PHYSICAL REVIEW E **78**, 016207 (2008)

Hysteresis and multiple pulsing in a semiconductor disk laser with a saturable absorber

Esa J. Saarinen,[*] Jari Lyytikäinen, and Oleg G. Okhotnikov
Optoelectronics Research Centre, Tampere University of Technology, P. O. Box 692, FIN 33101, Finland

(Received 27 December 2007; revised manuscript received 15 April 2008; published 11 July 2008)

We report on bistable mode-locking in a semiconductor disk laser. The disk laser mode-locked with a semiconductor saturable absorber is investigated for different designs of the gain medium that allow the hysteresis loop to be controlled. Hysteresis formation in the pulsed regime of a semiconductor oscillator with saturable absorption and unsaturated gain is discussed qualitatively. The laser represents an attractive setup for generation and manipulation of dissipative solitons and observation of their interaction.

DOI: 10.1103/PhysRevE.78.016207 PACS number(s): 42.65.Pc, 42.65.Tg, 42.55.Xi, 42.55.Px

Dissipative soliton interactions inside laser cavities have been a subject of substantial research in nonlinear dynamics [1–5]. Cavity solitons are stable localized transverse structures that are formed in the dissipative environment and are controllable because they do not interact with other transverse structures or boundaries. In particular, the use of semiconductor cavities allows to support cavity solitons and has the potential for the development of all-optical processing devices. Nonlinear optical resonators offer broad possibilities to study the dynamical phenomena, especially bright soliton generation in lasers with a saturable absorber. The ability to switch cavity solitons and to control their location and motion makes them promising for reconfigurable arrays.

The generation of cavity solitons in an electrically pumped large area vertical cavity semiconductor microresonator has recently been demonstrated [1]. In this study, we show that an optically pumped vertical external-cavity surface emitting laser with a saturable absorber, also known as a semiconductor disk laser (SDL) [6], provides a convenient geometry for observation of dissipative soliton interaction inside the cavity. Flexible configuration of the disk laser facilitates a Fresnel number required to support cavity solitons, a broad wavelength tunability, and power scaling [7,8]. Although the laser studied here operates at a single transverse mode, semiconductor disk lasers have been shown to support monolithic integration of the gain and saturable absorber into a single semiconductor structure and, therefore, allow for large Fresnel numbers [9]. This concept of passively mode-locked lasers could also enable the scaling of pulse repetition rate to 100 GHz.

It is generally expected that a laser with a saturable absorber can exhibit bistability in the output characteristics at threshold [10]. With an increase in the pumping rate from a subthreshold state, the net gain exceeding the cavity losses, the radiation will eventually bleach the saturable absorption. The threshold condition can then be satisfied resulting in the start-up of the laser oscillation. With a decrease in the pump power, the absorption remains bleached as long as sufficient radiation density is stored in the cavity. This is a basic illustration of how hysteresis of the optical characteristics appears in a laser with a saturable absorber in the cavity.

Semiconductor disk lasers offer a unique combination of high average output power, high pulse repetition rate, short pulse width, and superb beam quality [11]. Another advantage of SDLs is the suppressed low-frequency instability, even with low-energy pulses, owing to high differential gain and low saturation fluence. This behavior is in contrast with solid-state or glass fiber gain media that have a low emission cross section and a high saturation fluence and frequently suffer from Q-switching instability, particularly for high repetition rate mode-locking. These low-frequency instabilities manifested as a kilohertz modulation envelope of the short-pulse train are unwanted for many applications in which constant pulse energy and high repetition rate are required [12].

In this paper, we present results on bistability and large hysteresis in the output characteristics of a mode-locked semiconductor disk laser with a saturable absorber mirror.

First, we assemble a laser with the gain medium based on a so-called resonant periodic gain (RPG) structure [13]. With this concept, an increased overlap between the gain section, e.g., quantum wells (QWs), and the electric field standing wave pattern within the cavity is obtained by placing the gain elements at the antinodes of the field. As a result, the effective gain (and also the differential gain) can be strongly enhanced. Although the apparent advantages of the RPG such as a reduced threshold and high efficiency inspire their use as a gain medium, we investigate this structure in a mode-locked SDL primarily because higher harmonic generation is expected, owing to the higher differential gain [14].

The resonant gain structure comprises a 2.5-λ-long gain section with three compressively strained InGaAs QWs and a GaAs/AlAs distributed Bragg reflector (DBR) with 27.5 pairs of quarter-wave layers. The QWs are 7 nm thick and enclosed between an InGaP etch-stop layer and the DBR. Each QW is sandwiched between 5-nm-thick GaAs barriers and placed at an antinode of the optical field by adjusting the width of strain-compensating GaInAsP spacer layers. Figure 1 shows the refractive index profile of the RPG structure together with the standing-wave optical field at 1060 nm.

Next, to validate the role of the unsaturable gain in the hysteresis formation, the RPG sample, originally uncoated, was modified to reduce the gain enhancement due to the cavity effect. Particularly, the reflectivity of the top surface was decreased from 30% to 5% by applying a dielectric coating using an electron beam evaporator.

Finally, we study the performance of a laser exploiting an alternative laser geometry, a so-called antiresonant gain

---

[*] esa.j.saarinen@tut.fi

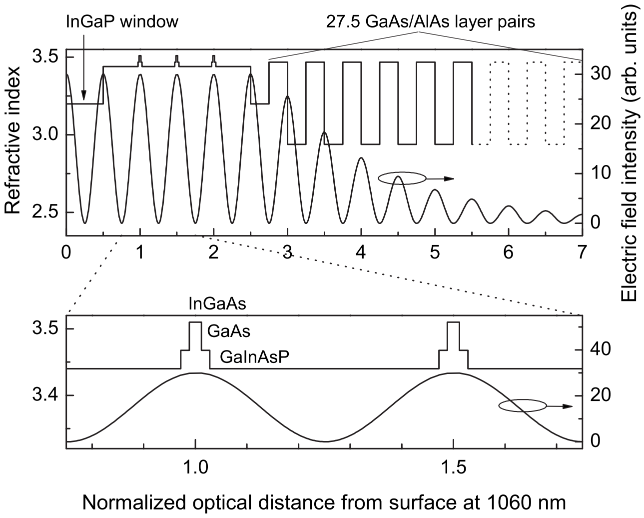

FIG. 1. Refractive index profile of the resonant gain design along with the optical field at 1060 nm.

structure, which can be exploited to decrease dispersion, nonlinear phase effects, and the consequent pulse broadening in mode-locked SDLs [15]. The antiresonant gain structure comprises five InGaAs QWs placed in a 3.75-λ-long gain section. The thickness of the InGaP etch-stop layer was increased from λ/2 to $\frac{3}{4}\lambda$ to fulfill the antiresonance condition. Otherwise the antiresonant structure was similar to the RPG sample used before. After bonding, a two-layer TiO_2/Al_2O_3 coating producing a reflectivity of ~10% was applied to the surface of the sample.

All structures studied here were grown on an *n*-type GaAs substrate in a single step by molecular-beam epitaxy. The DBR was grown last in the epitaxial process in order to facilitate flip-chip bonding of the samples. AuSn solder was used for attaching the chip to a composite diamond heat spreader. Finally, the substrate was removed by wet etching and the heat spreader was bonded to a copper heat sink with an indium solder.

The semiconductor saturable absorber mirror (SESAM) consists of three compressively strained InGaAs QWs and a GaAs/AlAs DBR with 27.5 layer pairs. The 9-nm-thick QWs are separated by 5-nm-thick GaAs barriers. The SESAM was irradiated with heavy ions to shorten the recovery time of absorption to ~2 ps. The modulation depth and the saturation fluence of the SESAM were measured to be ~1% and ~50 $\mu J/cm^2$, respectively. Even though the amount of saturable absorption is low in mode-locked SDLs compared to edge-emitting passively mode-locked lasers [10], a large hysteresis loop was observed in the experiment. Obviously, this feature benefits from the high sensitivity of SDL cavity to losses.

The laser setup used in the experiment is shown in Fig. 2. The Z-shaped 15-cm-long laser cavity is formed between the SESAM and a curved output coupler with a radius of curvature of 50 mm. The semiconductor gain chip and a curved high reflector serve as folding mirrors in the cavity. The 30-mm radius of curvature of the high reflector ensures tight focusing of the beam onto the SESAM. A fiber-coupled pump diode emitting at 808 nm is focused on a spot of ~165 μm to match the diameter of the mode. This setup was used throughout the study unchanged except for the output coupler, which was adapted for each gain medium exploited. Output coupling was 3% when the uncoated resonant gain structure was employed. With the coated RPG and antiresonant structures, the output coupling was decreased to 1% and 0.5%, respectively, in order to compensate for the lower gain of these gain designs. The output beam passed through an optical isolator that prevented back-reflections to the laser. The output was monitored with an autocorrelator, an optical spectrum analyzer, and a fast (12.5 GHz) photodiode connected to an electrical spectrum analyzer and a communications signal analyzer. The pulse duration in this study ranged from 5 to 35 ps, depending on the output power and harmonic number, as described in previous reports [14,16]. The fundamental pulse repetition rate was 1.03 GHz.

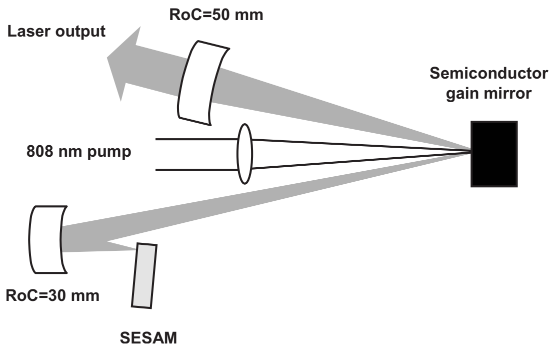

FIG. 2. Schematic of a mode-locked disk laser. RoC denotes radius of curvature.

The average output power for the uncoated RPG gain medium is plotted in Fig. 3 as a function of pump power. It can be seen that up to three harmonics of the fundamental cavity frequency could be achieved. Figure 4 shows the oscilloscope traces of the corresponding pulse trains with one (top), two, and three pulses circulating in the cavity. The radiofrequency (rf) spectra of the mode-locked pulse trains are shown in Fig. 5. We find that harmonic modes exhibit nearly equal pulse-to-pulse spacings with large supermode suppression, >45 dB, in the rf spectrum. The hysteresis near the

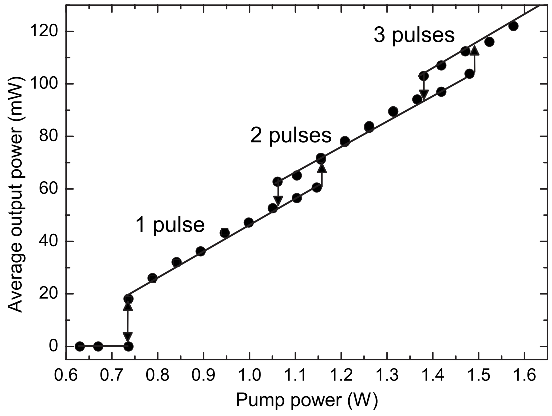

FIG. 3. Output characteristics for the mode-locked disk laser using a resonant periodic gain medium. Operation at the fundamental, second, and third harmonic frequencies has been achieved.

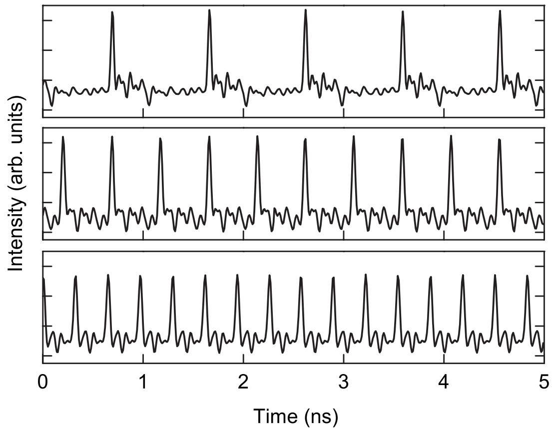

FIG. 4. Oscilloscope traces of the mode-locked pulse sequence obtained for different pump power levels corresponding to the states illustrated in Fig. 3 with one, two, and three pulses circulating in the laser cavity.

laser threshold, which may be expected from the abrupt power rise and indeed seen for other gain designs presented below (in Figs. 7 and 9), could not be measured for this laser configuration. The switching between harmonics with hysteresis behavior was observed with a change in pump power or by blocking and unblocking the laser cavity. The size of the hysteresis loop between the different harmonic states was, however, small, which can be attributed to the enhanced differential gain in the RPG medium resulting in an efficient rise in the unsaturable gain with pump power.

An interesting observation made during the experiments is that the laser could operate only in the mode-locked regime, i.e., other regimes, particularly continuous-wave oscillation, could be entirely avoided. This means that the lowest lasing threshold is always attained through mode-locked operation. A typical autocorrelation trace and a pulse spectrum for fundamental mode-locking at pump power of 0.84 W are shown in Fig. 6. It can be seen that the pulse is strongly chirped, which is a typical observation for mode-locked SDLs because of strong gain saturation and the consequent refractive index variation, which causes a large nonlinear phase change [14,16,17].

As expected, the hysteresis in the power characteristic was accompanied by hysteresis in the pulse duration and operation wavelength. Transition to a state with a higher harmonic number results in a decrease in the pulse energy and in consequent improvement of the pulse duration and quality, since the nonlinear distortions are less pronounced with a lower pulse energy [14,16].

The average output power for the coated RPG sample is plotted in Fig. 7 as a function of pump power. The figure shows that the loop size has increased essentially, indicating

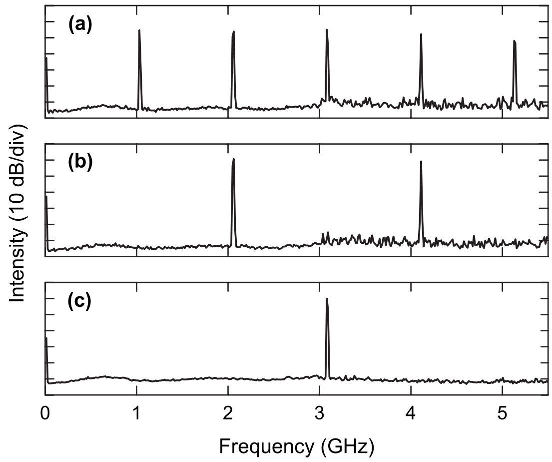

FIG. 5. rf spectra of the pulse trains for the (a) fundamental, (b) second harmonic, and (c) third harmonic state obtained with the RPG sample. Background noise depends slightly on the frequency range due to the automatic switch in the sensitivity and averaging of the detection system of the rf analyzer.

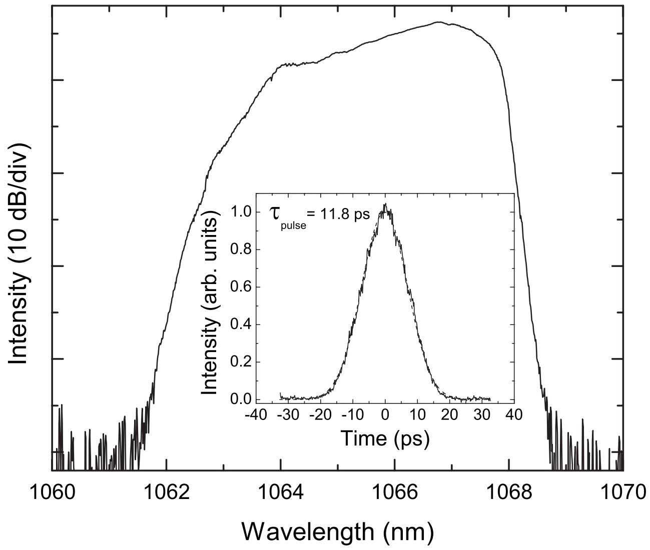

FIG. 6. Pulse spectrum and corresponding autocorrelation in the inset for fundamental one-pulse mode-locking with pump power of 0.84 W.

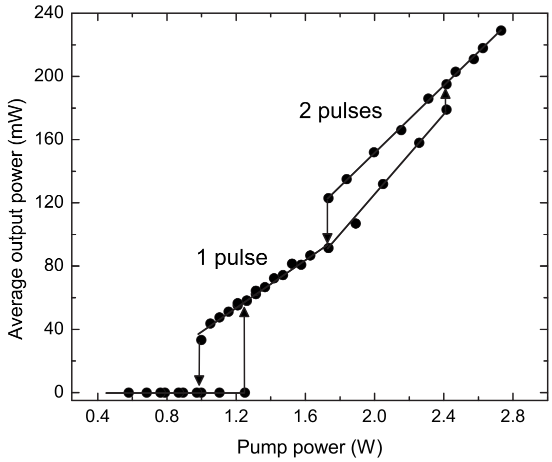

FIG. 7. Output characteristics for the mode-locked disk laser using a resonant periodic gain medium with the top surface reflectivity reduced from ~30% for an uncoated sample to 5% after dielectric film coating. The fundamental and the second harmonic frequency have been achieved with a larger hysteresis loop compared to the uncoated sample presented in Fig. 3.

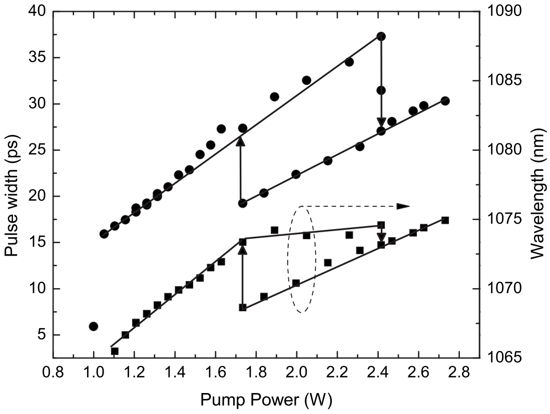

FIG. 8. Pulse width and operation wavelength for the coated RPG sample described in Fig. 7.

a reduction in the growth rate of unsaturable gain with pump power. Distinct hysteresis and bistability were also observed in the laser threshold when one-pulse mode-locking starts from noise and turns off. Figure 8 shows pulse width and central wavelength for mode-locking states with one (fundamental) and two pulses circulating in the laser cavity. The characteristic hysteresis loops are clearly seen in the dependence of pulse width and wavelength on the pump power. The spectrum exhibits a gradual redshift when the pulse energy is increased with an increase in the pump power, owing to more complete average gain saturation. However, there are "blue abrupt hops" in the wavelength with an increase in the average power corresponding to a simultaneous increase in the number of pulses in the cavity. The effective steplike blueshifts with an increase in the number of pulses indicate a reduced redshift in the gain medium because of less complete gain recovery between pulses with the higher repetition rate [14].

The enlarged size of the hysteresis loop obtained with reduced gain enhancement due to the weaker cavity effect can be understood from a simple analysis based on the rate equations. Qualitatively, the reduced gain, g, and differential gain, $\eta = \partial g / \partial P$ (P is the pumping rate), in a nonresonant medium result in an extended range of the pump power needed to reach the gain value required for start-up of mode-locking. Upon reduction in the pump power, the unsaturated gain decreases slowly owing to the small value of η, resulting in a large hysteresis loop that extends until the mode-locking and the entire laser action break off. Since the transient unsaturated gain is associated with semiconductor laser mode-locking [14,16], with a further increase in pump power the gain continues to increase, and eventually the one-pulse regime becomes unstable and mode-locking switches to a higher harmonic [14].

With the antiresonant structure, only operation at the fundamental frequency was observed for pump powers up to 3 W. The average output power and pulse duration are shown in Fig. 9 as a function of pump power. The hysteresis loop size and the corresponding bistability range are defined by the upper lasing threshold, when oscillation appears with an increase in the pump power, and the lower lasing threshold, when the lasing action stops with a decrease in the pumping rate. As expected, the value of the laser threshold for this configuration is higher than for the resonant gain active media. Because the unsaturated gain growth rate is low in the antiresonant material, we could not observe the higher harmonics.

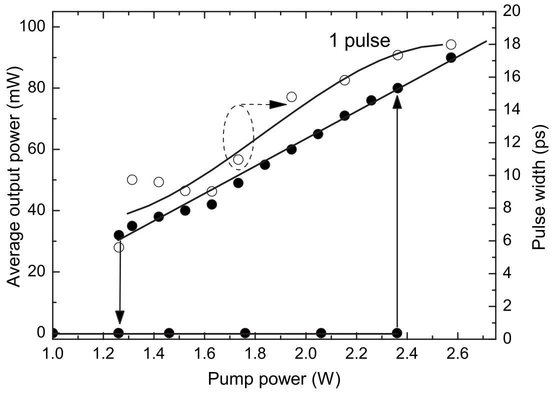

FIG. 9. Output power for the mode-locked disk laser using an antiresonant gain medium design. A large hysteresis loop exhibiting only a one-pulse state has been observed with this laser configuration.

In conclusion, we demonstrate experimental evidence of hysteresis with multiple pulse formation in the mode-locked regime of an optically pumped semiconductor disk laser. Pulsed operation in the disk laser initiated with a semiconductor saturable absorber exhibits bistability of a single pulse or multiple pulse harmonic mode-locking dependent on the intrinsic gain of the semiconductor medium. Bistability characteristics for lasers with a low and high differential gain inherent in the antiresonant and resonant design of the gain medium, respectively, have been studied. In particular, it was demonstrated that the size of the hysteresis loop and the number of harmonics observed at a given pump power could be varied by controlling the unsaturated gain, e.g., by detuning from the resonant wavelength of the gain structure or by changing the finesse of the microcavity. The mechanism for the hysteresis loop formation is based on the transient unsaturated gain in a mode-locked semiconductor laser having a fast gain recovery. A detailed theoretical analysis of the experimental results presented here is now in progress and will be used as a guideline for a future advanced study. The laser provides an attractive setup for generation and manipulation of dissipative cavity solitons and observation of their interaction.

The authors acknowledge the support of EU FP6 project NATAL (contract No. IST-016769) and the KAUTE Foundation. Thanks go to Lasse Orsila for the coating of the gain chip and to Soile Suomalainen for the growth of the SESAM. We are also grateful to N. N. Rosanov from Institute of Laser Physics, Vavilov State Optical Institute, St. Petersburg, for valuable discussion.

[1] S. Barland, J. R. Tredicce, M. Brambilla, L. A. Lugiato, S. Balle, M. Giudici, T. Maggipinto, L. Spinelli, G. Tissoni, T. Knödl, M. Miller, and R. Jäger, Nature **419**, 699 (2002).

[2] C. O. Weiss, M. Vaupel, K. Staliunas, G. Slekus, and V. B. Taranenko, Appl. Phys. B: Lasers Opt. **68**, 151 (1999).

[3] S. Fedorov, D. Michaelis, U. Peschel, C. Etrich, D. V. Skryabin, N. Rosanov, and F. Lederer, Phys. Rev. E **64**, 036610 (2001).

[4] P. Grelu and N. Akhmediev, Opt. Express **12**, 3184 (2004).

[5] N. Akhmediev, J. M. Soto-Crespo, M. Grapinet, and P. Grelu, Opt. Fiber Technol. **11**, 209 (2005).

[6] M. Kuznetsov, F. Hakimi, R. Sprague, and A. Mooradian, IEEE Photonics Technol. Lett. **9**, 1063 (1997).

[7] P. V. Paulau, A. J. Scroggie, A. Naumenko, T. Ackemann, N. A. Loiko, and W. J. Firth, Phys. Rev. E **75**, 056208 (2007).

[8] N. N. Rosanov and V. A. Smirnov, Sov. J. Quantum Electron. **10**, 232 (1980).

[9] D. J. H. C. Maas, A.-R. Bellancourt, B. Rudin, M. Golling, H. J. Unold, T. Südmeyer, and U. Keller, Appl. Phys. B: Lasers Opt. **88**, 493 (2007).

[10] S. Sanders, A. Yariv, J. Paslaski, E. Ungar, and H. A. Zarem, Appl. Phys. Lett. **58**, 681 (1991).

[11] E. Saarinen, A. Härkönen, S. Suomalainen, and O. G. Okhotnikov, Opt. Express **14**, 12868 (2006).

[12] C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, J. Opt. Soc. Am. B **16**, 46 (1999).

[13] M. Y. A. Raja, S. R. J. Brueck, M. Osinski, C. F. Schaus, J. G. McInerney, T. M. Brennan, and B. E. Hammons, IEEE J. Quantum Electron. **25**, 1500 (1989).

[14] E. Saarinen, A. Härkönen, R. Herda, S. Suomalainen, L. Orsila, T. Hakulinen, M. Guina, and O. G. Okhotnikov, Opt. Express **15**, 955 (2007).

[15] A. Garnache, S. Hoogland, A. C. Tropper, I. Sagnes, G. Saint-Girons, and J. S. Roberts, Appl. Phys. Lett. **80**, 3892 (2002).

[16] E. Saarinen, R. Herda, and O. G. Okhotnikov, J. Opt. Soc. Am. B **24**, 2784 (2007).

[17] R. Paschotta, R. Häring, A. Garnache, S. Hoogland, A. C. Tropper, and U. Keller, Appl. Phys. B: Lasers Opt. **75**, 445 (2002).