Continuous-wave mode-locked Nd:glass laser pumped by a laser diode

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We have demonstrated a diode-laser-pumped, cw, mode-locked Nd:glass laser oscillator. With a 0.5% output coupler the pump threshold for mode-locked operation was 22.9 mW. The mode-locked pulse width was shorter than 38.5 psec, which was the response time of the fast photodiode and the sampling oscilloscope. Diode-laser-pumped mode-locked operation was also extended to Nd:YAG.

Mode-locked Nd:glass lasers traditionally have been built as water-cooled, flash-lamp-pumped, pulsed sources. The recent availability of high-power cw GaAlAs diode lasers emitting at 800 nm permits the construction of diode-laser-pumped, cw, Nd:glass laser sources. We report successful operation of a 30-mW cw diode-laser-pumped, mode-locked Nd:glass laser oscillator. The mode-locked oscillator produced pulses shorter than 38.5 psec, the time response of the fast photodiode detection system. A 10-psec pulse width was estimated from autocorrelation measurements by simultaneous pumping with the diode laser and a dye laser. The same oscillator, when pumped by a 500-mW cw dye laser, generated pulses as short as 5.8 psec.

Mode-locked operation of Nd:glass was previously obtained under cw pumping with an argon-ion laser source. Active mode locking of a pulsed Nd:glass laser by using an electro-optic deflector recently generated trains of 6-psec pulses. Mode-locked operation of Nd:YAG (Ref. 4) with diode laser pumping and Nd0.3La0.7PO4 (Ref. 5) with argon-ion laser pumping has also been demonstrated. The prospect of diode laser pumping of Nd:glass did not appear to be promising because of the 1-order-of-magnitude smaller gain cross section of Nd:glass compared with Nd:YAG. However, the Nd:glass medium also has lower loss and higher absorption at diode laser wavelength than Nd:YAG, such that the gain-to-loss ratio, which is the factor important in determining threshold, is similar for Nd:YAG and Nd:glass. This was recently confirmed by the successful cw diode laser pumping of Nd:glass. The wide gain bandwidth of Nd:glass compared with Nd:YAG should lead to order-of-magnitude shorter mode-locked pulse widths.

Figure 1 shows a schematic of the experiment. The diode laser pump source is collimated and focused into a Brewster-angle-oriented 3-mm-thick disk of LG-760 Nd:glass with 4% doping. The active medium is placed at the focus of a three-mirror cavity, which is designed to minimize pumping threshold by minimizing the focal volume. The use of a Brewster plate eliminated the need for a special coating on the gain medium and permitted easy interchange of the gain media. The design of the three-mirror cavity is similar to that widely used in cw dye laser sources. The advantages of this resonator include a cavity length long enough to accommodate commercially available acousto-optic mode lockers with frequencies in the range of 30 to 150 MHz; a small spot size within the gain medium, which leads to a low pumping threshold; the capability to adjust cavity length without affecting the spot size in the gain medium; and the potential for pump multiplexing by dual-sided pumping to obtain higher average power output.

The standing-wave acousto-optic mode locker made by Newport EOS used in our experiment had a modulation index of 0.13 at 1 W of rf power at 1055 nm. The resonator length was 86.27 cm to correspond with 86.9-MHz mode-locker frequency. The astigmatism of the oblique-incidence center mirror was compensated for by the astigmatism of the Brewster-angle plate at an included angle of 20°, given by

\[ \frac{n^2 + 1)^{0.5(n^2 - 1)/n^4 = (R/2t)\sin \theta \tan \theta} \]

where \(n\) and \(t\) are the refractive index and the thickness of the gain medium, respectively, and \(R\) is the radius of curvature of the center mirror. In our case \(20° = 16.7°\). The stability range, defined as the

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amount by which the length of the short leg of the cavity can be changed without affecting the resonator stability, is given by $b = \frac{b}{2S}$, where $b$ is the length of the long arm of the cavity. The confocal parameter is given by $b = \frac{2S}{0.52}$ cm.

For a 3-mm-thick gain medium, the resonator spot size remains almost constant through the length of the gain medium, and the position of the gain medium can be varied by as much as 1 mm without significantly increasing the oscillation threshold. The TEM$_{00}$ mode spot size was calculated to be 29.5 $\mu$m by 45 $\mu$m with a geometrical average of 36.5 $\mu$m. The focused spot dimension in Nd:glass was 27 $\mu$m by 59 $\mu$m with a geometrical average of 40 $\mu$m.

The pump power threshold $P_{th}$ and the slope efficiency $\eta_s$ of an end-pumped laser are given by

$$P_{th} = \left(\frac{L}{n}v_p\sigma\eta_p\right)[\pi(w^2 + w_p^2)]$$

$$\times \exp[2\Delta x^2/(w^2 + w_p^2)], \quad (2)$$

$$\eta_s = (T/L)(\lambda_p/\lambda_{res}), \quad (3)$$

where $L$ is the round-trip cavity loss, $T$ is the output mirror transmission, $v_p$ is the pump frequency, $\sigma$ is the emission cross section, $r$ is the fluorescence lifetime, $\eta_p$ is the efficiency of absorption of the pump light, $\lambda_p$ and $\lambda_{res}$ are the pump wavelength and the laser wavelength, respectively, $w$ and $w_p$ are the resonator and pump spot sizes, respectively, in the gain medium, and $\Delta x$ is the mismatch distance between the resonator and the pump spots in the gain medium.

The Nd:glass laser was pumped by a 30-mW cw single-stripe diode laser, which was temperature tuned to operate at the 802-nm pump absorption band. 80% of the diode laser power was incident upon the gain medium and was absorbed completely. The internal cavity loss was measured to be 1.43%. With a 0.5% output coupler, the threshold was 15.5 mW and the slope efficiency was 9.1%. By using the expressions given in Eqs. (2) and (3) and by assuming perfectly overlapping pump and resonator beams, the threshold and the slope efficiency were calculated to be 9.6 mW and 15.7%, respectively. The difference between the calculated and the actual results is attributed to the small residual mismatch between the pump focal spot and the resonator beam in the gain medium.

The diode-pumped cw Nd:glass laser was mode locked by applying 0.4 W of rf power. The laser oscillation threshold was 22.9 mW of diode laser power. The output was 0.3 mW at 27.6 mW of diode laser power. The mode-locked laser output was detected by using a fast InGaAs photodiode, which had a responsivity of 0.4 A/W at 1055 nm and a 3-dB rolloff at 22 GHz. The measuring setup, which consisted of the detector, the sampling module, and the connectors, had a measured rise time of 36.5 psec. At close to optimum mode-locking condition, the output pulse on the sampling scope had ringing and distortion, which suggested that the pulse width was shorter than 36.5 psec. A 2.9-GHz-bandwidth spectrum analyzer was used to observe in real time the axial mode mixing spectrum of the mode-locked laser. At near-optimum mode-locking condition, 15 beat notes were observed covering the range of the spectrum analyzer. A commercial autocorrelator, Femtochrome Research Model FR103, which is based on nonlinear second-harmonic generation at a 20-Hz repetition rate, was also used to measure the mode-locked pulse width. The scan range of this particular autocorrelator was 100 psec, and the pulse-width resolution was 50 fsec.

In our experiments, it was found that good mode-locking operation depended to a great extent on the cavity length and the position and orientation of the acousto-optic mode locker. Near the optimum mode-locker position and cavity length, coherence spikes on top of broad autocorrelation signals were observed. By further optimizing the position of the mode locker and the cavity length, a clean autocorrelation trace was obtained with a zero baseline, indicating the absence of a coherence spike. The transition to a smooth autocorrelation trace was accompanied by a considerable increase in the second-harmonic power generated in a LiIO$_3$ crystal. It was observed that the photodiode output as seen on a sampling scope went from a smooth pulse with ringing to a noisy pulse with considerable ringing when the transition to the shortest pulse was indicated by the autocorrelation measurement.

The output average power of 0.3 mW as obtained by pumping with a 30-mW diode laser was not enough to produce a clean signal on the autocorrelator. However, in the three-mirror cavity shown in Fig. 1 it was possible to increase the output power by pumping the gain medium simultaneously with a diode laser through the end mirror and with a dye laser through the center mirror. By separately noting the threshold with the diode laser and the dye laser, it was possible to express the combined input power in terms of an equivalent diode laser power. We decided to estimate the diode-laser-pumped mode-locked laser pulse width by making autocorrelation measurements at different values of equivalent diode laser power. Figure 2(a) shows an autocorrelation trace obtained by pumping with 41 mW of equivalent diode laser power, which was generated by 27.4 mW of diode laser power (the remaining power coming from the dye laser). The trace FWHM was 13.7 psec, corresponding to a Gaussian pulse width of 9.7 psec. When the pump power was increased to 63.1 mW, the pulse width decreased by a small amount to 9 psec. By extrapolating from these measurements at two different power levels, the pulse width obtained by 27.4 mW of diode laser pumping alone was estimated to be 10 psec.

It was of interest to find the shortest pulse that we could obtain in our setup by pumping with a much higher average power cw Rhodamine 6G dye laser and at higher rf power to the acousto-optic mode locker. With a 590-nm Rhodamine 6G dye laser as the pump source, the threshold for mode locking was 110 mW at 1.2 W of rf power to the mode locker. The FWHM of the autocorrelation trace was 8.2 psec. For a Gaussian pulse shape, this indicates a FWHM of 5.8 psec for the mode-locked pulse. This to our knowledge is the shortest pulse produced by active mode locking of Nd:glass. At 440 mW of dye laser power, the output power was 13 mW, and the peak power was 12.9 W.

In another experiment, the Nd:glass laser piece was
replaced by a 3-mm-thick Nd:YAG crystal. An estimated 59% of the diode laser light was absorbed in the gain medium. At 1 W of rf power and with a threshold of 18.7 mW of diode laser power, 105-psec pulses were obtained from the mode-locked Nd:YAG laser, as shown in Fig. 2(b).

The Nd:YAG laser was also pumped by a dye laser, and the rf power to the mode locker was varied. The pulse width was calculated from the homogeneous mode-locking theory. At low rf power levels, the pulse width varied in accordance with the homogeneous mode-locking theory. At greater than 0.6 W of rf, the smooth pulse envelope broke to give shorter pulses. The minimum pulse width obtained with 150 mW of dye laser pumping was 58 psec FWHM at 1 W of rf power. The mode-locking threshold was at 30.5 mW of dye laser power at 1 W of rf power.

The combination of the short gain medium with low loss, and with low material dispersion, large gain bandwidth of Nd:glass, and an efficient and stable diode laser as the pump source, produces short mode-locked pulses at high overall efficiency. This cavity is also unique in the sense that large cw pump power can be tolerated without thermal problems by slowly rotating and translating the disk and uniformly pumping over a large area. For example, the maximum temperature rise in a uniformly pumped Nd:glass disk of 1-cm radius and 2.5-mm thickness is calculated to be 16°C for pumping by 50 W of average diode laser power. It is possible to increase the pump power in this three-mirror geometry to 4 W by polarization multiplexing four 1-W gain-guided single-stripe diode lasers. For 200-μm spot size for both the resonator and the pump beams at the gain medium, the optimum output coupling is 7% for a round-trip internal loss of 4.8%. The laser threshold is calculated to be 1.6 W, and the output power at 4 W of pump power is estimated to be 0.85 W. The circulating peak intensity at the gain medium is calculated to be 8.7 MW/cm², which is expected to produce the same 5.8-psec pulse width as was obtained in our dye-laser-pumped Nd:glass laser, for which the peak intensity was 61 MW/cm². The shortest possible pulse width in Nd:glass is approximately 0.13 psec, which is difficult to obtain in active mode locking because of the cavity synchronism requirement. Assuming a 5.8-psec cw mode-locked pulse width the peak power is projected to be 0.83 kW, which will permit pulse compression to 90 fsec in a two-stage fiber-grating pulse compressor.

It should be noted that this mode-locked laser source required no cooling water and operated at less than 30 W of input electrical power. To demonstrate the low input power requirements, the mode-locked Nd:glass laser was also run from a rechargeable battery, which had the capacity of providing continuous power to the laser diode, the thermoelectric cooler, and the rf driver for more than 2 h. Possible applications of such a solid-state mode-locked source are in electro-optic sampling and in frequency conversion. This diode-laser-pumped and mode-locked source is also an ideal source for chirped pulse amplification and for injection mode locking of Q-switched oscillators, both of which generate high peak power.

References