60-fs pulses from a diode-pumped Nd:glass laser

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We demonstrate 60-fs pulses with an average output power of 84 mW from a diode-pumped Nd:glass laser mode locked by a low-finesse antiresonant Fabry–Perot saturable absorber (A-FPSA). The mode-locked spectrum spreads over most of the available Nd:glass fluorescence bandwidth. At increased pulse energy fluence or decreased negative group-velocity dispersion, multiple pulsing was observed. We experimentally characterize this behavior, which can be explained by the saturation behavior of the A-FPSA and the limited available gain bandwidth. These considerations are significant for the design of saturable absorbers to achieve stable passive mode locking.   © 1997 Optical Society of America

Diode-pumped femtosecond Nd:glass lasers offer a cost-effective and compact alternative to Ti:sapphire lasers operated near 1.06 μm, with applications such as seeding of high-power amplifiers, pumping of femtosecond optical parametric oscillators, and ultrafast spectroscopy. The absorption band of Nd:glasses at ~800 nm allows for diode pumping,[1] resulting in a compact, wall-plug-driven setup, which does not require water cooling. Typical Nd:glasses have a fluorescence bandwidth of 20–30 nm FWHM, supporting sub-100-fs pulse generation at a wavelength of ~1.06 μm. Until recently, the shortest pulses from a (bulk) Nd:phosphate laser,[2] 88 fs, were produced by additive-pulse mode locking. Semiconductor saturable absorber mirrors[3] in various Nd:glass lasers[4,5] have supported pulses as short as 130 fs for diode pumping and 90 fs for Ti:sapphire pumping. In this Letter we demonstrate 60-fs pulses from an optimized diode-pumped Nd:glass laser, using an antiresonant Fabry–Perot saturable absorber[6,7] (A-FPSA). The ratio of the intracavity pulse energy fluence to the saturation fluence of the A-FPSA is shown to be an important design parameter for avoiding multiple intracavity pulses. Simple arguments can explain the occurrence of double or multiple pulses at increased pulse fluence.

Figure 1 shows the experimental results of 60-fs pulses from a Nd:fluorophosphate (LG-810, 3% Nd) laser at an average output power of 84 mW with a total absorbed pump power of 1.1 W. We also obtained 68-fs pulses from a Nd:silicate laser glass (LG-680, 3% Nd) at an output power of 32 mW (absorbed pump power 0.37 W from both diodes). The spectrum of the 60-fs pulses is 21.6 nm wide (FWHM) and fills most of the available gain bandwidth of the LG-810 [Fig. 1(b)]. The time–bandwidth product is 0.34, within 10% of the transform limit. These pulses were stable over an experimental period of more than 1 h. Mode locking was generally self-starting. The laser cavity was easy to align and did not have to be operated close to the resonator stability limit. Additionally, no hard aperture was present. This rules out Kerr-lens mode locking[8] as a significant mode-locking effect.

We used an optimized low-finesse A-FPSA[9,10] (Fig. 2, inset) with an increased maximum modulation depth of 1% but with the trade-off of increased insertion loss (at low intensities) of 2%. The bitemporal impulse response of the A-FPSA is similar to that of the device used in Ref. 5, with a fast time constant of 200 fs followed by a slow time constant of 25 ps, as determined by a standard pump–probe measurement. The saturation fluence F_{sat} of the A-FPSA was measured to be 116 μJ/cm^2, as determined in a setup similar to that of Ref. 11.

The pump and cavity layout (Fig. 2) is based on a standard delta-cavity design similar to that of Ref. 5. The laser beam is focused onto the A-FPSA to a calculated beam waist of approximately 63 μm $\times$ 70 μm (radius). The cavity repetition rate was typically 114 MHz. The calculated beam radius in the laser material is approximately 47 μm $\times$ 66 μm. The Nd:glass laser is cw pumped by two diode lasers (Spectra Diode Laboratories SDL-2360-C, 1.2 W, emitting wavelength ≈803 nm) focused to a beam radius of approximately 40 μm $\times$ 50 μm.
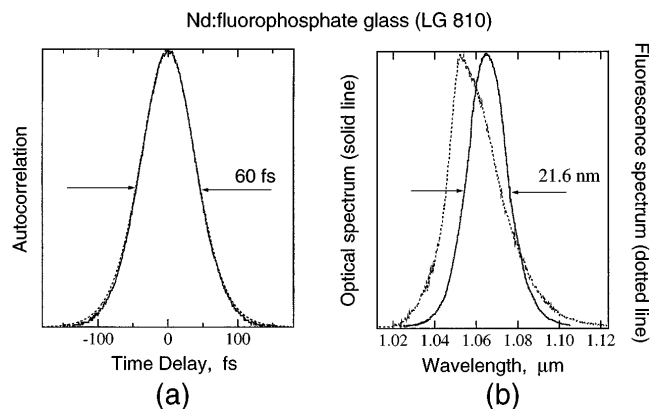

Nd:fluorophosphate glass (LG 810)

Fig. 1. (a) Noncollinear autocorrelation and (b) spectrum of the shortest pulses obtained from a diode-pumped Nd:fluorophosphate laser. The dotted curve in (a) is a fit to an ideal sech^2 pulse shape. The dotted curve in (b) shows the fluorescence spectrum of LG-810, indicating that the pulse spectrum spreads over most of the available gain bandwidth.
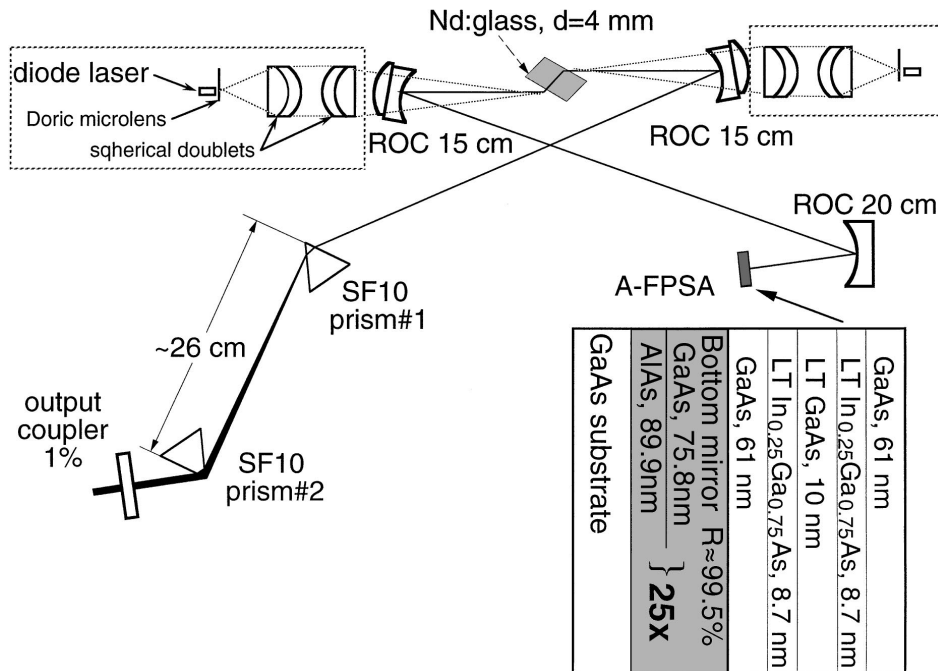
Fig. 2. Diode-pumped Nd:glass laser setup. Inset: structure of the low-finesse A-FPSA. ROC, radius of curvature; LT, low temperature grown.

The higher doping level and the reduced absorption length (2 mm) of the Nd:fluorophosphate, compared with those of Ref. 5, result in improved mode matching of the pump beam to the laser mode over the absorption length. This makes up for the increased loss of the A-FPSA, thus causing only a slight decrease in output power. The Nd:silicate glass (LG-680) used in some experiments had 3% Nd doping with an absorption length of 2.5 mm at the pump wavelength. We chose LG-810 and LG-680, which are inhomogeneously broadened, because mode locking is obtained more easily than with the homogeneously broadened Nd:phosphate.[5]

In the experiments described above, we verified that a single intracavity pulse was present. However, we observed a breakup into two or more pulses at increased intracavity energy (Fig. 3) or at a decreased amount of negative group-velocity dispersion, $|D|$, i.e., increased prism insertion (Fig. 4). The spacing between the pulses in the cavity ranged from 90 ps to half the cavity round-trip time and was subject to spontaneous changes. We monitored the pulse train with a 50-GHz fast photodiode and a 20-GHz sampling scope (Tektronix CSA 803) with a time resolution better than 20 ps. Additionally, the autocorrelation span was increased to >20 ps to monitor possible smaller pulse spacings. However, such smaller spacings were not observed.

Figure 3 shows the pulse width as a function of the total intracavity pulse energy E_p but at a constant negative dispersion in the Nd:silicate laser (the fluorophosphate laser showed similar behavior). As we increased the pump power and thus the pulse energy E_p, the measured transform-limited pulse width decreased approximately inversely proportionally to E_p, as the soliton mode-locking model predicts.[12,13] The observed deviation is most likely due to thermal lensing effects.

At sufficiently high E_p of ≈ 35 nJ with a pulse energy fluence incident upon the A-FPSA of ≈ 250 μJ/cm^2, i.e., ≈ 2.2 times F_{sat}, the intracavity pulse breaks up into two separate pulses, accompanied by a jump in pulse width by a factor of ~ 2. Correspondingly, the spectrum narrows by a factor of $\sim 1/2$, as we would expect for a soliton with half the energy.

For a fixed absorbed pump power of 658 mW in the Nd:silicate and an intracavity pulse energy of 46 nJ, which corresponds to 2.8 times F_{sat}, we observed an analogous behavior as we increased the insertion of one intracavity prism, thereby decreasing $|D|$ (Fig. 4). The transform-limited pulse width decreases for smaller $|D|$, i.e., increased prism insertion, until the pulse breaks up into two pulses of longer width. We observed a linear dependence both in the single- and
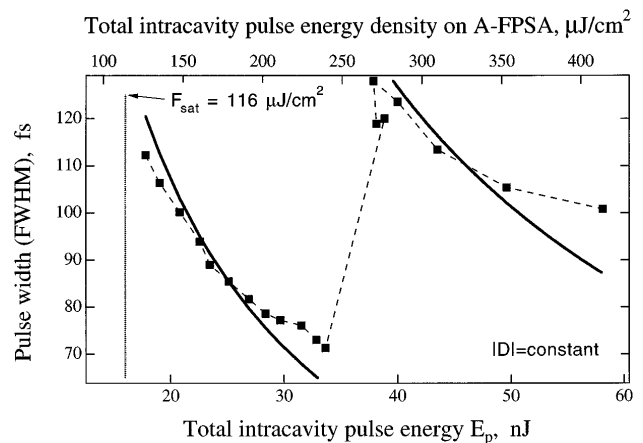

Fig. 3. Dependence of the pulse width on the total intracavity pulse energy in the Nd:silicate laser. The data are fitted to $\sim 1/E_p$ (soliton). At an energy of 35 nJ, the pulse breaks up into two intracavity pulses that have longer pulse widths.
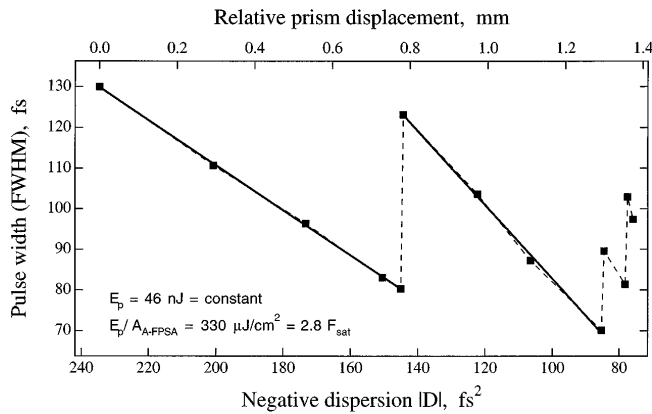
Fig. 4. Dependence of the pulse width on the total intracavity group-velocity dispersion $|D|$ in the Nd:silicate laser. The solid lines are fits to a straight line.

the double-pulse regimes, well in agreement with the soliton mode-locking model.[12,13] At an even smaller $|D|$, we could also observe a transition to more than two intracavity pulses. Again, the increased number of pulses was accompanied by a jump in pulse width.

To explain these multiple-pulse observations, we considered both the saturable absorption of the A-FPSA and the limited gain bandwidth of the laser medium. The reflectivity of the A-FPSA increases with increasing pulse energy fluence and eventually goes into saturation (see, for example, Fig. 8 of Ref. 11). Given an energy fluence many times the saturation energy fluence F_{sat}, the reflectivity is strongly saturated and therefore similar to the reflectivity for a pulse of half the energy. Therefore the A-FPSA provides reduced discrimination between single and double pulsing at increased incident pulse energy fluence. In addition, the limited gain bandwidth of Nd:glass prefers double pulsing over single pulses because the two longer intracavity solitons, which have a narrower spectrum, see more gain than a single shorter intracavity soliton. Therefore the laser prefers two intracavity pulses over a single pulse for a sufficiently broad mode-locked spectrum with a given saturation level of the saturable absorber. A more detailed treatment of this behavior is under investigation.

In conclusion, we have demonstrated a diode-pumped passively mode-locked Nd:glass laser producing pulses as short as 60 fs with an average output power of 84 mW. In comparison with previous research[4,5] we obtained these improvements by increasing the modulation depth of the saturable absorber and increasing the small-signal gain, using better mode matching. The trade-off with increased modulation depth (obtained with a thicker absorber layer at a constant top reflector of the A-FPSA) is increased nonsaturable losses.[11] In addition, the onset of multiple-pulsing instabilities sets a limit to how strongly the absorber can be saturated, which then limits the useful modulation depth of the device and further increases its residual insertion loss.

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