New frontiers in ultrafast all-solid-state lasers

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Today's ultrafast all-solid-state lasers continue to demonstrate unsurpassed performances in terms of pulse duration (≈5-fs range), pulse repetition rates (≈80 GHz) and average power (27-W for picosecond pulses and 16-W for femtosecond pulses).

Today's ultrafast all-solid-state lasers continue to demonstrate unsurpassed performances in terms of pulse duration, pulse repetition rates, average power and wavelength range: Optical pulses in the 5-femtosecond range are produced by a variety of methods [1]. Although different in technical detail, each method relies on the same three key components: spectral broadening due to the nonlinear optical Kerr effect, dispersion control, and ultrabroadband amplification. Pulses as short as 5.8 fs have been generated directly from a Ti:sapphire laser without any external pulse compression [2], [3]. The shortest pulses generated to date all rely on chirped mirrors [4] for dispersion compensation. A major limitation in chirped mirror design arises due to interference between light reflected at different penetration depths inside the mirror structure. This results in residual oscillations in the group delay dispersion (GDD) which ultimately limits pulse shortening. Unfortunately, there is always a trade-off between GDD-oscillations and reflection bandwidth. The double-chirped mirror technique (DCM, [5]) reduced GDD oscillations and resulted in the sub-6-fs pulses. Novel DCM designs result in a sufficiently large reflection bandwith that could, in principle, support 4-fs pulses.

The technique of Kerr lens modelocking (KLM) [6], successful with Ti:sapphire, has not performed so well in directly diode-pumped lasers. Early intracavity saturable absorbers produced at best stable Q-switched modelocked pulses, where the pico- or femtosecond modelocked pulses are inside much longer Q-switched pulse envelopes. Semiconductor saturable absorber mirrors (SESAMs) [7], [8] were a breakthrough resulting in the first demonstration of self-starting and stable passive mode locking of diode-pumped solid-state lasers with an intracavity saturable absorber. The design freedom of SESAMs has allowed us systematically to investigate the stability regime of passive cw modelocking with an improved understanding and modeling of Q-switching instabilities [9]. Today SESAMs are well-established as a useful device for passive mode-locking and Q-switching of many kinds of solid-state lasers [10]. Initially, semiconductor saturable absorber mirrors were used in coupled cavities [11], because they introduced too much loss inside solid-state lasers with small gain cross-sections (i.e. 10^{-19} cm^2 and smaller). Two years later in 1992, this work resulted in a new type of intracavity saturable absorber mirror, the antiresonant Fabry-Perot saturable absorber (A-FPSA) [7], where the absorber was integrated inside a Fabry-Perot structure and where the lower Fabry-Perot reflector was a high-reflector (i.e. approximately 100%). The Fabry-Perot was operated at antiresonance to obtain broad bandwidth and low loss. The A-FPSA mirror was mainly based on semiconductor Bragg mirror and absorber layers and therefore allowed for a large variation of the absorber. The result was a much better understanding of the absorber and laser design necessary to obtain stable passive modelocking or Q-switching of many different solid-state lasers. In 1995 it was further realized that the intracavity saturable absorber can be integrated in a more general mirror structure that allows for both saturable absorption and negative dispersion control, which is now generally referred to as a semiconductor saturable absorber mirror (SESAM) [8]. In a general sense we then can reduce the design problem of a SESAM to the analysis of multilayered interference filters for a given desired nonlinear reflectivity response for both the amplitude and phase. The A-FPSA [7], the saturable Bragg reflector (SBR) [12] and the dispersive saturable absorber mirror (D-SAM) [13] are then special examples of SESAM designs. In the future chirped SESAMs [14] will provide unsurpassed ultrabroadband performance with negative dispersion compensation.

Simple design guidelines for the laser cavity and the SESAM [9] allowed us to push the frontiers of ultrafast solid-state lasers: Presently the frontiers in average output power are diode-pumped Nd:YAG (27 W average output power and 19 ps pulse duration) [15], Yb:YAG (16 W and 730 fs) [16] and Nd:glass (1.4 W, 275 fs) [17] lasers. This basically means that µJ-level pulse energies in both the pico- and femtosecond regime are available directly from compact solid-state lasers without any cavity dumping or further pulse amplification [18]. Such high average output power will find many applications in micromachining and nonlinear frequency conversion, as for example for RGB generation for digital cinema. Efficient second harmonic generation with 58% conversion efficiency has been demonstrated with only one single-pass through an LBO crystal [16]. In addition, more recently we demonstrated a novel type of synchronously pumped optical parametric oscillator (OPO). This fiber feedback OPO [19] is based on feedback through a single-mode fiber in combination with a very high gain in the nonlinear medium, which is obtained with the high pump power of the thin-disk modelocked laser. Our concept lead to a very stable and compact OPO setup which is unusually insensitive against intracavity losses and drifts of the OPO cavity length. Even with non-optimized optical components, we obtained up to 2.7 W of average power in 900-fs pulses around 1.45 µm. In contrast to many other OPOs in this pulse duration regime, the fiber-feedback OPO does not need an active stabilization of the cavity length.

The frontiers in pulse repetition rate has been pushed from a few gigahertz to nearly 80 GHz [20] using quasi-monolithic miniature Nd:YVO_4 laser cavities at 1.064 µm wavelength. Following again the simple design guidelines for stable passive modelocking [9], we have demonstrated that solid-state lasers can be passively mode-locked at many GHz repetiton rates. This resulted initially in 13 GHz [21] and then with a very compact, quasi-monolithic setup, in 29 GHz [22] and even up to 59 GHz [23]. Our concept is based on a miniature Nd:YVO_4 laser, which is mode-locked with a SESAM attached to the laser crystal. Such lasers are interesting sources for optical clocking or electro-optic sampling for example. Compared to mode-locked semiconductor lasers [24], much higher pulse energies can be obtained, while our setup is still very simple and compact compared to a harmonically mode-locked fiber laser [25]. With 59 GHz repetition rate [23], we initially reached a limit which is given by the pulse duration in the order of 5 ps: the pulses began to overlap temporally. For further increases of repetition rate, shorter pulses are required, and the suppression of Q-switching instabilities [9] would also be a challenging task. More recently, we demonstrated that we could overcome the two limitations mentioned above and demonstrated a mode-locked laser with a repetition rate as high as 77 GHz with clearly separated pulses of 2.7 ps duration. We achieved this by employing soliton modelocking [26], with negative dispersion generated in a GTI-like structure. An alternative would be to use a specially designed SESAM with negative dispersion [13, 14]. Repetition rates greater than 100 GHz should be feasible with this approach. In addition, this approach should also greatly increase the repetition rates which can be obtained at other wavelengths, such as 1.5 µm with Cr:YAG [27] or 1.3 µm with Nd:YVO_4 [28].

References

[1] G. Steinmeyer, D. H. Sutter, L. Gallmann, N. Matuschek, U. Keller, "Frontiers in Ultrashort Pulse Generation: Pushing the Limits in Linear and Nonlinear Optics," *Science*, vol. 286, pp. 1507-1512, 1999.

[2] D. H. Sutter, G. Steinmeyer, L. Gallmann, N. Matuschek, F. Morier-Genoud, U. Keller, V. Scheuer, G. Angelow, T. Tschudi, "Semiconductor saturable-absorber mirror-assisted Kerr-lens mode-locked Ti:sapphire laser producing pulses in the two-cycle regime," *Opt. Lett.*, vol. 24, pp. 631-633, 1999.

[3] U. Morgner, F. X. Kärtner, S. H. Cho, Y. Chen, H. A. Haus, J. G. Fujimoto, E. P. Ippen, V. Scheuer, G. Angelow, T. Tschudi, "Sub-two-cycle pulses from a Kerr-lens mode-locked Ti:sapphire laser: addenda," *Opt. Lett.*, vol. 24, pp. 920, 1999.

[4] R. Szipöcs, K. Ferencz, C. Spielmann, F. Krausz, "Chirped multilayer coatings for broadband dispersion control in femtosecond lasers," *Optics Lett.*, vol. 19, pp. 201-203, 1994.

[5] F. X. Kärtner, N. Matuschek, T. Schibli, U. Keller, H. A. Haus, C. Heine, R. Morf, V. Scheuer, M. Tilsch, T. Tschudi, "Design and fabrication of double-chirped mirrors," *Opt. Lett.*, vol. 22, pp. 831-833, 1997.

[6] D. E. Spence, P. N. Kean, W. Sibbett, "60-fsec pulse generation from a self-mode-locked Ti:sapphire laser," *Opt. Lett.*, vol. 16, pp. 42-44, 1991.

[7] U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, M. T. Asom, "Solid-state low-loss intracavity saturable absorber for Nd:YLF lasers: an antiresonant semiconductor Fabry-Perot saturable absorber," *Opt. Lett.*, vol. 17, pp. 505-507, 1992.

[8] U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, J. Aus der Au, "Semiconductor saturable absorber mirrors (SESAMs) for femtosecond to nanosecond pulse generation in solid-state lasers," *IEEE J. Sel. Top. Quantum Electron.*, vol. 2, pp. 435-453, 1996.

[9] C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, U. Keller, "Q-switching stability limits of continuous-wave passive mode locking," *J. Opt. Soc. Am. B*, vol. 16, pp. 46-56, 1999.

[10] U. Keller, "Semiconductor nonlinearities for solid-state laser modelocking and Q-switching," in *Chapter 4 in Nonlinear Optics in Semiconductors* E. Garmire, A. Kost, Eds. (Academic Press, Inc., Boston, 1999), vol. 59, pp. 211-286.

[11] U. Keller, W. H. Knox, H. Roskos, "Coupled-Cavity Resonant Passive Modelocked (RPM) Ti:Sapphire Laser," *Optics Lett.*, vol. 15, pp. 1377-1379, 1990.

[12] S. Tsuda, W. H. Knox, E. A. d. Souza, W. Y. Jan, J. E. Cunningham, "Low-loss intracavity AlAs/AlGaAs saturable Bragg reflector for femtosecond mode locking in solid-state lasers," *Optics Letters*, vol. 20, pp. 1406-1408, 1995.

[13] D. Kopf, G. Zhang, R. Fluck, M. Moser, U. Keller, "All-in-one dispersion-compensating saturable absorber mirror for compact femtosecond laser sources," *Opt. Lett.*, vol. 21, pp. 486-488, 1996.

[14] R. Paschotta, G. J. Spühler, D. H. Sutter, N. Matuschek, U. Keller, M. Moser, R. Hövel, V. Scheuer, G. Angelow, T. Tschudi, "Double-chirped semiconductor mirror for dispersion compensation in femtosecond lasers," *Appl. Phys. Lett.*, vol. 75, pp. 2166-2168, 1999.

[15] G. J. Spühler, T. Südmeyer, R. Paschotta, M. Moser, K. J. Weingarten, U. Keller, "Passively mode-locked high-power Nd:YAG lasers with multiple laser heads," *Appl. Phys. B*, vol. 71, pp. 19-25, 2000.

[16] J. Aus der Au, G. J. Spühler, T. Südmeyer, R. Paschotta, R. Hövel, M. Moser, S. Erhard, M. Karszewski, A. Giesen, U. Keller, "16.2 W average power from a diode-pumped femtosecond Yb:YAG thin disk laser," *Opt. Lett.*, vol. 25, pp. 859, 2000.

[17] J. Aus der Au, F. H. Loesel, F. Morier-Genoud, M. Moser, U. Keller, "Femtosecond diode-pumped Nd:glass laser with more than 1-W average output power," *Opt. Lett.*, vol. 23, pp. 271-273, 1998.

[18] R. Paschotta, J. Aus der Au, G. J. Spühler, F. Morier-Genoud, R. Hövel, M. Moser, S. Erhard, M. Karszewski, A. Giesen, U. Keller, "Diode-pumped passively mode-locked lasers with high average power," *Appl. Phys. B*, vol. 70, pp. S25-S31, 2000.

[19] T. Südmeyer, J. Aus der Au, R. Paschotta, U. Keller, P. G. R. Smith, G. W. Ross, D. C. Hanna, "Femtosecond fiber-feedback OPO," *submitted to Opt. Lett.*, Sept. 2000.

[20] L. Krainer, R. Paschotta, M. Moser, U. Keller, "77 GHz soliton modelocked Nd:YVO_4 laser," *Electron. Lett.*, accepted for publication 27. Sept. 2000

[21] L. Krainer, R. Paschotta, J. Aus der Au, C. Hönninger, U. Keller, M. Moser, D. Kopf, K. J. Weingarten, "Passively mode-locked Nd:YVO_4 laser with up to 13 GHz repetition rate," *Appl. Phys. B*, vol. 69, pp. 245-247, 1999.

[22] L. Krainer, R. Paschotta, G. J. Spühler, M. Moser, U. Keller, "29 GHz modelocked miniature Nd:YVO_4 laser," *Electron. Lett.*, vol. 35, pp. 1160-1161, 1999.

[23] L. Krainer, R. Paschotta, M. Moser, U. Keller, "Passively modelocked picosecond lasers with up to 59 GHz repetition rate," *Appl. Phys. Lett.*, vol. 77, pp. 2104-2105, 2000.

[24] S. Arahira, Y. Matsui, Y. Ogawa, "Mode-locking at very high repetition rates more than terahertz in passively mode-locked distributed-Bragg-reflector laser diodes," *IEEE J. Quantum Electron.*, vol. 32, pp. 1211-1224, 1996.

[25] E. Yoshida, M. Nakazawa, "80~200GHz erbium doped fibre laser using a rational harmonic mode-locking technique," *Electron. Lett.*, vol. 32, pp. 1370-1372, 1996.

[26] F. X. Kärtner, I. D. Jung, U. Keller, "Soliton Modelocking with Saturable Absorbers," *Special Issue on Ultrafast Electronics, Photonics and Optoelectronics, IEEE J. Sel. Topics in Quantum Electronics (JSTQE)*, vol. 2, pp. 540-556, 1996.

[27] T. Tomaru, H. Petek, "Femtosecond Cr4+:YAG laser with an L-fold cavity operating at a 1.2 GHz repetition rate," *Opt. Lett.*, vol. 25, pp. 584-586, 2000.

[28] R. Fluck, G. Zhang, U. Keller, K. J. Weingarten, M. Moser, "Diode-pumped passively mode-locked 1.3 µm Nd:YVO4 and Nd:YLF lasers by use of semiconductor saturable absorbers," *Opt. Lett.*, vol. 21, pp. 1378-1380, 1996.