Subpicosecond pulse generation from a Nd:glass laser using a nonlinear external cavity

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An actively mode-locked, continuous-wave Nd:glass laser pumped by a krypton laser at 0.8 μm has been coupled to a nonlinear external resonator. The 20-psec pulses produced by active mode locking are shortened to less than 1 psec with the nonlinear external cavity feedback. Subpicosecond pulse generation has been achieved at a pump power as low as 500 mW.

Mode locking with nonlinear external resonators is based on interference of a coherent optical pulse with its slightly modified replica, which results in pulse shortening if the phase difference between the two pulses is properly adjusted.[1] Reinjection of a shortened, nearly transform-limited pulse into the master oscillator may give rise to pulse shortening, in the same way that reinjection of a phase-modulated pulse of (nearly) unchanged duration will. The former effect can be utilized when the nonlinear element in the auxiliary cavity provides pulse compression, such as an optical fiber in the wavelength region of anomalous dispersion.[2] By contrast, the latter mechanism requires only self-phase modulation of the reinjected pulse without the necessity for any kind of pulse shaping in the external nonlinear cavity.[3] This effect was used in a number of experiments to improve the mode-locking performance of color-center lasers.[4–7]

Recent experiments with Ti:Al_2O_3 lasers[8,9] demonstrated that self-phase modulation of the external pulse provided efficient pulse shortening after recombination with the main pulse even if significant pulse broadening occurred in the control cavity owing to high positive group-velocity dispersion in the nonlinear fiber. As a consequence, this kind of passive mode locking appears to be operative in the entire visible and near-infrared regions of the optical spectrum. Stimulated by these findings, we have developed a continuous-wave coupled nonlinear cavity Nd:glass laser operating at 1.054 μm.

Recently, it has been shown that continuous-wave operation of a Nd:glass laser is possible with low threshold and high slope efficiency.[10] Thermal problems can be avoided by careful design and proper host selection. Owing to its broad gain profile ($\approx$20 nm), Nd:glass is able to amplify pulses of the order of 100 fsec. Additionally, it has the advantage that it can be efficiently pumped by diode lasers near 0.8 μm. These properties make Nd:glass an attractive material for ultrashort-pulse generation and amplification. Active mode locking of continuous-wave Nd:glass lasers has yielded pulses shorter than 10 psec,[11–14] whereas feedback-controlled passive mode locking has produced pulses near 1 psec.[15]

A schematic diagram of the coupled nonlinear cavity Nd:glass laser is shown in Fig. 1. The main cavity was designed to compensate for astigmatism caused by the active material. A Brewster-angle-oriented 2-mm-thick plate of Nd:glass (Schott LG-760) with a 4% Nd^{3+} concentration by weight was inserted at the cavity mode waist in the Z-shaped resonator. The laser was pumped at the 0.8-μm line of a krypton laser. Concave mirrors M1 and M2 had high-reflectivity coatings both at the pump and the laser wavelengths. The pump beam was coupled through the dichroic flat mirror M3 into the cavity.

Active mode locking of the laser was accomplished by a standing-wave acousto-optic modulator (AOM) placed near the 80% reflectivity output coupler (OC). With a 20% output coupler the mode-locking threshold was approximately 200 mW. At an absorbed pump power of 500 mW and a modulation depth of 40%, the laser produced a 90-MHz train of 20-psec pulses with an average power of 80 mW.

In order to generate shorter pulses, we coupled to the laser a resonant nonlinear control cavity. The auxiliary resonator was formed by the output coupler of the glass laser, a 65% reflecting beam splitter (BS), and a small high-reflectivity mirror M4 mounted on a piezoelectric translator (PZT). The choice of output coupler and beam-splitter reflectivities was a compro-

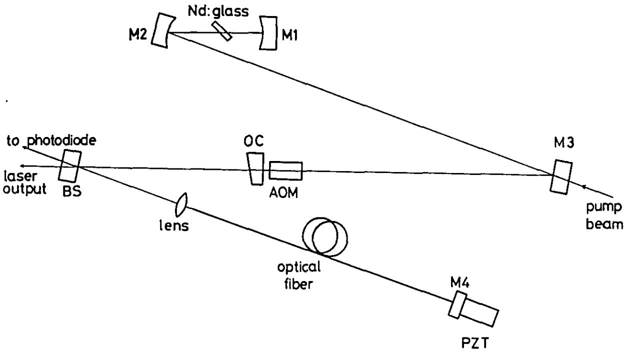

Fig. 1. Diagram of the coupled-cavity Nd:glass laser. M1–M4 are high-reflectivity mirrors at 1.054 μm with radii of curvature of $R_1 = 5$ cm, $R_2 = 10$ cm, and $R_3 = R_4 = \infty$.

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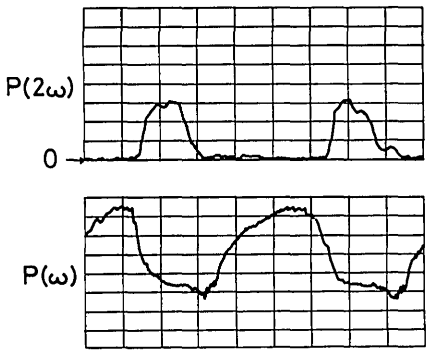

Fig. 2. Oscilloscope traces of the laser output and its second harmonic (both time averaged) as a function of the length of the external cavity. A full period corresponds to a 2π change in the relative phase. The modulation depth of $P(\omega)$ is approximately 30%.

mise between high output power and a large nonlinear phase shift for efficient pulse shortening.

The nonlinearity in the auxiliary cavity was provided by a single-mode non-polarization-preserving fiber (Lightwave Technologies F1060C) 85 cm long. The fiber had a core diameter of 6.7 μm and a numerical aperture of 0.11. Optimum matching between the cavity and fiber mode was achieved with a lens of 10-mm focal length. The typical fiber coupling efficiency with the uncoated lens was 70%.

When the control cavity was unblocked and its length was made (approximately) equal to that of the main cavity, the frequency-doubled laser output fluctuated by orders of magnitude, indicating large changes in pulse duration. Variations of the difference between the lengths of the main cavity and control cavity due to mechanical vibration and thermal drift caused the passive mode-locking operation to turn on and off depending on whether the relative phase ϕ of the external cavity was inside or outside the interval where pulse shortening occurred. To keep ϕ at a constant value for optimum mode locking required a stabilization of the relative cavity lengths to within a fraction of a wavelength.

The correct relative phase could be stabilized by servo control of the external cavity length by utilizing the fact that not only the pulse width but also the average output power is a sensitive function of ϕ. The laser output power was monitored and compared with a reference voltage level by an electronic circuit, and the suitably amplified and integrated error signal was applied to the low-voltage PZT.[16] ϕ could then be adjusted by changing the reference voltage in the stabilization circuit.

Before operating the laser with the control electronics, we applied a voltage ramp to the PZT and monitored the laser output and its second harmonic simultaneously. The oscilloscope traces are shown in Fig. 2. ϕ could be swept over several cycles (corresponding to a cavity length detuning of $\approx$20 μm) without considerable reduction of the second-harmonic intensity. The shortest pulses (maximum second-harmonic intensity) were observed near antiresonance, where the control cavity power was minimum. This suggested that the peak nonlinear phase shift was greater than $\pi/2$. Passive mode-locked operation occurred only on one side of antiresonance and tolerated a detuning of $\approx\pi/2$. Both results agree with the trends predicted by the theory of Ippen *et al.*[3] Unfortunately, it is difficult to achieve stable operation near the extremes of the control signal, where the slope with respect to the parameter to be controlled is nearly zero. Most stable operation was expected when the set point for the feedback circuit might be somewhere in the middle of the range of control signals (output powers).

It should be noted that the oscilloscope traces in Fig. 2 were taken at a slightly reduced feedback with respect to its maximum value under our experimental conditions. Increasing the feedback sometimes led to large oscillations of both the fundamental and the second-harmonic signal in the phase interval of the large second harmonic. These took place on a time scale of tens of microseconds, which indicates relaxation oscillations. This instability may be explained by the fact that excessive feedback resulted in a significant distortion of the pulse coupled out of the master cavity and thereby impaired the pulse-shortening process. On the other hand, a weak reinjected pulse implies a low modulation index,[8] which reduces pulse shortening as well. Obviously, there is some optimum value of the overall attenuation in the external cavity (including beam-splitter transmission) minimizing pulse duration. This optimum value is a function of parameters such as output coupling and peak nonlinear phase shift. A full exploitation of coupled-cavity mode-locking performance requires further experimental and theoretical investigations of this problem.

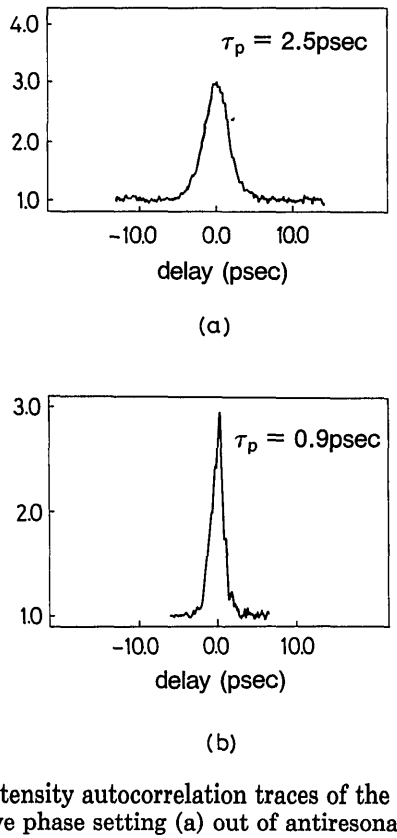

Fig. 3. Intensity autocorrelation traces of the laser pulses at a relative phase setting (a) out of antiresonance and (b) near antiresonance. The pulse widths were obtained by assuming sech^2 pulse shapes.

After the control electronics were turned on, the relative phase ϕ was stabilized to within $\Delta\phi \approx \pi/10$ as measured from the fluctuations of the difference signal at the input of the stabilization circuit. The laser output was monitored with a fast photodiode, and the pulse widths were measured using the standard collinear autocorrelation technique. In accordance with Fig. 2 the output pulse duration was sensitive to the reference voltage level in the control circuit. Figure 3(a) shows the autocorrelation trace of 2.5-psec pulses produced at a reference level near the middle of the range of control signals. As the antiresonance was approached, further pulse shortening occurred, reducing the pulse duration to below 1 psec as shown in Fig. 3(b). The shortest pulse duration that we measured was 650 fsec. However, close to antiresonance the laser suffered dropouts on a millisecond time scale because of the stabilization problems mentioned above.

All these measurements were carried out at a pump power of 500 mW. The average output power was approximately 50 mW. We calculated the peak nonlinear phase shift for the subpicosecond pulses to be $\approx 3\pi/2$, which is consistent with the observation that the shortest pulses were generated near antiresonance.

It is worth reporting that coupled-cavity mode locking could be started and maintained with a loss-modulation depth of less than 5% in the main cavity. This low value suggests that self-starting passive mode locking of a Nd:glass laser should be possible when the pump power is sufficiently increased and the laser parameters are optimized. Also, parameter optimization should further reduce the pulse duration and permit highly stable operation by pushing the relative phase for shortest-pulse production away from antiresonance. The replacement of the pump source by a high-power diode laser in addition to these improvements will permit the construction of an all-solid-state femtosecond laser in the near future.

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