Self-starting diode-pumped femtosecond Nd fiber laser

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A self-starting passively mode-locked diode-pumped neodymium fiber laser with a semiconductor antiresonant Fabry–Perot saturable absorber (A-FPSA) is demonstrated for the first time to our knowledge. Mode locking can be initiated and maintained by the semiconductor absorber, and pulse durations down to 260 fs are routinely obtained. Alternatively, shorter pulses (60 fs) were generated by exploition of nonlinear polarization evolution in the fiber (in combination with a stronger pump source) where the A-FPSA simply initiates the pulse-forming process.

Single-mode rare-earth-doped fibers[1] are now a well-established medium for the generation of ultrashort pulses. In recent experiments pulse widths as short as 32 and 84 fs have been obtained directly from neodymium and erbium fiber lasers, respectively.[2,3] Generally, the shortest pulses are produced by a combination of amplitude and phase modulations that arise from a near-instantaneous Kerr nonlinearity, which favors mode-locked over cw operation. Although this approach permits one to mode lock nearly the full bandwidth of the gain medium, the polarization dependence of these modulation mechanisms is subject to long-term environmental changes and may thus require sophisticated fiber designs and control mechanisms[4] in a practical device. In addition these lasers typically do not self-start owing to spurious intracavity reflections[5] and periodic index modulations in the gain medium.[6] Environmentally stable and self-starting operation has recently been obtained by incorporation of a bulk semiconductor saturable absorber and a polarization-maintaining erbium fiber into the cavity.[7] A major limitation of this type of cavity design is that the semiconductor introduces large excess loss into the cavity (up to 10 dB). The corresponding large gain gratings[6] are found to inhibit self-starting operation severely unless high-power pump sources are used.

In this Letter we present the use of a multiple-quantum-well (MQW) saturable absorber with optimized saturation characteristics in combination with a fiber laser. In this case the MQW layer is integrated inside a nonlinear antiresonant Fabry–Perot mirror[8] (A-FPSA). The resulting decrease in the intracavity loss allows direct diode-pumped operation of this type of mode-locked laser for the first time to our knowledge. In addition, mode locking is self-starting owing to the bitemporal impulse response of the A-FPSA,[9] where the slow nonlinearity of the semiconductor is used to start the mode-locking process and the fast nonlinearity is used to sustain it. In contrast to mode locking with Kerr-effect absorbers, the pulse-width-limiting mechanism is now the fast response time of the semiconductor, which is ≈300 fs in most materials. Furthermore, similar to the femtosecond Nd:glass laser[10] we also demonstrate that the A-FPSA may simply be used to start passive mode locking in a cavity where a fast Kerr nonlinearity determines the final pulse width. This allows the generation of 60-fs pulses, which are to our knowledge the shortest pulses obtained from a self-starting fiber laser to date.

The semiconductor absorber was a low-temperature (340 °C) molecular-beam-epitaxy-grown InGaAs/GaAs MQW structure of 50 periods with a band gap near the central laser wavelength of 1.06 μm. Each period consists of a 6-nm-thick GaAs barrier and a 6.2-nm $In_xGa_{x-1}As$ well with $x = 0.29$. The absorption dynamics in the MQW are dominated by a slow and a fast time constant that result from carrier recombination and nonequilibrium carrier distribution. The carrier lifetime can be controlled by the growth temperature and was chosen to be 35 ps to allow an easy start-up.[9] The measured fast thermalization time constant was

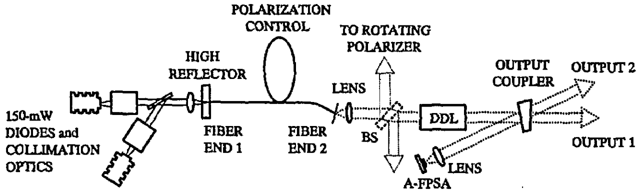

Fig. 1. Cavity design for the self-starting Nd fiber laser oscillator. DDL, dispersive delay line; BS, beam splitter (only used to measure the polarization state, here the output coupler was replaced with a high reflector).

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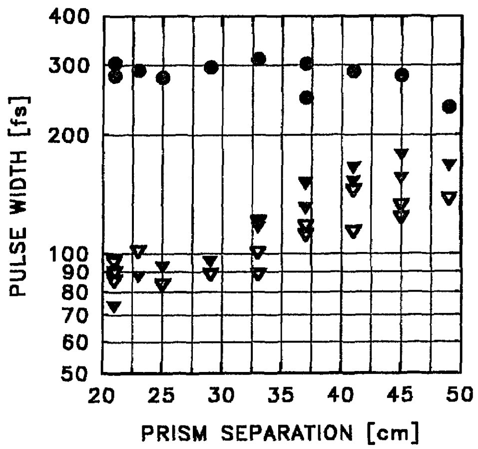

Fig. 2. Pulse length under different mode-locking schemes over prism separation. ●, Mode locking based on the A-FPSA; △, ▲, output 1 and output 2 under NPE-based mode locking, respectively. (To allow comparison, all curves were recorded with 290 mW of absorbed pump light from a Kr^{3+} laser.)

≈300 fs. The MQW was grown on top of a dielectric GaAs/AlAs mirror ($R = 96\%$) fabricated at normal MBE temperature. The 30% Fresnel reflection from the front surface yields a weak A-FPSA structure, and the low-power reflectivity was measured to be ≈80%.

The experimental setup is shown in Fig. 1. A weakly birefringent silica fiber (NA = 0.17, core diameter 5 μm, $\beta_2 = 27$ ps^2/km, and an Nd^{3+}-doping level of 1700 parts in 10^6) as short as 20 cm was used in the cavity. The special arrangement of the dispersive delay line, as described in Ref. 11, yields an output free of any spatial chirp and provides easy control of overall dispersion. For focusing onto the A-FPSA we used antireflection-coated lenses with focal lengths of 5.6–15 mm. With the *ABCD* matrix formalism we estimate the spot sizes on the saturable absorber to vary between $w_0 \approx 5$ and 20 μm. Therefore, with data from previous measurements[12] we can deduce a peak reflectivity change of the uncoated A-FPSA of ≈5–10% for typical pulse-energy densities of 0.75–1.4 mJ/cm^2 ($f = 5.6$–15 mm) and a repetition rate of 50 MHz.

For the first experimental part we used two polarization-multiplexed 150-mW laser diodes that emitted at 808 nm as the pump source. For a 5% output coupler we measured a lasing threshold as low as ≈4 mW of absorbed pump power and a slope efficiency of ≈6% (output 1 and output 2 together). At launched pump powers >15 mW the laser turned into pulsed operation, and mode locking could be sustained down to 10 mW.

The cw optimization was performed with the focusing lens removed. The polarization state at fiber end 2 was adjusted to a linear horizontal eigenstate to minimize cw losses. Mode locking was achieved when focusing onto the absorber, where the A-FPSA starts and sustains pulsed operation. The single polarization state even under mode-locking conditions was verified by insertion of a beam splitter into the cavity (Fig. 1) and measurement of the polarization state of the pulses leaving the fiber with a rotating polarizer. Here no difference between cw and mode-locked operation was measurable, and the extinction ratio between the two polarization states was >30 dB. Thus pulse width was solely determined by the fast time constant of the semiconductor. The average mode-locking buildup time varied with pump power[9] and was ≈50 μs and ≈100 ms for maximum pump power and near the mode-locking threshold, respectively. Additionally we found that the pulse duration was not critically dependent on the intracavity power and overall dispersion as displayed in Fig. 2. Once in the overall negative dispersion regime the pulse length remained approximately constant at 280 fs ± 14% for a dispersion change of >17,000 fs^2. A fringe-resolved autocorrelation of the pulse train leaving the fiber implied the absence of chirp, and hence even the large amount of negative dispersion of the delay line or the large positive dispersion in one round trip through the fiber had little impact on the pulse length.

The radio-frequency spectrum gave evidence of the good quality of the pulses as no modulation sidebands were visible as observed in other systems.[8] The noise background was <70 dBc for offsets >8 kHz from the carrier (measurement limited). The total output power at 5% output coupling was 4 mW. A typical autocorrelation trace of the 260-fs pulse train together with the corresponding spectrum of a 5.1-nm FWHM bandwidth is displayed in Fig. 3. The time–bandwidth product is 0.35, which is close to 0.315 for a transform-limited sech^2 pulse.

We observed that with an imperfect alignment of the lens focusing onto the A-FPSA, stable pulse

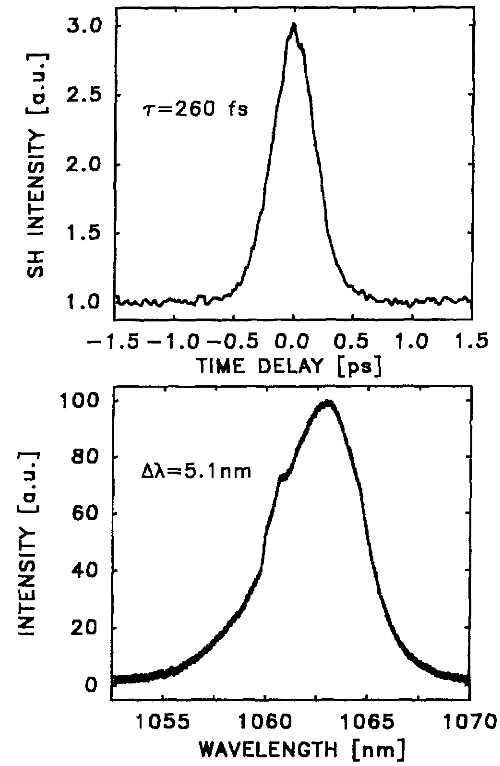

Fig. 3. Top: autocorrelation trace of the shortest pulses generated with the A-FPSA. Bottom: corresponding spectrum. $\Delta\nu\Delta\tau = 0.35$.

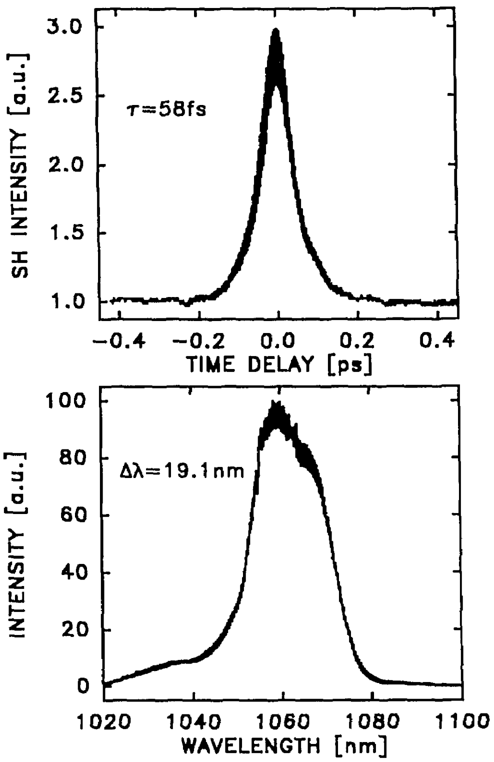

Fig. 4. Top: autocorrelation trace of the shortest pulses started with the A-FPSA and sustained by NPE. Bottom: corresponding spectrum. $\Delta\nu\Delta\tau = 0.3$.

bunching occurs, where the number and the amplitude of the pulses in a bunch could vary depending on the start-up conditions and intracavity power. We attribute this feature to spurious intracavity reflections.

Alternatively, when we used nonlinear polarization evolution[13] (NPE) in the fiber, pulses as short as 130 fs were generated. Here the A-FPSA acts only during the start-up phase,[10] and the final pulse duration is determined by the near-instantaneous saturable absorberlike action of the nonlinear polarization switch and by the amount of uncompensated cavity dispersion. The A-FPSA provides a sufficiently short seed pulse for the NPE mechanism, which is introduced to the A-FPSA mode-locked system by a subsequent change of the fiber birefringence via the polarization controller. However, when we maximized the passive amplitude modulation to generate the shortest possible pulses, we could no longer achieve self-starting. We consider this to be due to the large linear loss associated with the polarization bias.[2] This drawback can be overcome by use of longer fiber lengths or higher intracavity powers, which increase the nonlinearity. Pumping of the system with 350 mW (absorbed) of a Kr^{3+} laser and further optimization of the polarization state permitted the generation of pulses as short as 58 fs with a total output power of 6.5 mW (5% output coupling). The autocorrelation trace is shown in Fig. 4 together with the corresponding spectrum of 19.1 nm FWHM, which yields a time–bandwidth product of 0.3. With NPE as the mode-locking mechanism the pulse length varied considerably with dispersion[11] as displayed in Fig. 2. Note that the pulse length at output 2 is different from the pulse duration measured at output 1. Depending on the dispersion setting of the delay line, the incoming pulses are compressed or stretched, which indicates that an additional negative chirp is introduced by the absorption saturation in the sample.

In conclusion, we demonstrated self-starting operation of a diode-pumped Nd fiber laser with an A-FPSA for the first time to our knowledge, which yields pulses as short as 260 fs. The fiber laser is free of Q-switching instabilities and operates in a single polarization state, which will permit the use of high-birefringence fibers in the future to increase the environmental stability. Furthermore, when we applied NPE in the fiber, the A-FPSA participated only to initiate the mode locking. In this operating mode, self-starting pulses down to 60 fs were generated. Here the advantages of an energy-saturating and an intensity-dependent absorber are combined to provide both an easy start-up and a stable train of <100-fs pulses. This unique combination overcomes the restrictions of passively mode-locked solid-state lasers that tend not to self-start.

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Note added in proof: We recently generated self-starting pulses (diode pumped) as short as 130 fs with 70 cm of fiber relying on the NPE scheme with the A-FPSA active only during start-up.

References

1. S. B. Poole, D. N. Payne, and M. E. Fermann, Electron. Lett. **21**, 737 (1985).
2. M. H. Ober, M. Hofer, and M. E. Fermann, Opt. Lett. **18**, 367 (1993).
3. M. E. Fermann, M. J. Andrejco, M. L. Stock, Y. Silberberg, and A. M. Weiner, Appl. Phys. Lett. **62**, 910 (1993).
4. M. E. Fermann, M. J. Andrejco, M. L. Stock, and Y. Silberberg, Opt. Lett. **18**, 894 (1993).
5. H. A. Haus and E. P. Ippen, Opt. Lett. **16**, 1331 (1991).
6. F. Krausz and T. Brabec, Opt. Lett. **18**, 888 (1993).
7. E. A. DeSouza, C. E. Soccolich, W. Pleibel, R. H. Stolen, M. N. Islam, J. R. Simpson, and D. J. DiGiovanni, Electron. Lett. **29**, 447 (1993).
8. U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom, Opt. Lett. **17**, 505 (1992).
9. U. Keller, T. H. Chiu, and J. F. Ferguson, Opt. Lett. **18**, 217 (1993).
10. U. Keller, T. H. Chiu, and J. F. Ferguson, Opt. Lett. **18**, 1077 (1993).
11. M. Hofer, M. H. Ober, F. Haberl, and M. E. Fermann, IEEE J. Quantum Electron. **28**, 720 (1992).
12. U. Keller, L. E. Nelson, and T. H. Chiu, in *Advanced Solid-State Lasers,* Vol. 13 of OSA Proceedings Series (Optical Society of America, Washington, D.C., 1992), p. 94.
13. M. Hofer, M. E. Fermann, F. Haberl, M. H. Ober, and A. J. Schmidt, Opt. Lett. **16**, 502 (1991).