Femtosecond passive mode locking of a solid-state laser by a dispersively balanced nonlinear interferometer

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A Michelson interferometer containing a nonlinear fiber in one arm and dispersion control in the other arm has been used for passive mode locking of a continuous wave Nd:glass laser. We discuss scaling issues and demonstrate the usefulness of this technique by generating $\approx$300 fs pulses with only $P_f \approx 15$ mW of average power in the fiber and $\approx$100 fs pulses with a self-starting threshold of $P_f \approx 100$ mW.

Mirrors with intensity-dependent reflectivities have been devised and employed for mode locking of solid-state lasers for a long time.[1–3] Because of the weak nonlinear response of these devices, passive mode locking could only be achieved in pulsed operation. Dielectric waveguiding in low-loss single-mode optical fibers has resulted in a tremendous enhancement in the efficiency of nonlinear processes.[4] The exploitation of the Kerr nonlinearity of an optical fiber inserted in a coupled cavity led to successful passive mode locking of a continuous wave (cw) solid-state laser for the first time.[5] Pulse formation in this system relies essentially on the same mechanism as in earlier experiments and has been referred to as additive pulse mode locking (APM).[6] Since the first demonstration of this passive mode locking technique, APM has been used for passive ultrashort pulse generation in a number of different laser systems.[7–10] These lasers work in the normal dispersion regime of silica fibers ($\lambda < 1.3\ \mu$m), which has important implications on mode locking. Although subpicosecond pulse generation is possible in a limited range of system parameters,[10] broad-bandwidth APM systems typically generate strongly chirped picosecond pulses[5,11] owing to an interaction of accumulating positive chirp on the main cavity pulse with positive group velocity dispersion (GVD) in the fiber.[12] Compensation of the positive chirp by an appropriate amount of negative GVD in the main cavity is required to achieve femtosecond pulse generation.[13]

In this letter we report on dispersively compensated additive-pulse mode locking using a Michelson-cavity configuration. Dispersion compensation is shown to improve steady-state laser performance, facilitate self-starting, and reduce relaxation oscillation instabilities. Using Nd:phosphate glass as the active material we demonstrate the generation of stable femtosecond pulses at considerably reduced self-starting threshold in comparison with the conventional APM technique.

Consider a laser cavity terminated into a nonlinear Michelson interferometer as illustrated in Fig. 1. This Michelson cavity configuration is superior to the conventional coupled-cavity arrangement owing to its greater compactness due to a smaller number of cavity components and to a reduction of the physical extension of the system. Furthermore, the single-beam output leads to the production of more intensive output pulses. The beam splitter (BS) transmits a small part of the intracavity power into the weakly coupled nonlinear arm $M1$-BS containing a short length of a single-mode optical fiber with a positive Kerr nonlinearity and a positive group velocity dispersion (GVD) at the lasing wavelength.[14] The greater part of the power is fed into the dispersive linear arm $M2$-BS having a net negative GVD. This Michelson configuration viewed as a nonlinear dispersive termination transforms an incident pulse into a reshaped reflected pulse. In the limit of low dispersion this termination acts as a mirror with an intensity-dependent reflectivity. During the great part of transient evolution of mode locking the nonlinear phase shift in the fiber is low, thus the dynamic change in reflectivity can be expanded in power series to first order in $P(t)$:

$$\Delta R(t) = \kappa P(t), \tag{1}$$

where $P(t)$ is the instantaneous intracavity power incident upon the interferometer, and κ is given by

$$\kappa = -4\gamma L^3 r^2 (1 - r^2)^2 l_f \sin \phi. \tag{2}$$

Here γ is the nonlinear coefficient of the fiber,[4] $L(<1)$ denotes the attenuation factor of the electric field strength in the nonlinear arm, r^2 is the intensity reflectivity of beam splitter BS, l_f stands for the fiber length, and ϕ is the phase

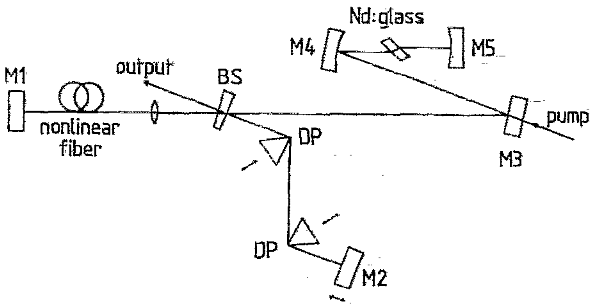

FIG. 1. Schematic diagram of the passively mode-locked laser (M1-5), high-reflectivity mirrors at the laser wavelength; (BS) 16% transmitting beam splitter; (DPs) dispersive prisms.

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bias of the nonlinear arm with respect to the linear arm of the interferometer. Pulse shortening occurs for $\kappa > 0$, i.e., for a phase bias of $-\pi < \phi < 0$, and κ takes its maximum value at $\phi = -\pi/2$. In contrast with a coupled cavity, κ does not go to zero as L approaches unity, i.e., the interferometric configuration does not require loss in conjunction with the nonlinearity for pulse shortening.

This model loses validity as soon as dispersion becomes significant. Actually, this situation can occur in the presence of negative GVD already at the beginning of the transient mode-locking process because the interaction between the accumulating positive chirp on the main cavity pulse and the negative GVD in the linear arm of the interferometer may result in efficient pulse shaping due to the strong coupling of the linear arm. Thus, the negative dispersion is able to not only prevent an excessive positive chirp from developing in the main cavity but also participate actively in the formation of the mode-locked pulse. The action of such a dispersive nonlinear interferometer on an incident wave is dependent on both phase and amplitude, and thus much more complex than that described by (1). It may be expected that APM pulse shaping will be enhanced by the negative dispersion leading to a more rapid buildup of the mode-locked pulse and a shorter steady-state pulse duration.

In order to verify these simple qualitative considerations we have carried out experiments using a cw Nd: phosphate glass laser. The schematic diagram of the passively mode-locked laser is shown in Fig. 1. BS is a flat 16% transmitting mirror representing a tradeoff between moderate round-trip cavity loss and strong pulse shaping. The weakly coupled arm $M1$-BS of the interferometer contains a single-mode nonpolarization-preserving silica fiber having a nonlinear coefficient[4] of $\gamma = 4.0 \times 10^{-3}$ $W^{-1} m^{-1}$ and a group-velocity dispersion[4] of $\beta_2 = 2.3 \times 10^{-2}$ ps^2/m. With $L^2 = 0.6$, $l_f = 1$ m, and $\phi = -\pi/2$, we obtain $\kappa = 1.6 \times 10^{-4}$ W^{-1} for our experimental conditions. In the strongly coupled arm $M2$-BS a pair of Brewster-angled dispersive prisms (DPs) made of SF10 glass is incorporated. The prism pair has a double-pass group delay dispersion of $D = \partial^2\varphi/\partial\omega^2 = -1.1 \times 10^{-2}$ ps^2 for $l_p = 1$ m of prism separation at $\lambda = 1.054$ μm (not including material dispersion). Each prism can be translated along a line normal to its base as indicated in Fig. 1. This motion introduces a positive dispersion of variable magnitude providing a convenient means of controlling the net dispersion. To stay at resonance, mirror $M2$ has to be shifted if either of the prisms is moved. $M2$ is mounted on a piezoelectric translator for fine adjustment and active stabilization of the phase bias ϕ. The laser medium, a 6-mm-wide Nd:phosphate glass slab with 2% Nd^{3+} concentration, is longitudinally pumped by the 752 nm and 799 nm krypton lines up to 1.5 W of pump power.

At sufficiently high intracavity powers, the laser immediately becomes mode locked when the relative phase is properly adjusted. The average output power of the mode-locked laser is 200 mW at a pump power of 1.5 W. Without dispersion compensation ($D \approx 0$) the laser produces

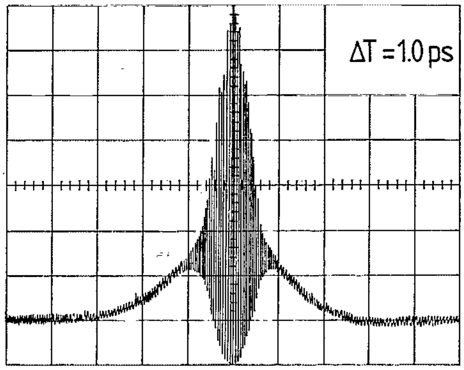

FIG. 2. Interferometric autocorrelation trace of the laser output taken with a fiber length of 60 cm in the absence of dispersion compensation.

strongly chirped pulses as predicted by numerical investigations.[12] Figure 2 shows the interferometric autocorrelation trace of the laser output for $D = 0$, $l_f = 60$ cm, and an intrafiber pulse energy of $E_p \approx 1.2$ nJ. The pulses are strongly chirped and 1 ps in duration. When dispersion in the linear interferometer arm is optimized, nearly bandwidth-limited femtosecond pulses are generated with pulse durations of 220 fs. The optimum value of the prism dispersion $D \approx -7 \times 10^{-3}$ ps^2 should be compared to the fiber dispersion $2\beta_2 l_f = 2.8 \times 10^{-2}$ ps^2. In contrast with femtosecond fiber lasers,[15] the positive GVD of the fiber can be compensated for by a significantly smaller amount of negative dispersion owing to the strongly different coupling of the two interferometer arms to the laser cavity. As a result, compensation can be achieved by a single pair of prisms separated by a distance approximately equal to the fiber length allowing a compact optical setup.

Dispersion compensation also reduces the self-starting threshold significantly. Figure 3 is a summary of the most important experimental results obtained with different fiber lengths. The threshold intrafiber average power P_{th}, above which mode locking is self-initiating is depicted by open and full circles obtained with and without GVD compensation, respectively. P_{th} is reduced by more than a factor of 3 with the introduction of negative GVD pointing to its significance even in the initial pulse evolution. As the self-starting threshold has been found to be inversely proportional to κ in APM lasers,[7,10,16] the additional pulse shaping due to negative dispersion leads in effect to an increase of κ by a factor of 3 during the transient buildup of mode locking. Owing to this improvement, passive femtosecond pulse generation becomes possible at extremely low powers (e.g., $P_{th} \approx 15$ mW for $l_f = 130$ cm). The fiber length is an important scaling parameter for both threshold power and steady-state pulse duration represented by triangles in Fig. 3. The pulse widths have been measured under optimized conditions (D,ϕ), for $E_p \approx 1.2$ nJ. Long fiber lengths allow low-power operation at the expense of an increase in pulse width, whereas short fiber lengths support shorter pulses at the cost of higher thresholds for passive mode locking. At a fixed fiber length the pulse duration is found to be only weakly dependent on the pulse energy.

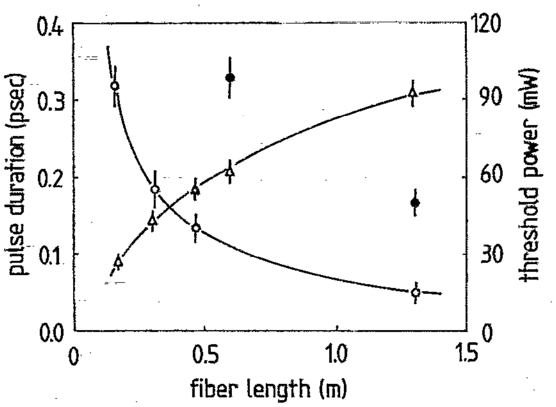

FIG. 3. Steady-state pulse durations (triangles), and intrafiber self-starting thresholds with (open circles) and without (full circles) dispersion compensation as a function of the fiber length.

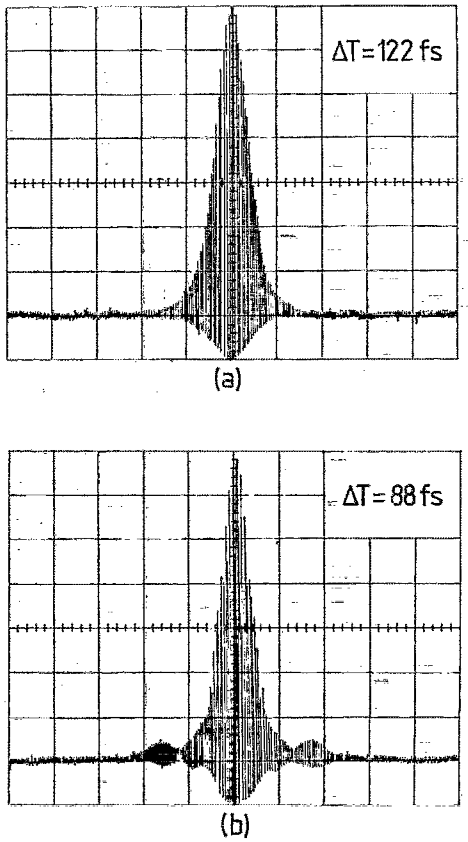

FIG. 4. Interferometric autocorrelation traces of the passively mode-locked laser with a fiber length of 18 cm for two different values of the relative phase bias.

In our experiments the shortest pulses have been generated at $l_f = 18$ cm with $D = -3.8\times10^{-3}$ ps^2. The interferometric autocorrelation traces for two different phase settings are shown in Figs. 4(a) and 4(b). The small wings in Fig. 4(b) arise from some nonlinear chirp on the main pulse, which cannot be compensated by the linear dispersion. The nonlinear chirp is superimposed on the main pulse by the interference of two differently chirped and shaped pulses, and is thus an intrinsic feature of dispersive APM systems. Careful optimization of system parameters might bring the phase settings for minimum pulse width and pedestal-free pulse generation closer together. Nevertheless, the 88 fs pulses represent the shortest optical pulses produced in a passively mode-locked Nd:glass laser to date. Note that the short fiber length improves the stability of the laser as well. Owing to the reduced extension of the interferometer, stable long-term operation is easily achieved with a servo-loop providing active stabilization.

A common feature of the laser outputs shown in Fig. 4 is a slight residual chirp carried by the optical pulses. This observation is consistent with the results of simple theoretical investigations which suggest that at least for pulse durations on the order of 100 fs pulse shortening should be dominated by the interaction between the negative GVD and some positive chirp of the main cavity pulse rather than the APM mechanism. A further manifestation of this additional pulse shaping is the complete disappearance of relaxation oscillation instabilities. This indicates that phase effects take command of mode locking in a dispersively compensated femtosecond APM laser.

In summary, we have demonstrated the potential of a dispersively balanced nonlinear interferometer to passively generate femtosecond pulses in a solid-state laser working in the normal dispersion regime of optical fibers. Compared to coupled-cavity APM systems, this technique provides a greater stability, shorter pulse durations, and lower self-starting thresholds. Experimental results with different fiber lengths demonstrate the scalability of the system for low threshold or short pulse duration allowing the applicability of this technology to a wide class of solid state lasers.

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[1] L. Dahlström, Opt. Commun. **5**, 157 (1972).
[2] K. Sala, M. C. Richardson, and N. R. Isenor, IEEE J. Quantum Electron. **QE-13**, 915 (1977).
[3] F. Ouellette and M. Piche, Opt. Commun. **60**, 99 (1986).
[4] G. P. Agrawal, *Nonlinear Fiber Optics* (Academic, New York, 1989).
[5] J. Goodberlet, J. Wang, J. G. Fujimoto, and P. A. Schulz, Opt. Lett. **14**, 1125 (1989).
[6] J. Mark, L. Y. Liu, K. L. Hall, H. A. Haus, and E. P. Ippen, Opt. Lett. **14**, 48 (1989).
[7] J. Goodberlet, J. Jacobson, J. G. Fujimoto, P. A. Schulz, and T. Y. Fan, Opt. Lett. **15**, 504 (1990).
[8] L. Y. Liu, J. M. Huxley, E. P. Ippen, and H. A. Haus, Opt. Lett. **15**, 553 (1990).
[9] J. M. Liu and J. K. Chee, Opt. Lett. **15**, 685 (1990).
[10] F. Krausz, Ch. Spielmann, T. Brabec, E. Wintner, and A. J. Schmidt, Opt. Lett. **15**, 1082 (1990).
[11] Ch. Spielmann, F. Krausz, T. Brabec, E. Wintner, and A. J. Schmidt, IEEE J. Quantum Electron. **27**, May (1991).
[12] T. Brabec, F. Krausz, M. Budil, Ch. Spielmann, and E. Wintner, J. Opt. Soc. Am. B (to be published).
[13] W. Sibett, *Ultrafast Phenomena VII* (Springer, New York, 1990), p. 2.
[14] The nonlinear arm is lossy due to fiber coupling losses therefore it may only be weakly coupled to avoid excessive round-trip cavity losses.
[15] M. Hofer, M. H. Ober, F. Hoberl, and M. E. Fermann, IEEE J. Quantum Electron. (to be published).
[16] F. Krausz, T. Brabec, and Ch. Spielmann, Opt. Lett. **16**, 235 (1991).