Diode-pumped mode-locked Nd:glass lasers with an antiresonant Fabry–Perot saturable absorber

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We demonstrate passively mode-locked diode-pumped Nd:glass lasers with different media such as silicate, phosphate, and fluorophosphate that are homogeneously or inhomogeneously broadened. An antiresonant Fabry–Perot saturable absorber starts and stabilizes the soliton mode-locked Nd:glass lasers, producing pulses as short as 130 fs at an average output power of 100 mW. With a cw Ti:sapphire pump laser we obtain pulses as short as 90 fs.

Neodymium-doped glass is an attractive laser medium for generating femtosecond pulses. Its broad emission bandwidth of 20–30 nm supports pulses of less than 100 fs,[1,2] and its absorption band near 800 nm permits diode laser pumping.[3] Compared with Ti:sapphire lasers operated near 1050 nm, a diode-pumped femtosecond Nd:glass laser can serve as a lower-cost and compact oscillator for such applications as seeding of a high-power Nd:glass amplifier and pumping of optical parametric oscillators and simply as a source for fixed-wavelength pump–probe measurements. After a brief review of initial results with a Ti:sapphire laser pump, we demonstrate diode-pumped passively mode-locked Nd:glass lasers. An InGaAs/GaAs antiresonant Fabry–Perot saturable absorber (A-FPSA) device[4,5] starts and stabilizes soliton mode locking.[6,7] We characterized and passively mode locked phosphate, silicate, and fluorophosphate Nd:glass lasers.

The various types of laser glass exhibit not only different optomechanical properties, i.e., thermal lensing, heat conductivity, and thermal expansion coefficient, but also different behavior concerning homogeneous or inhomogeneous linewidth broadening. This can be seen from the wavelength spectrum of the cw running laser shown in Fig. 1 at an absorbed pump power of ≈1 W. The Nd:phosphate (Schott LG-760) lases with a narrow linewidth near the peak of its gain spectrum, indicating a quasi-homogeneous broadening. Both the Nd:silicate (Schott LG-680) and the Nd:fluorophosphate (Schott LG-810) show a cw lasing linewidth of 8–10 nm as a result of their strong inhomogeneous broadening.

While the optomechanical properties affect only the general lasing performance, such as slope efficiency and output power, the linewidth-broadening characteristic of the laser directly affects the mode-locking performance. We observed this clearly with Ti:sapphire pumping,[2,8] in which the phosphate glass required a spectral filtering technique.[9] By inserting a long-pass wavelength filter using a knife-edge partially moved into the laser beam between the prism pair for dispersion compensation, we flattened the net gain profile, which allows for the generation of ≈100-fs short pulses.[2] However, no gain shaping for sub-100-fs pulse generation is required for inhomogeneously broadened glasses (Fig. 2) because the saturated gain spectrum is flattened over a spectral range with similar saturation energies within the inhomogeneously broadened linewidth.

The A-FPSA devices described throughout this Letter consist of a low-temperature (315 °C) molecular-beam-epitaxy-grown InGaAs/GaAs multiple-quantum-well saturable absorber grown on top of an AlAs/GaAs Bragg reflector and covered with an evaporated 96% top reflector. A detailed characterization and description was published in Ref. 10. These devices have been used now for several years in a number of experiments, indicating good long-term reliability. The strong starting mechanism of the A-FPSA makes the inhomogeneously broadened glass even easier to mode lock than the homogeneous one, in contrast to pre-

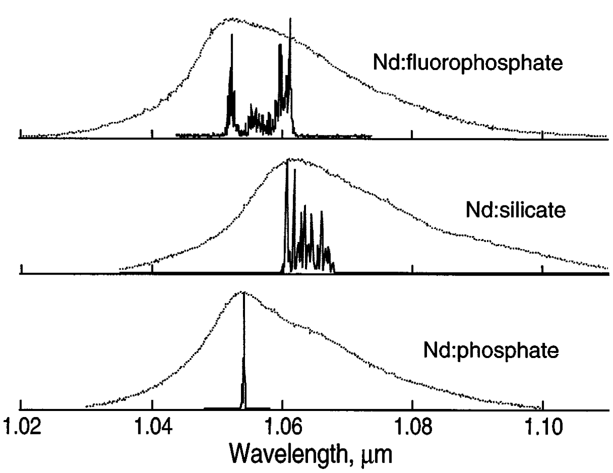

Fig. 1. Measured fluorescence spectra (dotted curves) and cw lasing output spectra (solid curves) at an absorbed pump power of ≈1 W for the three types of glass, reflecting the inhomogeneous broadening of the fluorophosphate and the silicate and homogeneous broadening of the phosphate.

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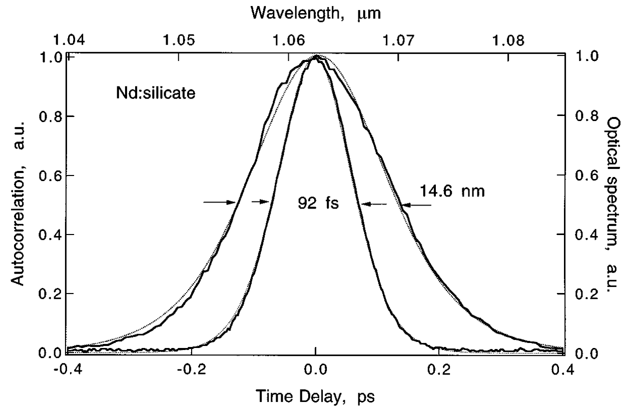

Fig. 2. Shortest pulse (autocorrelation and spectrum) obtained from the Ti:sapphire-pumped Nd:silicate laser. The dotted curves are fits to an ideal $sech^2$ pulse shape.

viously published results on an additive-pulse mode-locked system.[11]

The pulse generation process in these lasers is dominated by soliton mode locking[6,7] for which the soliton is formed as a result of negative group-velocity dispersion and self-phase modulation (SPM) and stabilized by the A-FPSA. The soliton phase shift per round trip[7] is of the order of several percent, whereas the saturable absorber modulation is less than 1%.[10] Thus the perturbational treatment of the soliton is justified. The relatively small amount of saturable absorption modulation is sufficient to start and stabilize the solitonlike pulses.[7] The theory presented in Ref. 7 assumes only a slow saturable absorber, whereas the semiconductor absorber used here has a bitemporal impulse response with an additional fast time constant of ≈180 fs.[10] Numerical simulations show that pulses down to 100 fs can be stabilized, in good agreement with our experimental results. The theoretical treatment describing the mode-locking mechanism analytically[6,7,9] also shows the importance of sufficiently large SPM and group-velocity dispersion for mode-locking stability. This has an effect on diode pumping, because both the pump and the laser mode cross section need to be increased to provide good mode matching of the non-diffraction-limited pump beam.[12]

In our diode-pumped Nd:glass laser setup (Fig. 3) we used the same cavity layout as with Ti:sapphire pumping, i.e., two curved folding mirrors [M1 and M2, radius of curvature (ROC) 10 cm], two SF10 prisms (28-cm separation) for dispersion compensation, a curved folding mirror (ROC 10 cm) to focus the laser mode onto the A-FPSA, and a flat 1% output coupler. The mode size at the laser material was approximately 30 μm × 50 μm radius and, at the A-FPSA, had a 30-μm circular radius. The cavity repetition rate was typically 180 MHz.

We used two diode lasers (Spectra Diode Laboratories, 1.2 W, 804 nm) that emit from a 100-μm stripe at a divergence of ±6°, corresponding to $M_x^2 \approx 20$, i.e., 20 times the diffraction limit in the direction parallel to the diode junction (slow direction). To collect the diode light in the strongly divergent (fast) direction, perpendicular to the diode junction, we used a single-axis collimator (SAC900, antireflection coated at 900 nm) with a throughput of ≈90%. The benefit of using these cylindrical microlenses is that they transform the stripelike emitting source into an almost square image by magnifying the 1-μm emitting facet into an ≈50-μm image. The following optics then simply consist of spherical achromats, rather than cylindrical lenses, which are not available as spherically compensated doublets. We used an achromat ($f = 100$ mm) to collimate the pump light after the microlens and a second achromat ($f = 76$ mm) to refocus through M1 into the Nd:glass medium. For compensation of the defocusing effect that was due to the concave curvature of the cavity mirror and for off-axis aberrations that were due to the tilt of M1, a plano-concave lens with approximately the same positive curvature was directly attached to the back of M1 (Fig. 3). We observed that this compensation was especially critical for focusing the pump to diameters of less than 100 μm.

With Nd:phosphate (LG-760, 4 mm thick, 2% Nd) as the laser medium, a maximum output power of 110 mW mode locked was achieved at 1.5-W absorbed pump power with a pulse width as low as 150 fs. In cw operation (with 2% output coupling and only highly reflecting mirrors, no prisms or A-FPSA), a maximum output power of 380 mW was obtained at a threshold of 60-mW absorbed pump power. The absorption length at the pump wavelength of 804 nm is approximately 1.5 mm. These cw results confirm that diode-pumped Nd:glass lasers can operate quite efficiently,[13] even comparably to Ti:sapphire pumping. The passively mode-locked Nd:phosphate laser operated at a center frequency of 1064 nm and was tunable to 1070 nm by variation of the knife position.

Using the Nd:silicate (LG-680, 4 mm thick, 3% Nd), we achieved pulses of 130 fs, centered at 1064 nm, at an average output power of 80 mW. As with Ti:sapphire pumping, no gain reshaping had to be applied for mode locking the inhomogeneously broadened laser. The maximum cw output power achieved was 220 mW (at 1.5-W absorbed pump power with a lasing threshold of 130 mW) with approximately the same absorption length as the 2%-doped Nd:phosphate. The output power was lower compared with that from phosphate glass because of the poorer thermal properties of the silicate. However, because no knife-edge gain filter was required, the mode-locked silicate glass laser had less intracavity loss, therefore improving the mode-locked output power.

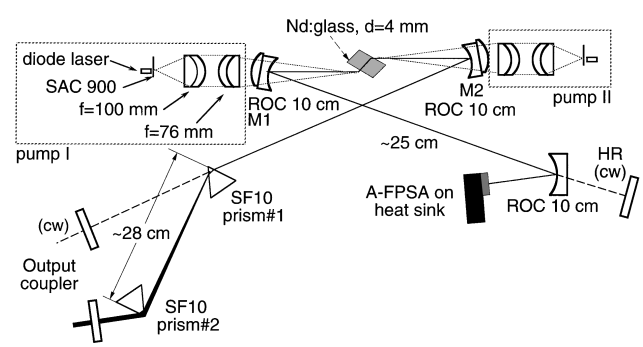

Fig. 3. Diode-pumped Nd:glass laser setup. HR, highly reflecting mirror.

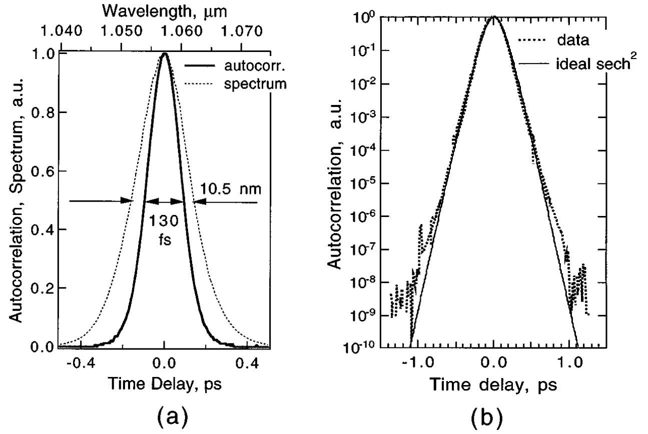

Fig. 4. Diode-pumped Nd:fluorophosphate laser: (a) noncollinear autocorrelation and spectrum, (b) high-dynamic-range autocorrelation.

The Nd:fluorophosphate (LG-810, 4 mm thick) used in our experiments had a longer absorption depth (3 mm). To better mode match the laser, we changed mirrors M1 and M2 to 15-cm ROC, increasing the mode size at the laser crystal to approximately 75 μm $\times$ 100 μm. However, because the mode size in the glass approximately doubled, the lasing threshold increased by a factor of 4 and SPM decreased by at least a factor of 4. For stable mode locking we inserted an additional glass plate at a second intracavity focus to increase the SPM.[14] This is again in good agreement with the theoretical treatment of soliton mode locking.[6,7,9]

We achieved better mode-locked results with the fluorophosphate by returning to the cavity with M1 and M2 of 10-cm ROC and slightly moving the laser glass plate out of the cavity focus (by $\approx$5 mm) for adequate mode matching. In addition, an intracavity aperture was used to suppress higher-order spatial modes by accepting an output power penalty of $\approx$10%. We obtained mode-locked pulses of 130-fs duration [Fig. 4(a)] at an average output power of 100 mW with an absorbed pump power of 1.4 W. The spectrum [Fig. 4(a)] for fluorophosphate when it was mode locked was centered at 1058 nm. Measurements with a high-dynamic-range autocorrelation[15] showed no pedestal down to more than 7 orders of magnitude below the peak [Fig. 4(b)]. The stability of the mode-locked pulse train was found to be comparable with that of Kerr-lens mode-locked Ti:sapphire lasers.

We observed stable mode locking even without the aperture used for spatial mode control, indicating that hard-aperture Kerr lensing[16] was not significantly contributing to the mode-locking process. We also observed mode locking over the entire cavity stability regime, which rules out soft-aperture Kerr lensing[17] as an important mode-locking contribution. These observations indicate that soliton formation is stabilized by the A-FPSA and that soliton mode locking[6,7] is the dominant mechanism.

In conclusion, we have demonstrated diode-pumped passively mode-locked Nd:glass lasers using homogeneously and inhomogeneously broadened glasses. Soliton mode locking is the dominant mode-locking mechanism for which the pulses are formed through soliton generation, and the mode-locking process is started with the 15-ps recovery time and stabilized with the 180-fs recovery time of an InGaAs/GaAs A-FPSA. We achieved approximately time–bandwidth-limited pulses of 130 fs FWHM for the inhomogeneously and 150 fs FWHM for the homogeneously broadened Nd:glass laser, close to the 90 fs FWHM with Ti:sapphire laser pumping. A high-dynamic-range autocorrelation measurement demonstrated that the pulses are clean down to 7 orders of magnitude. Mode-locked average output powers were approximately 100 mW with two 1.2-W diode-pumped lasers.

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