse maintains its narrow width with the strongest emission of photons, and eventually it decays and undergoes diffraction at later times (after $t > 60 \text{ ps}$), which is evidenced in the increase of the spatial width, Fig. 2d. The latter stage is the linear regime, where the gain and nonlinearity are much lower and do not sustain the soliton shape anymore.
The duration of the solitary lasing is short, about 20-30 ps, with an ultra-short rise time of approximately 3 ps, being limited by the temporal resolution of the setup. The observed fast response is a result of the onset of the stimulated emission and the ultrafast dynamics of electronic semiconductor nonlinearities occurring on the timescales of few picoseconds\textsuperscript{21,24–26}.

The three characteristic regimes in the dynamics are also distinguishable in the spatial shape of the emission as presented in Figs. 2e, f. At the onset of lasing, when the emission intensity is low, the mode is weakly localised around the gain spot with exponential spatial decay. Subsequently, the lasing intensity rises, reaching a maximum at around $t = 37$ ps, and the nonlinear trapping occurs at high photon densities. The mode shape, see Fig. 2f, reveals the solitary solution discussed in Fig. 1 and follows the analytical expression of Eq. 1. The mode confinement is most likely caused by the presence of nonlinear losses in the system, as any other nonlinearity (e.g. due to the Kerr effects, or free-carriers related) has the opposite sign and would lead to a trivial spatial shape, as shown in Fig. 1b. Additionally, we can safely rule out thermal effects, which would have much longer timescales and manifest themselves in a redshift of the lasing mode energy\textsuperscript{27}.

The far-field spectrum of the dissipative soliton contains two distinct peaks (Fig. 2c) due to the outward propagation of photons from the gain spot. This shape is the consequence of a dynamical balance of the energy flow characteristic of dissipative solitons: an inflow due to the nonresonant pump and outflow because of the nonlinear losses, which stabilises the soliton\textsuperscript{1,14,15} (see the scheme in Fig. 1a). Moreover, backscattering of these propagating waves on the intrinsic disorder of the sample causes the characteristic interference pattern observed on top of the solitary mode. This effect is seen both in time integrated, Fig. 1h, and time-resolved images, in Fig. 2b. The disorder scattering in the sample adds a small spatial modulation to the soliton envelope, the latter being independent of the particular position on the sample. At longer times after the pulse, the nonlinear trapping decays along with the lasing signal and the mode is once again exponentially confined with additional disorder-induced modulation. The nonlinear mechanism of the mode trapping is also manifested in the density-dependent measurements, where one can see a sharp decrease of the soliton width above the lasing threshold, Fig. 2g,h. The
minimum measured soliton width is due to the setup resolution, being also the limitation for the gain spot diameter, and is indicated by an horizontal dashed line in Fig.2 g,h.

Numerical modelling

To verify the interpretation of our experiment proposed above and understand the observed dynamics, we performed numerical simulations based on a complex Ginzburg-Landau equation including nonresonant pumping and dissipation in the system, taking into account nonlinear losses and simplified dynamics of the photo-excited reservoir of carriers (see Methods). The reservoir of carriers not only provides the gain to the system, but also leads to a local modulation of the cavity refractive index, so-called linewidth enhancement factor, which drops down when the reservoir is depleted by the stimulated laser emission and nonradiative decay.

![Figure 3. Numerical simulations of the soliton dynamics.](image)

**Figure 3. Numerical simulations of the soliton dynamics.** Numerical simulations of the recorded time dynamics presented in Figure 2. a, b, Spatial dynamics of the computed soliton mode emission in linear and logarithmic colour scale. All characteristics of experimental data are well reproduced. c, Far-field dynamics of the mode emission. d, e, Spatial distributions of the lasing mode at two different times: presenting the soliton mode at 35 ps and the diffracted mode at a later time 90ps. The roughness of the profiles is due to the presence of disorder similar to the experiments. f, Mode spatial width decrease with pump amplitude, proving the nonlinear narrowing above pump threshold. The mode width is limited by the width of the simulated gain spot.
Our numerical simulations successfully reconstruct, as shown in Fig. 3, all the characteristic features seen in the experiment: the soliton shape and dynamics in the real space as well as the far-field spectra. As shown in Fig. 3c, the soliton mode is mainly composed of two spatial wave vectors and is localised around the gain spot in real space. Power-dependent simulations also yield the mode width decrease, see Fig. 3f, which is the manifestation of the nonlinear trapping mechanism. Inclusion of nonlinear losses in the model is essential for reproducing the experimental shape of the soliton, as the model with only linear losses does not capture the dynamics presented in Fig. 3, neither does it show the mode width narrowing, as in Fig. 1b. Our model includes also a random disorder potential with similar characteristics to the one measured experimentally, which slightly modulates the soliton shape as measured in the experiment (see Supplementary Information). The soliton shape is found to be robust to the change of the particular realizations of the disorder, which are kept within the experimentally measured values.

**Discussion**

We have demonstrated one-dimensional gain-pinned dissipative solitons in VCSELs for which: (i) the experimental realization is particularly convenient due to a nonresonant pumping, (ii) the soliton size is limited by the gain profile and is therefore much smaller than the typical VCSEL solitons\cite{8-11} and comparable to the size of exciton-polariton solitons\cite{17,28}, and (iii) the soliton formation dynamics, being driven by stimulated laser emission, is an ultra-fast process in the range of single picoseconds, orders of magnitude faster than cavity solitons and of the same order of magnitude as exciton-polariton bright solitons\cite{17,29}. Although in our experiment we have investigated a quasi-one-dimensional version of a VCSEL laser, our results pave the way towards creating stable two-dimensional solitary modes, which, as predicted theoretically\cite{30}, are within reach in modern semiconductor microcavities of similar design. Manipulation of the soliton position can be performed by spatial modulation of the excitation beam, offering exciting possibilities for the creation of two-dimensional vortex solitons\cite{30-32} or multi-soliton structures\cite{33}. Furthermore, gain-pinned solitons presented here, due to their robustness and simple realisation, could be arranged in lattices forming a platform for simulations of classical Hamiltonians\cite{34,35},
studies of complex topological ordering\textsuperscript{36,37}, and spontaneous symmetry breaking in laser systems\textsuperscript{33,38,39}.

\textbf{Methods}

\textbf{Experimental details}

The sample under investigations is an AlAs/GaAs $\lambda/2$-long microcavity composed of two distributed Bragg reflectors (DBRs) enclosing two stacks of four InGaAs/GaAs quantum wells located at the antinodes of the photon field. The ground state of quantum wells is located around 1.262 eV. The one-dimensional microwires were created via electron beam lithography and etched using electron cyclotron-resonance reactive-ion-etching. The semiconductor-air interface on sidewalls of the microwire provides the spatial confinement of the photon modes in one of the in-plane directions. The sample was kept in a continuous flow liquid helium cryostat at a temperature $T = 5$ K.

The excitation was provided by a mode-locked tunable Ti:Sapphire laser emitting 140 fs pulses with 76 MHz repetition. The laser spot was focused via a high numerical aperture objective lens ($\text{NA} = 0.42$) to a diffraction limited spot of about 1.5 $\mu$m width. The laser wavelength was tuned to the reflectivity minimum of the microcavity, above the GaAs bandgap, around 1.55 eV, providing local modulation of the cavity refractive index due to photogenerated carriers. The emission from the sample was collected via the same objective, and then further transferred through a set of achromatic lenses to a spectrometer for near-field and far-field imaging. The monochromator (0.5 m focal length, Princeton Instruments) outputs were connected to a two-dimensional InGaAs near-infrared camera (NIRvana Princeton Instruments) and to a Hamamatsu streak camera (temporal resolution of about 3 ps). For imaging purposes, the monochromator grating was set to the zero-order mode.

\textbf{Theoretical model}

The soliton mode dynamics were modelled with a complex one-dimensional Ginzburg-Landau equation describing the lasing mode electric field envelope function $E(x, t)$, coupled to a rate equation for the carrier reservoir $N(x, t)$ providing gain:
\[
\frac{\partial}{\partial t} E(x, t) = \frac{ic^2}{2k_c n_c^2} \frac{\partial^2}{\partial x^2} E(x, t) + \frac{1}{2} (\Gamma N(x, t) - \gamma_c - \beta |E(x, t)|^2) E(x, t) \\
- i\alpha N(x, t) E(x, t) - iV(x) E(x, t),
\]
(2)
\[
\frac{\partial}{\partial t} N(x, t) = P(x, t) - \gamma N(x, t) - \Gamma |E(x, t)|^2 N(x, t),
\]
(3)

Here, the cavity photons are described by an effective mass along the microcavity stripe \( m^* = \frac{E_c(k_l=0)}{(n_c/c)^2} \), where \( E_c = \hbar k_c c \) is the cavity photon energy, \( n_c \) is the cavity refractive index, \( c \) is the speed of light, and \( k_c \) is the confined longitudinal mode wavenumber. The gain in the system is described by the coefficient \( \Gamma' \), and the linear loss (cavity photon lifetime) is denoted by \( \gamma_c \). The nonlinear losses (e.g., two-photon absorption) in the system are described by \( \beta \). The reservoir decay rate is determined by \( \gamma \). The nonresonant pumping of the system is described by the term \( P(x, t) \). This term can be constant for continuous wave simulations or can be expressed as \( P(x)\delta(t = 0) \) for a pulsed excitation, setting the initial spatial density distribution of carriers in the microcavity. Local modifications of the cavity refractive index are introduced with the carrier density and scaled with the linewidth enhancement factor parameter \( \alpha \). The material disorder is described as a static potential \( V(x) \).

Simulations were performed with a following set of experimentally valid parameters: \( \gamma_c = 1 \text{ ps}^{-1}, \ \gamma_r = 1 \text{ ns}^{-1}, \ m^* = 3.12 \cdot 10^{-5} m_0 \), where \( m_0 \) is the free electron mass, \( \Gamma = 0.01 \mu\text{m/ps} \), \( \beta = 1 \mu\text{m/ps} \) and \( \alpha = 4.6 \cdot 10^{-3} \mu\text{m/ps} \).

Acknowledgements

M.P would like to acknowledge fruitful discussions with Yuri S. Kivshar. The work was supported by the National Science Centre in Poland, by grant No. 2016/23/N/ST3/01350. The Würzburg group gratefully acknowledges support by the State of Bavaria. Assistance by F. Langer, M. Emmerling, and A. Wolf during sample fabrication is acknowledged.

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**Author contributions statement**

M.P. conceived the research project. M.P. and M.S. carried out the optical experiments and together with G.S. analysed the data. M.P., D.P. and E.A.O. done the theoretical analysis and M.P. performed numerical simulations. C.S. and S.H. fabricated the sample. All authors contributed to the results discussion. M.P. wrote the manuscript with an input from all authors.