Soliton mode-locked Er:Yb:glass laser

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We report on a simple diode-pumped passively mode-locked Er:Yb:glass laser generating transform-limited 1536-nm solitons of 255-fs duration with a repetition rate of 50 MHz and average power of 58 mW. We also discuss timing jitter and the trade-off between short pulses and high output power in these lasers. © 2005 Optical Society of America

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Er:Yb:glass is an attractive bulk gain medium because of its emission in the telecommunications C band near 1550 nm. It can be produced in large quantities at low cost with high optical quality, and it can be efficiently pumped with standard 980-nm telecommunications diode lasers. Therefore, it has found a wide range of applications: Er:Yb:glass has been used in high-quality, low-noise, widely tunable single-mode lasers[1] for spectroscopy applications, in compact Q-switched microchip lasers for sensing applications,[2] and in high-power lasers for military applications.[3] In the past few years, Er:Yb:glass lasers have also established their position as pulse-generating lasers for next-generation optical networks: Zeller *et al.*[4] developed passively mode-locked Er:Yb:glass lasers at repetition rates of up to 50 GHz (Ref. 4) that are extremely simple and compact, yield high-quality pulses with average powers of a few tens of milliwatts, and can be synchronized to an external clock with very low timing jitter.[5] This makes them interesting for applications in transmitters or receivers of telecommunications networks.[6] For increasing bit rates, shorter pulses are required; e.g., pulse durations well below 1 ps are required for a bit rate of 640 Gbits/s per channel. Therefore, in this Letter we want to explore the limits of bulk Er:Yb:glass in terms of pulse duration, starting at low pulse-repetition rates (a few tens of megahertz), at which many limitations are avoided. Er-fiber lasers regularly yield pulse durations of 70 fs or less.[7] However, they suffer from a rather complex setup and low output powers. Additionally, in the regime of very short pulses (less than a few hundred femtoseconds), their pulse quality is compromised: Satellite pulses can appear, and the spectrum often shows strong features. Here we show that a bulk laser can yield significantly cleaner (although somewhat longer) femtosecond pulses with higher average power levels from a simpler setup.

In the following we discuss how we optimized our Er:Yb:glass laser for generating short pulses with relatively high output power compared with earlier results.[8] The first aspect to be considered is the Er inversion level, which influences the gain bandwidth. For this, we determined the absorption and emission cross section by use of the reciprocity method[9] and the Füchtbauer–Ladenburg method, similar to what was reported in Ref. 10. Figure 1(a) shows the measured emission and absorption cross sections σ_{em} and σ_{abs} near 1550 nm of Er/QX phosphate glass, which has been doped with 4.5×10^{19} Er ions/cm^3 and 1.4×10^{21} sensitizing Yb ions/cm^3.[11] The reabsorption losses lead to an effective gain spectrum g that depends on the inversion level N_2. In Fig. 1(b) we calculated the gain spectra for different inversion levels in a 2-mm-thick Er:Yb:glass Brewster plate, using the measured cross sections

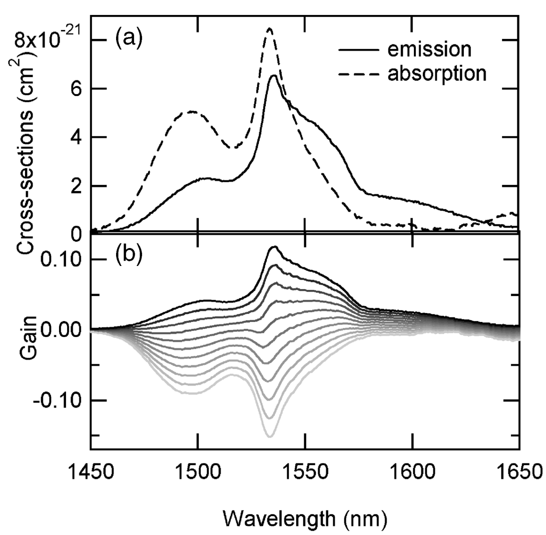

Fig. 1. (a) Measured emission and absorption cross sections of Er:Yb:glass. (b) Calculated gain of a 2-mm Er:Yb:glass. Brewster plate as a function of wavelength for inversions or 100% (black) to 0% (light gray) in steps of 10%.

according to the formula for the gain of a three-level laser: $g = 2L_g[N_2(\sigma_{em} + \sigma_{abs}) - N_{tot}\sigma_{abs}]$, where N_{tot} is the total number of active ions per volume and L_g is the length of the gain medium, which is passed twice per round trip. It can be recognized that the gain bandwidth is <15 nm for high inversion levels of >80%, whereas a much broader gain bandwidth of ≈40 nm is achieved for inversion levels in the range 70–80%. Please note that this flatness is not obtained with any gain-flattening filters or other additional cavity elements. The flatness can be achieved by proper balancing of emission and reabsorption in the three-level laser. Therefore shorter pulses can be obtained by minimizing the cavity losses, because this leads to a larger gain bandwidth as a result of lower Er inversion. Additionally, lower gain itself reduces the bandwidth-limiting effect of the gain medium. However, too low an output coupler transmission adversely affects the output power because of the stronger influence of parasitic losses; this is the reason for the moderate output power in the result of Ref. 8.

As the low nonlinearity of glass can be undesirably small in mode-locked bulk lasers, the length of the gain medium and the mode size in the gain medium are also important for the achievable pulse duration. These factors maximize the Kerr nonlinearity, so soliton pulse-shaping effects are enhanced. An alternative but more complicated way to increase the Kerr nonlinearity is to include an additional Kerr medium in the resonator.[8] Note that, in fiber lasers, the nonlinearity of the gain medium tends to be even larger than desirable, so short pulses are obtained, but often with decreased spectral and temporal purity.

A long gain medium also generates the gain with a lower Er inversion level, which increases the gain bandwidth, as shown above. Of course, a small laser spot in a long gain medium tightens the demands on the beam quality of the pump source. However, we can benefit from the recent progress on diffraction-limited 980-nm pump diodes, which led to fiber-coupled pump modules with 500-mW output power in a single-mode fiber. We used such a laser with a polarization-maintaining fiber to pump a 2-mm-thick Brewster-angle Er:Yb:glass plate with the above-mentioned doping levels (Fig. 2). The mode radius in the Er:Yb:glass piece was 13 μm × 20 μm. The cavity was a standard delta cavity with relatively long arm lengths and highly curved mirrors (M1 and M2) to yield the required small mode radius in the gain element (Fig. 2). The output coupling transmission was 1.7%, sufficient to obtain a few tens of milliwatts of average output power while keeping the intracavity power high and the inversion level as low as possible. Self-starting soliton mode locking[12] was achieved with a semiconductor saturable absorber mirror[13,14] (SESAM) with a modulation depth of 0.5%, a saturation fluence of 25 μJ/cm^2, and linear losses below 0.2%. Thus the intracavity power was not significantly reduced by the SESAM. Negative group-delay dispersion was obtained from a pair of fused-silica prisms that could easily be replaced with dispersive mirrors to make the setup more compact and to decrease the losses. The prism separation was experimentally optimized, as the exact nonlinear refractive index and dispersion of the Er:Yb:glass that we used were not known. The shortest pulses were obtained for a prism separation of 36.5 cm, corresponding to a group-delay dispersion ≈ −2900 fs^2 per round trip. Because of the moderate repetition rate and small mode radii, Q-switching instabilities[15] were observed only at very low pump powers (close to the lasing threshold). At a full pump power of 484 mW incident on the Er:Yb:glass, we obtained pulses of 255-fs duration, an average output power of 58 mW, and a repetition rate of 50 MHz. The spectral bandwidth was 9.9 nm, i.e., close to the estimated width of the gain at this level of inversion. The pulses were close to transform limited (time–bandwidth product, 0.32) and spectrum and autocorrelation suggest very clean solitons (Fig. 3). Operation was stable for hours.

A fundamental advantage of mode-locked solid-state lasers in terms of noise is that they usually operate with low intracavity losses. Thus the saturated gain is low, especially compared with typical fiber lasers or semiconductor lasers. According to Ref. 16 the quantum limit of the timing phase-noise power spectral density of a mode-locked laser is proportional to the saturated gain. Therefore we can expect a significantly lower quantum limit of the timing jitter from bulk solid-state lasers than from mode-locked semiconductor lasers or fiber lasers. We measured the timing phase noise of the 50-MHz Er:Yb:glass laser in its laboratory-style configuration, using the von der Linde method.[17] In the laboratory-style laser strong mirror vibrations and air currents are present, as the cavity contains several *xyz* stages and classic mirror mounts. Thus the laser operates far from the quantum limit. In this configuration we measured a rms timing jitter of 2.5 ps when integrating the sidebands of the photodiode signal of the 40th harmonic of the laser between offset frequencies of 10 Hz and 100 kHz. Because of the low repetition rate and short pulses, the power level on the fast photodiode had to be rather low to avoid damage. Thus, above 2 kHz the measurement was limited by thermal noise in the electronics. At frequencies below 2 kHz we observed a quadratic decay of the timing phase-noise power spectral density with offset frequencies, as expected from theory. We expect that with a ruggedized cavity setup (without *xyz* stages

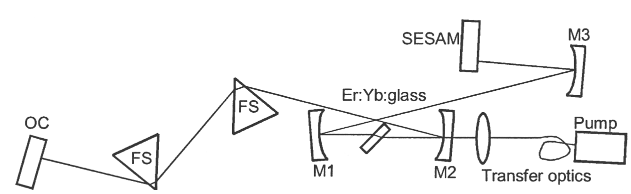

Fig. 2. Simplified schematic of the cavity. OC, output coupler; FSs, fused-silica prisms; M1, M2, high reflectors at 1550 nm, radius of curvature 75 mm; M3, high reflector at 1550 nm, radius of curvature 200 mm. Distances: SESAM–M3, 200 mm; M3–M1; 1000 mm; M2–OC; 1770 mm.

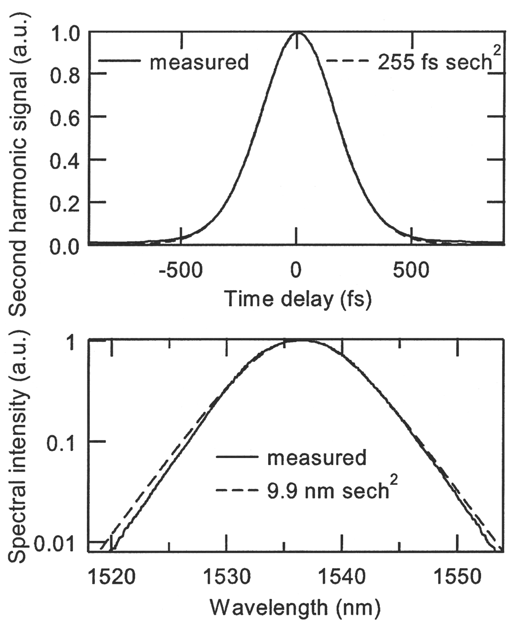

Fig. 3. Autocorrelation trace and optical spectrum confirming clean 255-fs solitons (time–bandwidth product 0.32).

and minimized air currents), together with feedback timing stabilization, sub-100-fs jitter should be readily obtained. Indeed a similar passively mode-locked solid-state laser (based on Cr:LiSAF) with a rms timing jitter of 20 fs (25 mHz–10 kHz) has been presented.[18] Additionally, according to Ref. 16, the quantum limit of the timing phase noise of a fundamentally mode-locked laser scales proportionally to the pulse-repetition rate and inversely proportional to the intracavity pulse energy. As we are operating at a 200 times lower pulse-repetition rate with similar intracavity powers and saturated gain levels, the quantum limit of the timing phase noise of the Er:Yb:glass laser with low repetition rates should be orders of magnitude lower than at 10 GHz, where we obtained timing jitters below 100 fs from our stabilized 10-GHz Er:Yb:glass lasers,[5] despite the high carrier frequency.

In conclusion, we have demonstrated a simple passively mode-locked Er:Yb:glass laser using a low-loss SESAM and a telecom-grade 500-mW diffraction-limited pump. The good pump-beam quality allowed us to optimize the design to mitigate the trade-off between short pulses and high output power. We obtained clean transform-limited pulses of 255-fs duration with 58-mW average power. Thus, applications such as supercontinuum generation that benefit from the peak power of clean pulses could significantly benefit from this laser. It could serve as a replacement for complex systems combining fiber lasers and Er-doped fiber amplifiers. In addition, this kind of laser has the potential to operate with very low timing jitter (<20 fs for a frequency range of a few hertz to a few megahertz). Therefore it can find applications in time-resolved measurements such as optical sampling[19] where low noise, high power, and short, clean pulses are required. We believe that despite the somewhat longer pulses, this kind of laser could become a significant competitor for mode-locked Er-doped fiber lasers because of its simplicity, ease of use, and clean, stable performance.

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References

1. S. Taccheo, G. Sorbello, P. Laporta, G. Karlsson, and F. Laurell, IEEE Photon. Technol. Lett. **13,** 19 (2001).
2. R. Fluck, R. Häring, R. Paschotta, E. Gini, H. Melchior, and U. Keller, Appl. Phys. Lett. **72,** 3273 (1998).
3. R. Wu, J. D. Meyers, and S. J. Hamlin, in *Advanced Solid State Lasers*, W. R. Bosenberg and M. M. Fejer, eds., Vol. 19 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 1998), p. 159.
4. S. C. Zeller, L. Krainer, G. J. Spühler, R. Paschotta, M. Golling, D. Ebling, K. J. Weingarten, and U. Keller, Electron. Lett. **40,** 875 (2004).
5. G. J. Spühler, M. Dymott, I. Klimov, G. Luntz, L. Baraldi, I. Kilburn, P. Crosby, S. Thomas, O. Zehnder, C. Y. Teisset, M. Brownell, K. J. Weingarten, R. Dangel, B. J. Offrein, G. L. Bona, O. Boccafusca, Y. Kaneko, L. Krainer, R. Paschotta, and U. Keller, Electron. Lett. **38,** 1031 (2002).
6. J. P. Turkiewicz, E. Tangdiongga, G. D. Khoe, H. deWaardt, W. Schairer, H. Rohde, G. Lehmann, E. S. R. Sikora, Y. R. Zhou, A. Lord, and D. Payne, in *Optical Fiber Communication Conference*, Vol. 95 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2004), paper PDP1.
7. H. Hundertmark, D. Kracht, D. Wandt, C. Fallnich, V. V. R. K. Kumar, A. K. George, J. C. Knight, and P. St. J. Russell, Opt. Express **11,** 3196 (2003); http://www.opticsexpress.org.
8. G. Wasik, F. W. Helbing, F. König, A. Sizmann, and G. Leuchs, in *Conference on Lasers and Electro-Optics (CLEO)*, Vol. 56 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2001), paper CMA4.
9. D. E. McCumber, Phys. Rev. **136,** 954 (1964).
10. P. H. Haumesser, R. Gaume, B. Viana, and D. Vivien, J. Opt. Soc. Am. B **19,** 2365 (2002).
11. V. P. Gapontsev, S. M. Matitsin, A. A. Isineev, and V. B. Kravchenko, Opt. Laser Technol. **14,** 189 (1982).
12. F. X. Kärtner, I. D. Jung, and U. Keller, IEEE J. Sel. Top. Quantum Electron. **2,** 540 (1996).
13. U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom, Opt. Lett. **17,** 505 (1992).
14. U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, IEEE J. Sel. Top. Quantum Electron. **2,** 435 (1996).
15. C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, J. Opt. Soc. Am. B **16,** 46 (1999).
16. R. Paschotta, Appl. Phys. B **79,** 163 (2004).
17. D. von der Linde, Appl. Phys. B **39,** 201 (1986).
18. H. Tsuchida, Opt. Lett. **24,** 1641 (1999).
19. N. Yamada, H. Ohta, and S. Nogiwa, IEICE Trans. Electron. **E86-C,** 1816 (2003).