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Efficient and tunable diode-pumped femtosecond Yb:glass lasers

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Diode-pumped Yb:phosphate and Yb:silicate glass lasers have been passively mode locked for the first time to the authors' knowledge. Reliable self-starting mode locking without critical cavity alignment has been achieved with intracavity semiconductor saturable-absorber mirrors and soliton mode locking. We generated pulses as short as 58 fs with the Yb:phosphate laser and 61 fs with the Yb:silicate laser at average output powers of 65 and 53 mW, respectively. The pulse repetition rate was 112 MHz. Additionally, we demonstrated tunability of femtosecond pulses from 1025 to 1065 nm for the Yb:phosphate and from 1030 to 1082 nm for the Yb:silicate glasses. The highest mode-locked output power was 405 mW, with 183-fs pulses from the phosphate glass. The diode pump power was 1.68 W, corresponding to 24% optical-to-optical efficiency. The highest cw output power was 510 mW at the same incident pump power. © 1998 Optical Society of America

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Yb-doped materials are interesting as diode-pumped, tunable, and ultrafast high-power laser sources because of their broad absorption and emission bandwidths and their low thermal loading. Additional benefits are the long fluorescence lifetime (1–2 ms), which is desirable for ultrashort pulse amplification or Q switching, and the simple electronic structure, which avoids loss processes such as excited-state absorption, upconversion, and concentration quenching.[1] Yb:YAG lasers have shown efficient cw laser action[2–4] and a tuning range from 1018 to 1053 nm.[3] Also, Yb:glass materials are interesting because they are significantly cheaper than crystals and have a smoother fluorescence spectrum, making them particularly attractive for generation of ultrashort pulses and as tunable laser sources. Compared with Nd:glass, Yb-doped glass has the advantage of a wider tuning range, especially to lower wavelengths, and a 2–3 times smaller quantum defect, which is favorable for operation at higher output powers at the watt level. The problems associated with Yb-doped laser materials are the quasi-three-level nature and the low emission cross section ($\sigma \approx 10^{-21}$–10^{-20} cm^2). The quasi-three-level nature requires a relatively high pump intensity for efficient laser operation. This is most easily provided by nearly diffraction-limited pump sources such as Ti:sapphire lasers and diode-pumped solid-state lasers. By pumping a 5%-Yb-doped phosphate glass with a diode-pumped, nearly diffraction-limited Nd:YAG laser operating at 946 nm, 440-mW average output power was achieved. This corresponds to an optical-to-optical efficiency of 22% for 2-W incident pump power.[5] Directly diode-pumped cw operation of Yb-doped fluoride phosphate glass lasers[6] and quasi-cw operation of a Yb-doped phosphate glass laser[7] have recently been demonstrated.

The first femtosecond Yb laser was a Yb:YAG laser with pulses as short as 540 fs at 1030 nm,[8] later improved to 340 fs.[9] Mode locking was achieved by use of semiconductor saturable-absorber mirrors (SESAM's).[9,10] More recently, pulses as short as 87 fs from a stretched-pulse Yb:silica fiber laser[11] and 160-fs pulses from a Kerr-lens mode-locked Ti:sapphire laser–pumped bulk Yb:fluoride phosphate glass laser were demonstrated.[12] The latter produced 250-mW output power at 1040 nm at an absorbed pump power of 1.2 W, corresponding to ≈2.4-W incident Ti:sapphire pump. No wavelength tuning of the laser was possible.

In this Letter we report what is to our knowledge the first demonstration of a diode-pumped, tunable femtosecond Yb:glass laser. Figure 1 shows the standard delta laser cavity with a prism pair for dispersion compensation. To obtain self-starting mode locking we focus the laser mode onto a SESAM to a spot of ≈180-μm diameter, resulting in a typical energy fluence that is 2–4 times the saturation fluence of the absorber ($E_{\mathrm{sat}} \approx 120\ \mu\mathrm{J/cm}^2$). The laser mode waist inside the gain medium is calculated by the *ABCD* matrix formalism to be $76\ \mu\mathrm{m} \times 50\ \mu\mathrm{m}$. The pulse repetition rate of the laser was 112 MHz. We used two different SESAM's, similar to the low-finesse antiresonant Fabry–Perot saturable absorber (A-FPSA) described in Refs. 8 and 9. The low-temperature molecular beam epitaxy–grown InGaAs absorber layers are 15 and 25 nm thick, resulting in maximum modulation depths of ≈0.5% and 0.6%, respectively. Both SESAM's exhibit a bitemporal impulse response[9] with a fast component of 150 fs for the 15-nm SESAM and 300 fs for the 25-nm SESAM, measured at 1060-nm wavelength. The slow components are ≈5 ps.

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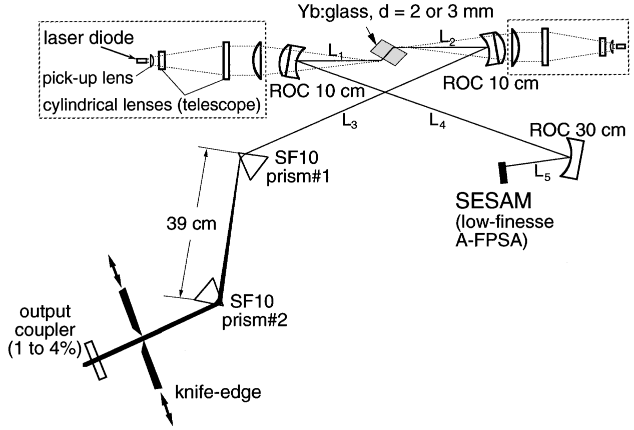

Fig. 1. Yb:glass laser setup: lenses L_1, L_2, 5 cm; L_3, 60 cm; L_4, 50 cm; L_5, 13.9 cm. Pump optics: The pick-up lens is aspherical ($f = 4.5$ mm; N.A., 0.55); the cylindrical lenses form a 1:15 Galilean telescope for the slow axis of the diode.

As gain materials we used two different 15 wt. % Yb_2O_3-doped glasses: a Kigre QX/Yb phosphate glass and a Kigre Q-246/Yb silicate glass. The glass is longitudinally pumped by either one or two high-brightness, broad-area InGaAs/GaAs laser diodes (Uniphase Laser Enterprise, maximum 840 mW each) with 30-μm ridge width, operated at $\approx$968 nm. The absorption lengths of the glasses at this pump wavelength were 2.2 mm for the QX and 3.4 mm for the Q-246 glasses. The gain medium was not actively cooled. Pumping through the 10-cm radius-of-curvature (ROC) cavity mirrors requires a special mirror coating because of the close vicinity of pump and laser wavelengths. The mirrors were >90% transmissive for the pump and highly reflective for wavelengths above 1030 nm. To achieve optimum pump-to-laser mode matching we focused the pump light down to a spot of 60 μm × 50 μm diameter, as measured in air. Inside the glass, this resulted in a confocal parameter of $\approx$1.3 mm for the slow axis of the diodes (horizontal in Fig. 1; $M^2_{\mathrm{slow}} = 7$). In the fast axis (vertical in Fig. 1) the diodes are nearly diffraction limited, with $M^2_{\mathrm{fast}} = 1.3$.

Using the 3-mm thick QX/Yb phosphate glass in cw configuration (i.e., the SESAM is replaced by a high reflector and no prisms are inside the cavity), we achieved a maximum output power of 510 mW at 1055 nm. To date, this is the highest cw output power from a QX/Yb glass laser of which we are aware. The pump power was 1.68 W, resulting in a high optical-to-optical efficiency of 30%, which corresponds to an efficiency of 38% with respect to the 1.34-W absorbed pump power. The output coupling was 4%.

The highest obtained mode-locked output power was 405 mW; 3% output coupling and the 15-nm SESAM were used. The pulse duration was 183 fs. Shorter pulses of 120 fs at a slightly lower output power of 380 mW were achieved with the 25-nm SESAM with its larger modulation depth. The small drop in output power results from increased residual losses introduced by the thicker low-temperature molecular beam epitaxy–grown semiconductor material. We determined a round-trip small-signal gain of 1.23 by measuring the relaxation oscillation frequency of the mode-locked laser[13] with a microwave spectrum analyzer. Soliton mode locking[14] is verified as the pulse-generation mechanism because the pulse width increased linearly with the negative intracavity dispersion and because approximately transform-limited, self-starting pulses were obtained without critical cavity alignment.

The tunability of the Yb:phosphate glass laser was demonstrated at a total pump power of 1.3 W with the 25-nm SESAM. We tuned the wavelength by inserting a knife-edge in the spatially dispersed beam between the second prism and the output coupler. We achieved a tuning range of 40 nm from 1025 to 1065 nm (Fig. 2). The output power varied from 91 to 237 mW, and the pulse duration varied from 115 to 350 fs. The fluorescence spectrum of the phosphate glass indicates that there is still bandwidth left on either side of the demonstrated tuning range. At lower wavelengths we were limited by the reabsorption of the quasi-three-level material. This problem could be addressed by use of a lower Yb doping of the glass. However, the optical-to-optical efficiency of the laser would then also be reduced. At longer wavelengths we were limited by the bandgap of the semiconductor saturable-absorber material, which is determined by the indium content of the InGaAs absorber and lies at $\approx$1060 nm. As shown in Fig. 2, the reflectivity curve of the SESAM is not a limiting factor in our case. Within our tuning range, the transmission of the output coupler was (3.3 ± 0.3)%.

The shortest pulses achieved with the Yb:phosphate glass laser were 58 fs at a center wavelength of 1058 nm (Fig. 3). We used a 2-mm-thick glass for better pump-to-laser mode matching and a lower output coupling of 2% to increase the effective absorber modulation.[14,15] The glass was pumped at 710 mW, yielding an average output power of 65 mW. Further reduction of the pulse duration might be possible by use of an absorber with a larger modulation depth.

An interesting Yb:glass material for the longer-wavelength regime is Q-246/Yb silicate glass. Our

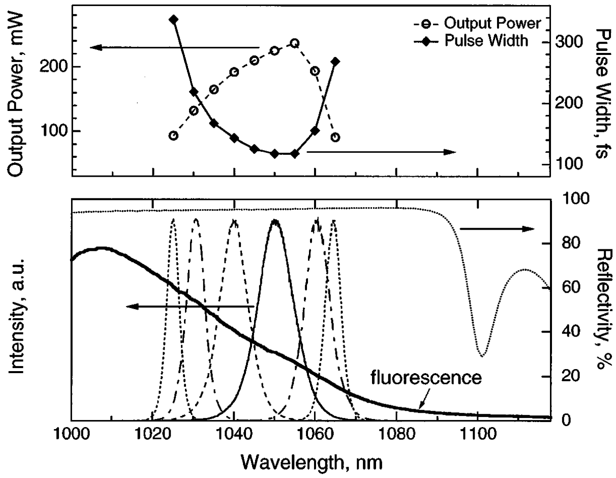

Fig. 2. Tunability of the phosphate glass (QX/Yb). Bottom, various pulse spectra, fluorescence spectrum (thick curve), and reflectivity curve of the SESAM (dotted curve). Top, corresponding measured output powers and pulse widths.

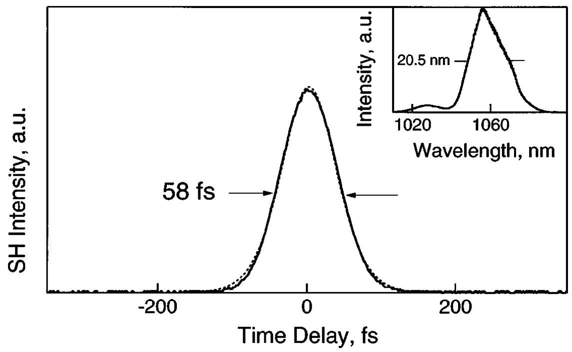

Fig. 3. Shortest pulse intensity autocorrelation (SH, second harmonic) and spectrum obtained with the QX/Yb glass. Dotted curve, fit assuming a sech^2 pulse shape.

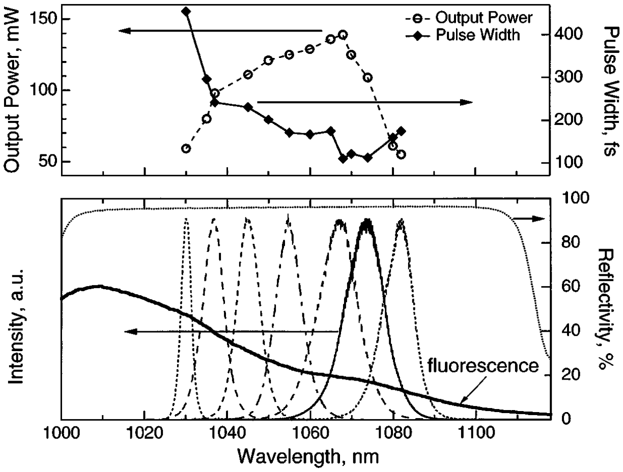

Fig. 4. Tunability of the Q-246/Yb silicate glass. Bottom, various pulse spectra, fluorescence spectrum (thick curve), and reflectivity curve of the SESAM (dotted curve). Top, corresponding measured output powers and pulse widths.

results with 2-mm-thick Q-246 glass are shown in Fig. 4. The fluorescence spectrum is extended to longer wavelengths compared with that of the Yb:phosphate glass. We achieved a 52-nm tuning range, from 1030 to 1082 nm. At an incident pump power of 1.3 W we achieved output powers ranging from 55 to 152 mW and pulse durations from 110 to 450 fs. The transmission of the output coupler was ≈2.3% for wavelengths between 1010 and 1080 nm. We used the 15-nm SESAM with a bandgap at ≈1080 nm corresponding to the long-wavelength limit of the obtained tuning range. Using a 1% output coupler and a pump power of 710 mW, we generated 61-fs pulses at 53-mW output power and 1080-nm center wavelength. The lower output power for the silicate glass laser compared with that of the phosphate glass laser is due mainly to the longer absorption length, which leads to imperfect pump-to-laser mode overlap. The absorption length for the silicate glass can be reduced by use of a pump diode emitting at ≈5-nm longer wavelength.

In conclusion, we have demonstrated what we believe is the first diode-pumped femtosecond Yb:glass laser. We obtained a high optical-to-optical efficiency of 30% for cw and 24% for mode-locked operation of a Yb:phosphate glass laser. Because of the low quantum defect and the excellent thermomechanical properties of the QX-based glasses, high-power operation at the watt level should be possible by application of the thin-disk concept[16] or other power scalable geometries.[17] A compact, watt-level, tunable femtosecond laser at ≈1 μm could serve as an alternative to Ti:sapphire lasers operated in this wavelength regime. Potential applications are seeding of high-peak-power amplifiers based on Nd or Yb glass, pumping of femtosecond optical parametric oscillators, and ultrafast spectroscopy.

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References

1. L. D. DeLoach, S. A. Payne, L. L. Chase, L. K. Smith, W. L. Kway, and W. F. Krupke, IEEE J. Quantum Electron. **29,** 1179 (1993).
2. P. Lacovara, H. K. Choi, C. A. Wang, R. L. Aggarwal, and T. Y. Fan, Opt. Lett. **16,** 1089 (1991).
3. U. Brauch, A. Giesen, M. Karszewski, C. Stewen, and A. Voss, Opt. Lett. **20,** 713 (1995).
4. H. Bruesselbach and D. S. Sumida, Opt. Lett. **21,** 480 (1996).
5. R. Koch, W. A. Clarkson, D. C. Hanna, S. Jiang, M. J. Myers, D. Rhonehouse, S. J. Hamlin, U. Griebner, and H. Schönnagel, Opt. Commun. **134,** 175 (1997).
6. T. Danger, E. Mix, E. Heumann, G. Huber, D. Ehrt, and W. Seeder, in *Advanced Solid State Lasers*, Vol. 1 of OSA Trends in Optics and Photonics Series, S. A. Payne and C. Pollock, eds. (Optical Society of America, Washington, D.C., 1996), p. 23.
7. U. Griebner, R. Koch, H. Schönnagel, S. Jiang, M. J. Myers, D. Rhonehouse, and S. J. Hamlin, in *Conference on Lasers and Electro-Optics*, Vol. 9 of 1996 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1996), paper CThI1.
8. C. Hönninger, G. Zhang, U. Keller, and A. Giesen, Opt. Lett. **20,** 2402 (1995).
9. 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).
10. U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom, Opt. Lett. **17,** 505 (1992).
11. V. Cautaerts, D. J. Richardson, R. Paschotta, and D. C. Hanna, Opt. Lett. **22,** 316 (1997).
12. V. Petrov, U. Griebner, D. Ehrt, and W. Seeber, Opt. Lett. **22,** 408 (1997).
13. K. J. Weingarten, B. Braun, and U. Keller, Opt. Lett. **19,** 1140 (1994).
14. F. X. Kärtner, I. D. Jung, and U. Keller, IEEE J. Sel. Top. Quantum Electron. **2,** 540 (1996).
15. H. A. Haus, J. Appl. Phys. **46,** 3049 (1975).
16. A. Giesen, H. Hügel, A. Voss, K. Wittig, U. Branch, and H. Opower, Appl. Phys. B **58,** 363 (1994).
17. D. Kopf, K. J. Weingarten, G. Zhang, M. Moser, M. A. Emanuel, R. J. Beach, J. A. Skidmore, and U. Keller, Appl. Phys. B **65,** 235 (1997).