Soliton bound states in semiconductor disk laser

Evgeny A. Viktorov, Mantas Butkus, Thomas Erneux, Craig J. Hamilton, Graeme P. A. Malcolm, et al.

Evgeny A. Viktorov, Mantas Butkus, Thomas Erneux, Craig J. Hamilton, Graeme P. A. Malcolm, Edik U. Rafailov, "Soliton bound states in semiconductor disk laser," Proc. SPIE 9134, Semiconductor Lasers and Laser Dynamics VI, 913417 (2 May 2014); doi: 10.1117/12.2052534

SPIE.

Event: SPIE Photonics Europe, 2014, Brussels, Belgium

Soliton bound states in semiconductor disk laser

Evgeny A. Viktorov[a,b], Mantas Butkus[c], Thomas Erneux[b], Craig J. Hamilton[d], Graeme P. A. Malcolm[d], Edik U. Rafailov[c]
[a]National Research University of Information Technologies, Mechanics and Optics, 199034, Birzhevaya Liniya, 14, St Petersburg, Russia;
[b]Optique Nonlineaire Theorique, Universite Libre de Bruxelles, Campus Plaine CP 231 Bld du Triomphe, B-1050 Bruxelles, Belgium;
[c]Photonics & Nanoscience Group, School of Engineering, Physics and Mathematics, University of Dundee,Dundee, DD1 4HN, UK;
[d]M Squared Lasers Ltd, 1 Kelvin Campus, West of Scotland Science Park, Glasgow, G20 0SP, UK

ABSTRACT

We report what we believe is the first demonstration of a temporal soliton bound state in semiconductor disk laser. The laser was passively mode-locked using a quantum dot based semiconductor saturable absorber mirror (QD-SESAM). Two mode-locking regimes were observed where the laser would emit single or closely spaced double pulses (soliton bound state regime) per cavity round-trip. The pulses in soliton bound state regime were spaced by discrete, fixed time duration. We use a system of delay differential equations to model the dynamics of our device.

Keywords: semiconductor lasers; mode-locked lasers

1. INTRODUCTION

Mode-locked semiconductor disc lasers (SDLs) were recently a subject of intense research. Most valuable technical achievements include sub-100 fs pulse duration [1], average output power above 5 W [2] and high repetition rates up to 200 GHz [3]. Meanwhile, the typical repetition rate of the modelocked SDLs is in multi-GHz range [4]. The minimum repetition rate has been limited to 200 MHz which originates from ns carrier lifetimes in semiconductor material [5, 6].

SDLs are sufficiently different from solid state lasers which feature microsecond and millisecond material lifetimes that allows mode-locked solid state lasers operate at extremely low MHz repetition rates, and therefore, achieve large pulse energies [7]. Ultralow sub -100 MHz repetition rate will enable the use of SDLs as a seed source for regenerative amplifiers, and other new applications, especially where high peak power is an advantage [8, 9].

2. EXPERIMENTAL SET UP AND SAMPLES

The SDL gain structure operates at an emission wavelength of 980 nm and was grown by Metal Organic Vapour Phase Epitaxy (MOPVE). The gain section consisted of 16 InGaAs quantum wells sandwiched between GaAs barriers and strain compensating GaAsP layers. The structure was grown on top of a Distributed Bragg Reflector (DBR) which had 30 pairs of ¼ lambda thick GaAs/AlGaAs layers. Semiconductor chip (3x3mm2 size) was cleaved from the wafer and bonded to an intracavity diamond heat spreader using liquid capillary bonding technique. The heat spreader had a wedge of 2 degrees and was antireflection coated for both, pump and emission wavelengths.

A QD SESAM was chosen due to its low saturation fluence and faster recovery time as compared to its QW based counterparts [10, 11]. The SESAM was grown by Molecular Beam Epitaxy (MBE) and designed for 980 nm. The absorbing section contained 2 layers of InGaAs quantum dots (QDs) sandwiched between GaAs barriers. The absorbing structure was resonant and grown on top of a DBR which had 28 pairs of ¼ lambda thick GaAs/AlGaAs layers. The peak absorption was at 967 nm.

A multi-folded cavity was formed around the gain chip with a total cavity length of 1.76 m. The SESAM served as one of the cavity end mirrors. The temperature of heatsinks with gain and SESAM was set to 20 °C and 25 °C respectively. A commercially available fiber-coupled 808 nm diode laser was used as a pump source. The laser beam diameter was calculated to be 300 μm on the gain medium and 120 μm on the SESAM. The TEM00 mode output beam was linearly

Semiconductor Lasers and Laser Dynamics VI, edited by Krassimir Panajotov, Marc Sciamanna, Angel Valle, Rainer Michalzik, Proc. of SPIE Vol. 9134, 913417 · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2052534

polarized. A stable mode-locked operation was achieved by pumping the gain chip with 14 W of 808 nm light which resulted in 360 mW average output power.

3. EXPERIMENTAL RESULTS

In order to investigate the dynamical properties of the device, we used the standard set of measurements: time traces of laser output, radio frequency spectra and optical spectra. We observed two stable mode-locking regimes of operation: fundamental mode-locking and soliton bound state. The temporal patterns of the two regimes were measured using a photodetector with 29 GHz optical bandwidth . Figure 1 shows a fundamental mode-locked operation with the cavity round-trip time of 12 ns.

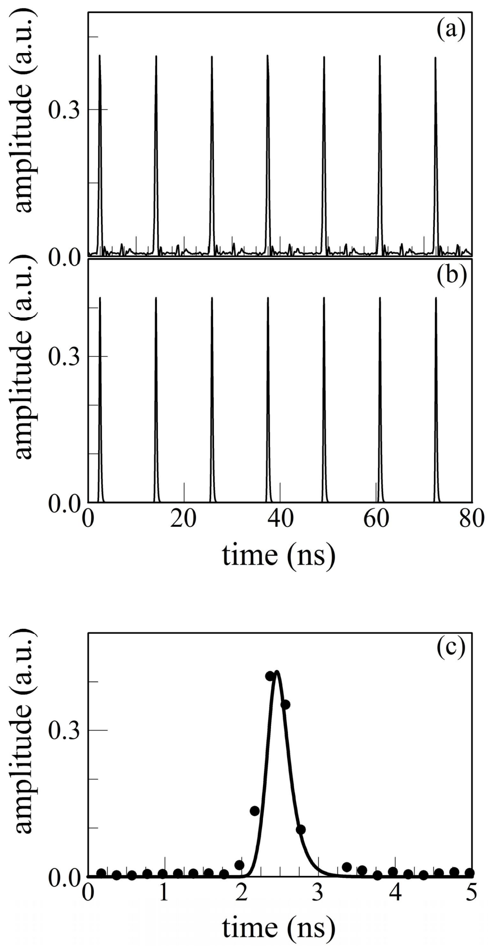

Figure 1. Fundamental regime of modelocking: an experimental pulse train (a), simulated pulse train (b). Pulse shapes calculated numerically (thin lines) and measured experimentally (dots) (c).

The alternative regime of the soliton bound state where two pulses spaced by fixed time interval of 1 ns were circulating in the cavity is shown in Figure 2. The pulse width was ~ 60 ps in the fundamental and ~50 ps in the soliton bound state regimes, the difference is most likely due to the binding energy required for the formation of the bound state.

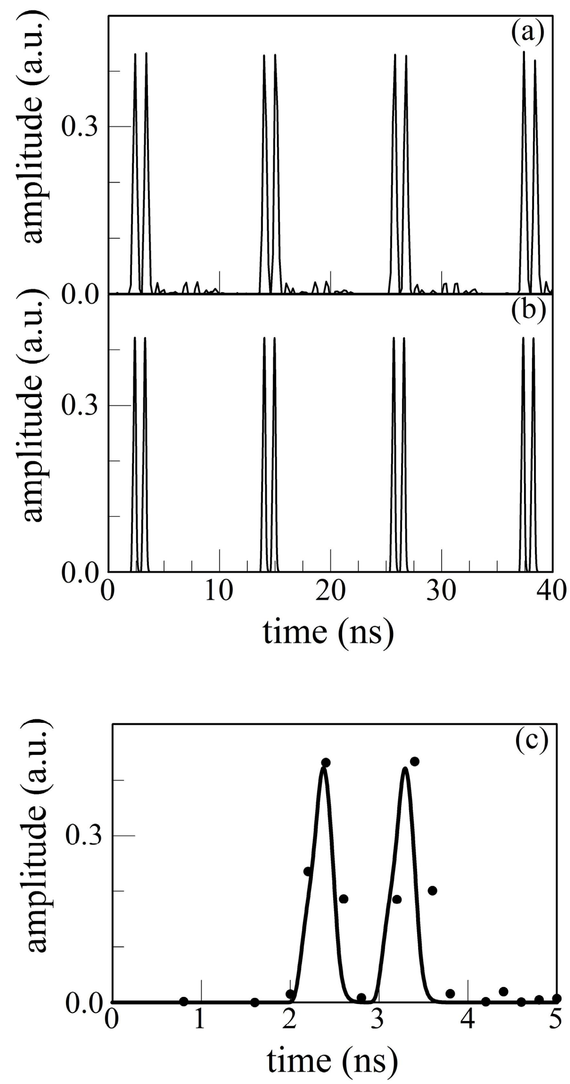

Figure 2. Soliton bound state: an experimental pulse train (a), simulated pulse train (b). Pulse shapes calculated numerically (thin lines) and measured experimentally (dots) (c).

Narrow RF spectra were observed at the cavity repetition rate for both regimes and are shown in Figure 3-4(a) for fundamental and bound state mode-locking. A large number of subsequent RF harmonics in Figures 3-4(b) indicate well-defined mode-locked operations.

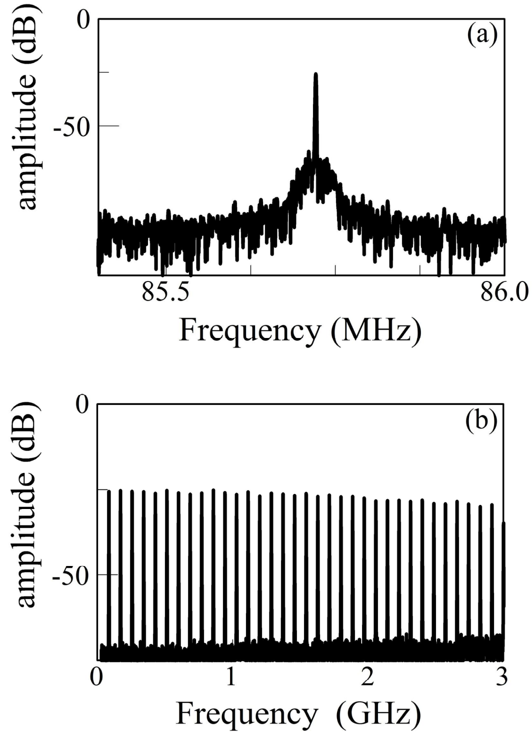

Figure 3. Radio frequency spectrum of the semiconductor disk laser mode-locked at low repetition rate in fundamental regime (a) and a number of RF harmonics (b).

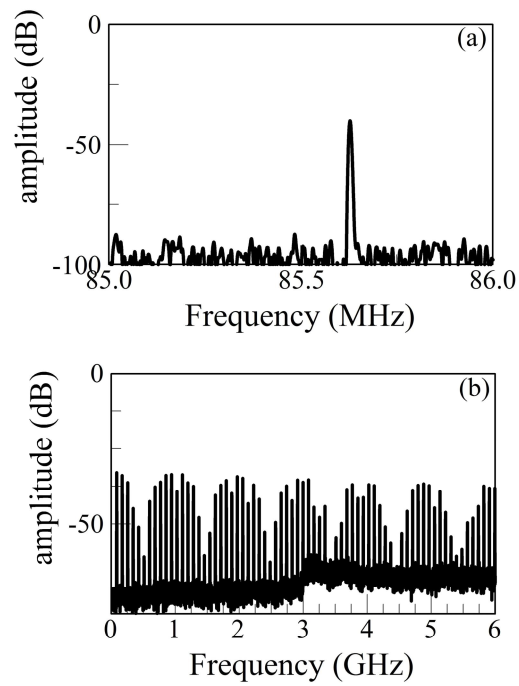

Figure 4. Radio frequency spectrum of the semiconductor disk laser mode-locked at low repetition rate in soliton bound state (a) and modulated RF harmonics (b).

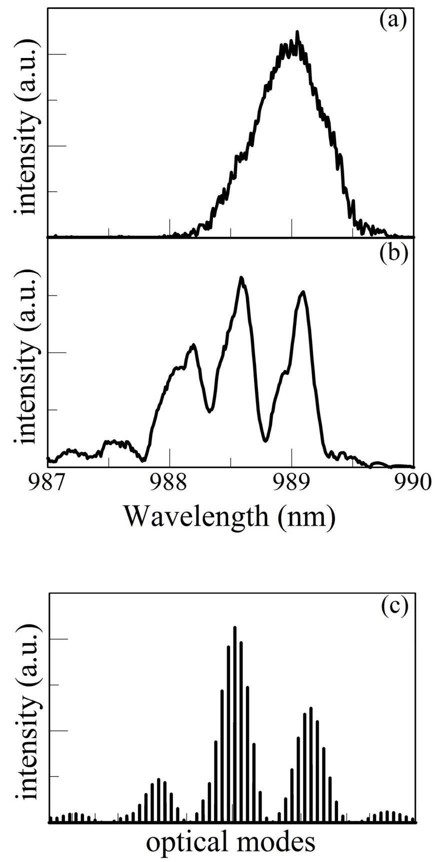

Figure 5. Optical spectra for fundamental modelocking (a) and soliton bound state regime: experimental (b) and simulated (c). The spectrum of bound state shows a strong modulation which is characteristic to such regime.

Optical spectra are shown in Figure 5. The optical spectrum for fundamental mode-locking was centred at 989 nm, and the strongly modulated spectrum of bound state was slightly blue-shifted to 988.5 nm due to the asymmetry provided by the non-zero and non-identical α-factors in the gain and absorption sections. The physical mechanisms for the spectral shifts in SDLs are discussed in [12]. Similar spectral blue-shifting has been reported for the harmonically mode-locked SDL [13].

The soliton bound state is a pulse train with discrete, fixed, but non- identical time separations between multiple soliton-like pulses. and is, therefore, different from the harmonic mode-locking where pulses circulate in the cavity with constant separation. Temporal patterns of multiple pulses spaced by fixed time interval were previously observed in fiber lasers [14]. It attracts significant attention in nonlinear and laser optics in terms of fundamental science and applications for high bit rate communications [15].

Formation of the bound soliton state proves that the interaction of the pulses in the duplet is phase sensitive [16], and indicates the importance of the phase-amplitude coupling for long cavity SDLs. We use a system of delay differential equations (DDE) to simulate dynamics in our system. Similar approach has been proved as a reliable approach to model modelocking in semicondictor lasers [17].The magnitude of the phase-amplitude coupling in semiconductor devices can be conveniently estimated by using α-factors [18]. In QD absorbers, α-factor depends on the relationship between the lasing wavelength and spectral position of peak absorption [16], what allows additional control of phase-amplitude coupling. We find that the asymmetry in α-factors is crucial to the formation of the bound soliton state which is always bistable to the fundamental regime of modelocking. An example of the multiplet bound soliton state shown in Figure 6.

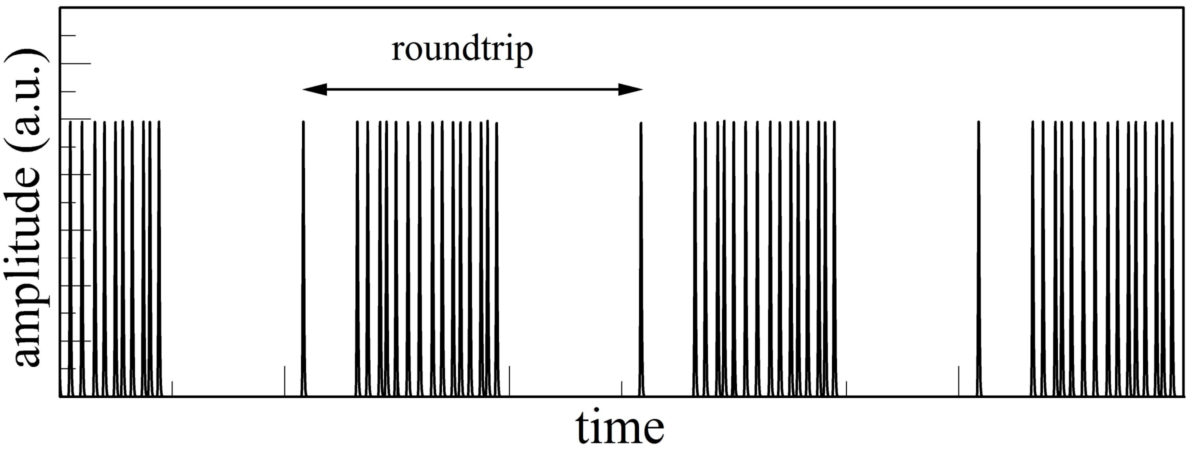

Figure 6. Theoretical time traces of different bound states which coexist with the regime of fundamental mode locking and duplet in Figures 1-2.

4. SUMMARY

We demonstrate, experimentally and theoretically, that a low repetition rate SDL can operate in the regime of the bound soliton state previously unknown for semiconductor devices, and discuss the role of the phase-amplitude coupling in the formation of the multiplets.

REFERENCES

[1] A. H. Quarterman, K. G. Wilcox, V. Apostolopoulos, Z. Mihoubi, S. P. Elsmere, I. Farrer, D. A. Ritchie,and A. Tropper, "A passively mode-locked external-cavity semiconductor laser emitting 60-fs pulses," Nat.Photonics 3(12), 729–731 (2009).

[2] M. Scheller, T. L. Wang, B. Kunert, W. Stolz, S. W. Koch, and J. V. Moloney, "Passively modelocked VECSEL emitting 682 fs pulses with 5.1W of average output power," Electron. Lett. 48(10), 588–589(2012).

[3] E. J. Saarinen, A. Rantamaki, A. Chamorovskiy, and O. G. Okhotnikov, "200 GHz 1 W semiconductor disc laser emitting 800 fs pulses," Electron. Lett. 48(21), 1355–1356 (2012).

[4] K. G. Wilcox, A. H. Quarterman, H. E. Beere, D. A. Ritchie, and A. C. Tropper, "Repetition-frequency tunable mode-locked surface emitting semiconductor laser between 2.78 and 7.87 GHz," Opt. Express 19(23), 23453–23459 (2011).

[5] Y. C. Chen, P. Wang, J. J. Coleman, D. P. Bour, K. K. Lee, and R. G. Waters, "Carrier recombination rates in strained-layer InGaAs-GaAsquantum-wells," IEEE J. Quantum Electron. 27(6), 1451–1455 (1991).

[6] J. E. Ehrlich, D. T. Neilson, A. C. Walker, G. T. Kennedy, R. S. Grant, W. Sibbett, and M. Hopkinson, "Carrier lifetimes in MBE and MOCVD InGaAs quantum-wells," Semicond. Sci. Technol. 8(2), 307–309(1993).

[7] V. L. Kalashnikov, E. Podivilov, A. Chernykh, S. Naumov, A. Fernandez, R. Graf, and A. Apolonski, "Approaching the microjoule frontier with femtosecond laser oscillators: theory and comparison with experiment," New J. Phys. 7, 217 (2005).

[8] R. Aviles-Espinosa, G. Filippidis, C. Hamilton, G. Malcolm, K. J. Weingarten, T. Südmeyer, Y. Barbarin, U. Keller, S. I. C. O. Santos, D. Artigas, and P. Loza-Alvarez, "Compact ultrafast semiconductor disk laser:targeting GFP based nonlinear applications in living organisms," Biomed. Opt. Express 2(4), 739–747(2011).

[9] K. G. Wilcox, A. C. Tropper, H. E. Beere, D. A. Ritchie, B. Kunert, B. Heinen, and W. Stolz, "4.35 kW peak power femtosecond pulse mode-locked VECSEL for supercontinuum generation," Opt. Express 21(2),1599–1605 (2013).

[10] E. U. Rafailov, S. J. White, A. A. Lagatsky, A. Miller, W. Sibbett, D. A. Livshits, A. E. Zhukov, and V. M. Ustinov, “Fast quantum-dot saturable absorber for passive mode-locking of solid-state lasers,” IEEE Photon. Technol. Lett. 16(11), 2439–2441 (2004).

[11] D. J. Maas, A. R. Bellancourt, M. Hoffmann, B. Rudin, Y. Barbarin, M. Golling, T. Südmeyer, and U.Keller, “Growth parameter optimization for fast quantum dot SESAMs,” Opt. Express 16(23), 18646–18656 (2008).

[12] R. Paschotta, R. Haring, A. Garnache, S. Hoogland, A. C. Tropper, and U. Keller, “Soliton-like pulseshaping mechanism in passively mode-locked surface-emitting semiconductor lasers,” Appl. Phys. B. 75(4-5), 445–451 (2002).

[13] E. J. Saarinen, A. Härkönen, R. Herda, S. Suomalainen, L. Orsila, T. Hakulinen, M. Guina, and O. G.Okhotnikov, “Harmonically mode-locked VECSELs for multi-GHz pulse train generation,” Opt. Express 15(3), 955–964 (2007).

[14] Y. Gong, P. Shum, T. Hiang, Q. Cheng, Q. Wen, D. Tang, “Bound soliton pulses in passively mode-locked fiber laser,” Opt. Commun. 200(1-6), 389–399 (2001).

[15] P. Grelu and N. Akhmediev, “Dissipative solitons for mode-locked lasers,” Nat. Photonics 6(2), 84–92(2012).

[16] A. G. Vladimirov and D. Turaev, “Model for passive mode locking in semiconductor lasers,” Phys. Rev. A72(3), 033808 (2005).

[17] C. H. Henry, “Theory of the linewidth of semiconductor-lasers,” IEEE J. Quantum Electron. 18(2), 259–264 (1982).

[18] T. Piwonski, J. Pulka, E. A. Viktorov, G. Huyet, and J. Houlihan, “Refractive index dynamics of quantum dot based waveguide electroabsorbers,” Appl. Phys. Lett. 97(5), 051107 (2010).