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Self-starting additive-pulse mode locking of a Nd:glass laser

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Self-starting cw mode-locked operation of a Nd:glass laser has been achieved by using a nonlinear external resonator. The coupled cavity incorporating an optical fiber initiates and sustains ultrashort-pulse generation, resulting in a stable train of 380-fsec pulses.

Coupled nonlinear cavities have been shown to improve the mode-locking performance of lasers.[1,2] Although there are a number of different light–matter interactions that provide the required nonlinearity (saturable absorption or amplification, second-harmonic generation, etc.), self-phase modulation in an optical fiber proved to be superior to other types of nonlinearity in its simplicity and capability of providing a completely symmetric pulse shaping down to the femtosecond regime. The pulse-shortening process in a coupled-cavity laser using an optical fiber as the nonlinear element has been described by a time-domain theory referred to as additive-pulse mode locking[3,4] (APM). This technique has been used in several experiments to shorten the pulses in actively mode-locked lasers.

Recently, Goodberlet *et al.* found APM to be self-starting in a Ti:sapphire laser.[5] This was the first demonstration of cw passive mode locking in a laser without the need for pulse shaping by the gain material and thus a milestone in the development of ultrafast technology. Self-starting APM is expected to be applicable in all-solid-state lasers having long relaxation times and large saturation fluences. In addition to Ti:sapphire, the most important solid-state laser materials currently are neodymium-doped crystals (YAG, YLF) and glasses. Researchers recently reported successful self-starting APM of cw Nd:YAG and Nd:YLF lasers, producing pulses as short as a few picoseconds.[6–8] These pulse widths are close to the theoretical limit set by the bandwidths of the gain materials. In this Letter we describe the self-starting mode-locking operation of a cw Nd:glass laser by using a nonlinear optical fiber in a coupled external cavity. The laser generates stable subpicosecond pulses of 380-fsec duration.

Whereas cw mode-locked crystalline neodymium lasers have been widely used for over 20 years, the application of Nd:glass laser material in lamp-pumped cw systems has been prevented by its low thermal conductivity. The replacement of lamps by narrow-line pump sources (lasers) has made the large bandwidth of Nd:glass available for cw ultrashort-pulse generation.[9] This alternative is especially attractive in light of recent developments in high-power diode lasers. Active mode locking of a diode-array-pumped cw Nd:glass laser yielded pulses shorter than 10 psec.[10] Although the width of the laser spectrum is much less than that of the fluorescence line (≈20 nm), it is hard to achieve further pulse shortening because of inherent limitations of conventional active mode locking.[11]

In order to better exploit the large bandwidth of Nd:glass, which is capable of supporting sub-100-fsec pulses, we employed the APM technique. Figure 1 shows the coupled-cavity Nd:glass laser used in our investigations. The diode array was replaced by a krypton laser that provided higher pump power. The gain medium, a 2-mm-thick phosphate glass plate (Schott LG-760) with a 4 wt. % Nd^{3+} concentration, was placed at Brewster's angle at the focus of a Z-shaped (mirrors M1–M3 and output coupler OC) astigmatically compensated cavity. The resonator was designed to minimize the pumping threshold by minimizing the pumped volume.[12] With a 5% output coupler, the pumping threshold was 50 mW when the system was pumped simultaneously at 752 and 799 nm. At 800 mW of absorbed pump power the laser delivered nearly 300 mW of output power at 1054 nm. For this experimental setup, critical pump powers indicating the onset of undesirable thermal effects were above 1 W.[12]

Initially the master oscillator was actively mode locked by a standing-wave acousto-optic modulator. Twenty-picosecond pulses produced by active mode locking were then compressed to below 1 psec using the nonlinear external cavity feedback.[13] In these initial experiments we were defeated in our attempt to

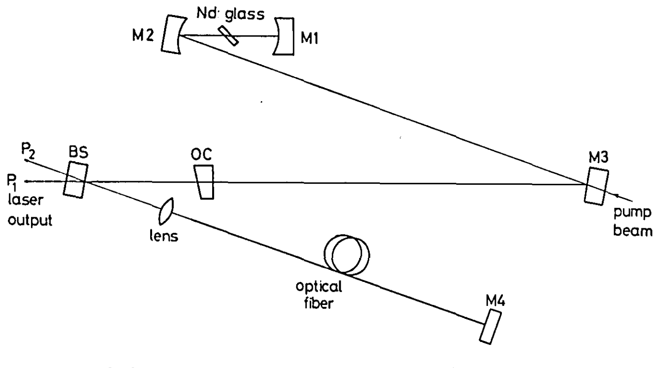

Fig. 1. Schematic of the passively mode-locked Nd:glass laser. M1, M2, high-reflectivity mirrors with radii of curvature of 5 and 10 cm, respectively; M3, dichroic plane mirror; OC, output coupler with 80% reflectivity; BS, beam splitter with 80% reflectivity; M4, high-reflectivity plane mirror.

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achieve self-starting APM operation. We found étalon effects in the master cavity to be responsible for this failure. One source of the étalon effects was the antireflection-coated modulator itself. Étalons appeared to be present, however, even after the modulator was removed from the cavity, as revealed by the periodically modulated spectral profile of the laser output. Although noncollinear to the cavity axis and partly noncollimated, reflections from the rear ends of the 99.9% reflectivity mirrors M1–M3 turned out to cause the residual étalon effects. The rear end of the 20% output coupler OC was antireflection coated and wedged at 10°. Supplying mirrors M1 and M2 with mat rear faces and increasing the incidence angle at mirror M3, we succeeded in obtaining a laser spectrum free of étalon effects and with a width of approximately 0.05 nm. This narrow spectrum suggests that the laser transition in our Nd:phosphate glass may be regarded as dominantly homogeneously broadened in accordance with the results of recent investigations.[12] After suppression of the unwanted étalon effects in the master cavity, self-starting mode locking of the coupled-cavity laser was readily achieved.

The sensitivity of passive APM to intracavity étalons in the master cavity can be easily understood. Even comparatively long pulses circulating in the cavity may get noticeably dispersed when passing through a thick étalon. In the self-starting process the incipient pulse shortening is small owing to the low intensity and can be balanced by a small amount of spreading caused by a weak étalon. Thereby pulse shortening may be stopped at an early stage of pulse evolution. It should be noted that if the spatial length of the initial pulse is shorter than the étalon thickness, the buildup of mode locking should not be impaired by the étalon. By contrast, étalons in the external cavity are expected to have much less significance because spreading of the external pulse still permits shortening of the main pulse.[4]

In order to facilitate self-starting we used a comparatively long fiber and achieved a strong feedback from the auxiliary cavity. Eighty percent of the output power from the main cavity was directed into a 90-cm length of a single-mode non-polarization-preserving fiber having a core diameter of 6.7 μm, a numerical aperture of 0.11, a nonlinear index of refraction $n_2 = 3.2 \times 10^{-16}$ cm^2/W, and a dispersion parameter $D = -38$ psec/(nm × km) at $\lambda = 1.054$ μm. With an antireflection-coated lens of 10-mm focal length, a 75% fiber coupling efficiency was typically obtained. Beveling the input fiber end at an angle of ~5° prevented the Fresnel reflection from returning to the main cavity. The optical beam was retroreflected back to the fiber by mirror M4 with index-matching fluid at the mirror–fiber interface to suppress unwanted étalon effects. With the above external cavity parameters the pumping threshold of the free-running coupled-cavity laser was ~100 mW (absorbed power). In the pumping region of 100–400 mW no enhancement of the second-harmonic intensity was observed when the external cavity was tuned to resonance. At ~400 mW some kind of transient mode locking occurred. Microsecond trains of 40–50-psec pulses appeared spontaneously at random intervals on a 100-μsec time scale. Deterministic self-starting APM was achieved at pump powers ≥500 mW. The experiments described below were carried out at an absorbed pump power of 600 mW. Typical average power levels at important locations in the coupled laser system were primary laser output (see Fig. 1) $P_1 = 60$ mW, incident power into the fiber $P_i = 240$ mW, power reflected back from the fiber terminated into mirror M4 $P_r = 180$ mW, and secondary laser output $P_2 = 36$ mW.

With the external cavity tuned to resonance, mode locking turned on and off owing to drift of the relative phase ϕ_{rel} between the two cavities. The mode-locked train remained stable typically for hundreds of milliseconds, permitting convenient autocorrelation measurements even without the use of stabilizing electronics. With an active-feedback control,[14] long-term stability of the pulse duration and output power was obtained although transient dropouts occurred owing to occasional mechanical vibrations that could not be tracked by the servo loop. Given the correct interferometric phase mismatch ϕ_{rel} between the two cavities, passive mode-locking operation tolerated absolute cavity length mismatches of $\Delta l = \pm 10$ μm.

Other than ϕ_{rel} and Δl, the amount of external feedback was the only adjustable parameter in our experimental setup. In fact, P_r could be continuously varied by removing mirror M4 from the fiber end. Mode-locked pulse widths are shown in Fig. 2 as a function of the ratio of P_r to P_i. Δl and ϕ_{rel} were optimized for minimum pulse duration at each particular value of P_r/P_i. The pulse widths were measured by using the standard collinear autocorrelation technique and assuming sech^2 pulse profiles.

At first, these results seem surprising. The pulse shortening by the external cavity is expected to be proportional to both the nonlinearity and the feedback. Accordingly, an increase in the feedback should lead to shorter steady-state pulse durations. Excessive nonlinearity and/or feedback, however, may lead to a stop in pulse shortening and even to instabilities as found by recent numerical simulations. At maximum feedback the peak nonlinear phase shift turns out to exceed 2π significantly under our experimental conditions. Consequently, the shortest pulses, having a duration of 380 fsec, were generated at considerably reduced feedback. Mode locking was extinguished when P_r/P_i was decreased below 0.2.

The autocorrelation trace of the 380-fsec pulses is shown in Fig. 3. The output spectrum was measured to be within 1.2 times the transform-limited band-

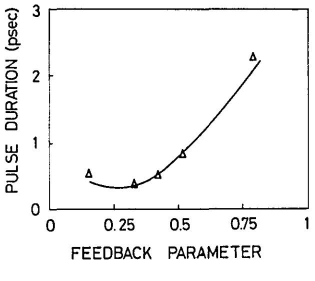

Fig. 2. Pulse durations from the passively mode-locked Nd:glass laser as a function of the feedback parameter P_r/P_i.

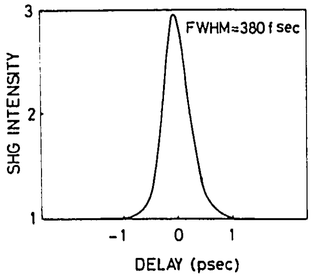

Fig. 3. Collinear autocorrelation trace of the laser output at a feedback parameter of $P_r/P_i = 0.3$. SHG, second-harmonic generation.

width. Second-harmonic fluctuations of less than 10% were observed with the servo loop in operation, pointing to an excellent stability of the mode-locked pulse train. Compared with results of previous experiments, in which active loss modulation was used to initiate the buildup of short pulses, significantly enhanced stability was achieved. The explanation for this improvement is that the laser becomes passively mode locked when reaching the steady state even if external modulation is present.[14] The passively mode-locked state, however, has its own repetition rate, which is unavoidably different from the external frequency owing to thermal and mechanical drifts. As a consequence, the loss modulation appears to be an undesirable perturbation of the steady-state mode-locked operation.

An interesting feature of APM systems is the existence of a self-starting threshold that exceeds the pumping threshold for free-running operation.[5,7,8] Recently a simple theoretical analysis of the transient mode-locking process in lasers containing a fast saturable absorber, or a related nonlinearity, was developed.[15] During the initial pulse development the action of the resonantly coupled cavity incorporating a fast Kerr nonlinearity may be written as[4,6]

$$\Delta L(t) = -\kappa s(t), \tag{1}$$

where $\Delta L(t)$ is a dynamic change in the round-trip loss of the main cavity, $s(t)$ is the instantaneous photon flux in the main cavity, and κ is a proportionality factor depending on the coupled-cavity parameters.

The transient pulse evolution may be regarded as a competition between mode locking due to the nonlinearity and disturbances of the fixed phase and amplitude relations between axial cavity modes by random processes. An initial pulse arising from mode beating will decay in the absence of nonlinearity. The characteristic time for this decay, the so-called mode correlation time τ_c, can be obtained experimentally by measuring the bandwidth of the first beat note of the laser.[15] Similarly, we may characterize the transient mode-locking process in the absence of the disturbances with a critical buildup time given by[15]

$$T_{\text{crit}} = \frac{T_R}{\kappa S_0 \ln m_i}, \tag{2}$$

where T_R is the cavity round-trip time, S_0 is the average photon flux in the cavity, and m_i is the number of initially oscillating modes. Deterministic self-starting calls for a T_{crit} somewhat shorter than τ_c. We measured the mode correlation time to be $\tau \approx 100$ μsec in our Nd:glass laser (with the coupled cavity blocked). At the threshold of self-starting APM we obtained from Eq. (2) $T_{\text{crit}} \approx 80$ μsec, i.e., $\tau_c/\tau_{\text{crit}} \approx 1.25$, in excellent agreement with the prediction of the theory.

In conclusion, we have demonstrated self-starting APM of a cw Nd:glass laser for what is to our knowledge the first time. Stable subpicosecond pulses of 380-fsec duration have been achieved that are the shortest obtained directly from a self-starting APM laser so far. Diode pumping of the laser and optimization of the self-starting APM will permit the construction of an all-solid-state femtosecond laser in the near future.

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