Femtosecond diode-pumped Nd:glass laser with more than 1 W of average output power

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We have demonstrated 175-fs pulses with 1 W and 300-fs pulses with 1.2 W of average output power at a pulse repetition rate of 117 MHz from a Nd:phosphate (Schott LG 760) glass laser pumped by a 1-cm-wide, 20-W diode laser bar. Stable soliton mode locking was achieved by use of an intracavity semiconductor saturable absorber mirror. We obtained more than 2 W of average power without mode locking. Using cylindrical cavity mirrors, we adapted the laser mode inside the Nd:glass to the highly elliptical pump beam in both dimensions (tangential and sagittal axes) while maintaining a nearly ideal circular TEM_{00} output beam with $M^2 \approx 1.2$. Overpumping the laser mode in the tangential plane and efficient unidirectional heat removal in the sagittal plane using a 0.8-mm thin Nd:glass also contributed to the good output-beam quality. © 1998 Optical Society of America

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Femtosecond laser sources in the wavelength range near 1 μm are important for various applications, such as seeding of ultrahigh-peak-power amplifier systems, pumping of femtosecond optical parametric oscillators, ultrafast metrology, and spectroscopy. Diode-pumped Nd:glass is a well-known laser material in this wavelength range and is attractive as a potentially compact ultrafast source owing to its fluorescence bandwidth of 20–30 nm, which is sufficient for femtosecond pulse generation, and its absorption band centered at ≈800 nm, which allows for diode pumping. These lasers can also provide an interesting alternative to large-frame-pumped Ti:sapphire systems at wavelengths of >1 μm. The first diode-pumped cw Nd:glass laser generated an average output power of 3.2 mW.[1] Active mode locking of diode-pumped Nd:glass lasers[2–4] generated pulses as short as 7 ps at an average output power of ≈5 mW.[3] A regeneratively actively mode-locked Nd:glass laser produced pulses as short as 310 fs by use of Ti:sapphire laser pumping.[5] The first passive cw mode-locked Nd:glass laser produced pulses as short as 88 fs at 200-mW average power with krypton-ion laser pumping and a nonlinear coupled-cavity mode-locking technique, termed additive-pulse mode locking.[6] Previous attempts to passively mode lock Nd:glass lasers, starting as early as 1966,[7] resulted in Q-switched mode locking. Stable passive cw mode locking was also obtained later with an intracavity semiconductor saturable absorber mirror (SESAM) that generated 130-fs pulses with 160-mW average output power by Ti:sapphire laser pumping.[8] The first femtosecond pulses from a diode-pumped Nd:glass laser were obtained with intracavity SESAM's.[9,10] Pulses as short as 60 fs at 84-mW average output power[10] were generated using standard diode pumping with two high-brightness 1.2-W diode lasers with a stripe length of 100 μm each. To date, the average output power of diode-pumped bulk Nd:glass lasers have been limited to ≈380 mW cw and ≈100 mW mode locked.[9]

In this Letter we demonstrate a significant improvement in the average output power of a diode-pumped Nd:glass laser, achieving more than 1 W of power when the laser is mode locked and 2 W cw. We used a 1-cm wide 806-nm 20-W diode bar and a strongly elliptical pump beam inside the gain medium, as initially demonstrated by Kopf *et al.* for Cr:LiSAF.[11] The highly elliptical pump mode allows for improved heat removal by use of a very thin (0.8-mm-thick) Nd:glass material. However, we did not strictly follow the guidelines for optimized mode matching (OMM) in the gain material in both the fast (i.e., sagittal) and the slow (i.e., tangential) axes of the diode laser, because we had to overpump the laser mode in the tangential plane to reduce the thermal lens. With OMM, we ideally set both confocal parameters of the astigmatic pump beam to be approximately equal to the absorption length of the Nd:glass. Applying OMM to both axes results in a highly elliptical laser mode inside the gain medium, because the pump beam can be focused much smaller in the diffraction-limited fast (sagittal) axis than in the slow (tangential) axis. Soliton mode locking with SESAM's allows us to achieve mode locking in this highly asymmetric regime, which would be more difficult with traditional methods such as Kerr-lens mode locking.

Nd:glass is a thermally challenged laser material because of its poor thermal conductivity (≈20 times lower than YAG and ≈5 times lower than Cr:LiSAF). In addition, the tendency toward Q switching becomes more difficult to suppress because of the long upper-state lifetime (≈350 μs) and the small gain cross section (4.2×10^{-20} cm^2) of the Nd:phosphate glass laser.[12] One can most easily achieve stable passive mode locking by maximizing the laser's small-signal gain, i.e., by minimizing the laser mode size within the constraints of efficient pump overlap. With standard diode pumping mentioned above, we used high-brightness diode arrays and applied OMM only in the tangential axis of the diodes, which resulted in an approximately round pump beam of ≈40-μm waist radius that becomes slightly elliptical when the laser crystal is pumped at Brewster's angle.[9,10] Standard diode pumping with high-power, 1-cm-wide diode bars would result in a pump volume much too large to achieve good passive mode locking.

Figure 1 shows the schematic setup of the high-average-power diode-pumped Nd:glass laser. The flat–Brewster-cut Nd:glass piece is ≈7.5 mm long in the middle. The flat surface is antireflection coated for the pump and high-reflection coated for the laser wavelength. The 806-nm pump light from a 1-cm-wide 20-W diode bar was collimated by a cylindrical microlens and additional cylindrical shaping lenses, resulting in a beam with $M^2_{\mathrm{sag}} \approx 7$ in the sagittal axis and with $M^2_{\tan} \approx 1800$ in the tangential axis of the laser resonator. We then divided the diode beam into two parts, each with $M^2_{\tan} \approx 900$, improving the beam quality in the tangential plane and also reducing the thermal load inside the laser glass. The focused spot radius was approximately 120 μm × 1100 μm with a confocal parameter at least as long as the absorption length of 5.8 mm in the 1% Nd-doped LG 760 glass. Ideally for OMM we would have predicted tighter focusing of the pump beam to nearly half the spot radius in both the sagittal and the tangential planes. We attribute this focusing degradation to a lower beam quality of the diode (i.e., a "smile" specification of <10 μm) and to the position accuracy of the cylindrical microlens. However, the pump volume is small enough that one can achieve a sufficiently high small-signal gain. We achieved improved heat removal from the glass medium in the sagittal direction by reducing the thickness of the glass to 0.8 mm and by actively cooling only the upper and the lower sides of the laser glass. Aperture losses owing to the thin medium were negligible. An upper-limit heating estimation follows from numerical heat-flow simulations,[13] for which we assume a relatively high thermal load of 4.8 W (i.e., ≈49% of the maximum absorbed pump power of 9.8 W). This estimation results in a temperature increase of 280 °C for a 4-mm-thick piece of glass but an increase of only 80 °C for the 0.8-mm-thick glass. The unidirectional heat flow generates weaker tangential stress components, which significantly reduces the thermal stress birefringence and the probability of thermal stress fracture. The thermal lens is determined by the curvature of the temperature profile, which is ~100 times smaller in the tangential plane ($\partial^2 T/\partial x^2 = -1.1 \times 10^7$ K/m^2) than in the sagittal plane ($\partial^2 T/\partial x^2 = -1.0 \times 10^9$ K/m^2) for an 0.8-mm-thick glass. With the reduced thickness of the glass, we slightly reduced the thermal lens in the tangential plane. However, the sagittal lens was not affected, because the curvature of the sagittal temperature profile does not change with a thinner glass.

We also made the tangential laser mode inside the gain medium somewhat smaller than the pump size to reduce thermal lensing. The inset in Fig. 1 shows that the tangential temperature profile has a small curvature close to the center of the pump beam, resulting in a weak thermal lens. The large curvature in the wings produces a stronger and more aberrated thermal lens. The cavity mode radius was chosen to be ≈700 μm in the tangential plane, whereas the pump mode radius was 1100 μm. This overpumping resulted in an improved beam quality with a measured M^2 of ≈1.2 for both axes, even at maximum output power (Fig. 2). Higher transverse modes in the tangential direction were suppressed by the stronger mean thermal lens, which actually makes the cavity unstable for these modes according to our simulations. We obtained a cw output power as high as 2 W, with a slope efficiency of 26% (Fig. 3).

For femtosecond pulse generation, we modified the cavity by inserting an SF10 prism pair and a SESAM as the end mirror (Fig. 1). The SESAM design was a low-finesse antiresonant Fabry–Perot saturable absorber,[12] consisting of a 25-nm-thick InGaAs absorber layer. The measured nonlinear reflectivity showed a maximum modulation depth of 1.3% and an unsaturable loss of 1%. The bitemporal impulse response of the SESAM showed a fast time constant of 200 fs and a slow time constant of 9 ps. We focused the intracavity beam onto the SESAM with a cylindrical mirror to

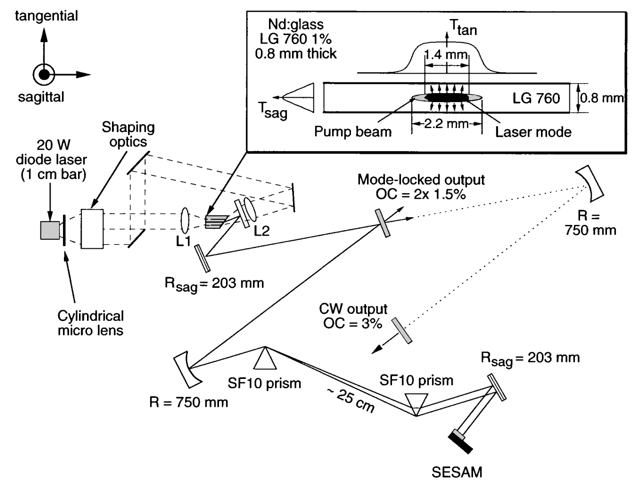

Fig. 1. Schematic setup of the high-power Nd:glass laser pumped by a 1-cm diode laser bar. The solid lines represent the beam in the mode-locked cavity, and the dotted lines indicate the cw laser setup. R, radius of curvature of the concave spherical mirrors; R_{sag}, radius of curvature of the cylindrical mirrors; L1, L2, lenses; OC, output coupler. The inset shows the laser and pump modes and the calculated temperature profiles (i.e., T_{sag} and $T_{\tan}$) at the flat end of the glass.

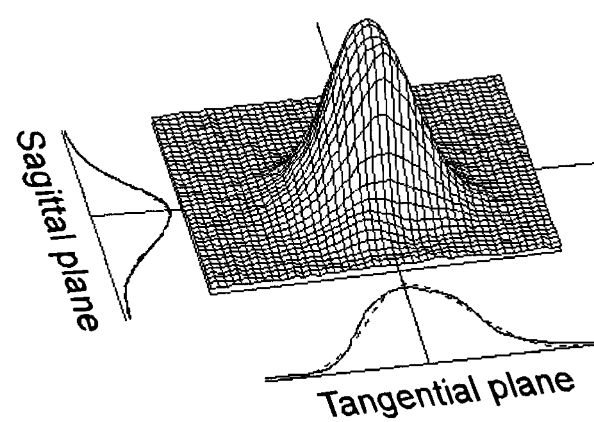

Fig. 2. Transverse mode at 2-W cw output power. The line plots represent the cross-section intensity profiles in the sagittal and the tangential planes. The dashed curves are fits assuming ideal Gaussian beam shapes.

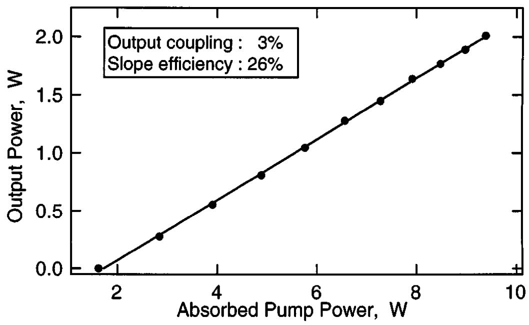

Fig. 3. Measured cw output power at ≈1054 nm as a function of absorbed pump power from the diode laser. The output coupling was 3%, and the Nd:glass heat sink was kept at a temperature of 18 °C. The cavity was realigned for each pump power.

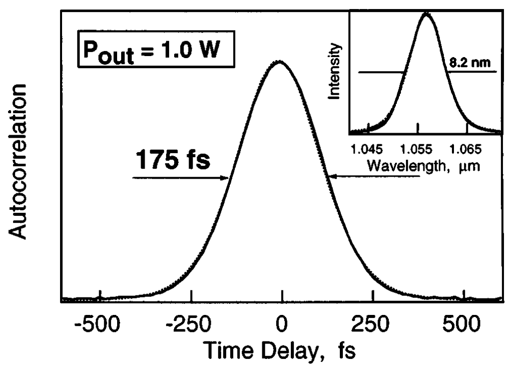

Fig. 4. Typical noncollinear autocorrelation of 175-fs pulses at a total output power of 1.0 W. Inset, corresponding spectrum centered at 1056.6 nm. Dotted curves, fits assuming an ideal sech^2 pulse and spectrum (inset) shape.

prevent a spectral flip in the tangential plane. A spherical focusing mirror would reflect the longer wavelength into the path of the shorter wavelength. The spot-size radius on the SESAM was calculated with standard *ABCD*-matrix calculations to be approximately 320 μm × 120 μm. Thus the pulse-energy density that was incident upon the SESAM was 233 $\mu J/cm^2$ (for 1-W output power), which corresponds to approximately 2 times the saturation fluence of 120 $\mu J/cm^2$ of the device. With a total output coupling of 3%, we obtained reliable self-starting mode locking with pulses as short as 175 fs (Fig. 4) and a total output power of 1 W at a pulse repetition rate of 117 MHz. For comparison, a similar Nd:glass laser produced 150-fs pulses with 110-mW average output power with standard diode pumping.[9] Soliton mode locking was the dominant pulse-formation process, as was experimentally confirmed by measurement of the linear dependence of the pulse duration with the negative intracavity dispersion.[14] The time–bandwidth product was measured to be 0.40. The highest mode-locked output power was 1.2 W with 306-fs pulses. The M^2 of the mode-locked output beams was the same as for the cw output.

In conclusion, we have demonstrated what we believe to be the highest reported average output power from a diode-pumped cw mode-locked femtosecond Nd:glass laser. At present, we have two output beams when the laser is mode locked (Fig. 1), which could be avoided with a different cavity design. We achieved these results by highly elliptical mode matching the diode pump beam to the intracavity beam and using a unidirectional cooling scheme. This technique could be scaled to even higher pump powers. By use of Gires–Tournois interferometers for dispersion compensation one could make the cavity more compact.[15] Furthermore, alternative laser glasses with broader emission could yield pulses shorter than 100 fs.

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