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Generation of optical pulses shorter than 0.1 psec by colliding pulse mode locking

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We report a novel passive mode-locking technique in which two synchronized counterpropagating pulses interact in a thin, saturable absorber to produce a short pulse. Continuous stable trains of pulses shorter than 0.1 psec are obtained using a ring laser configuration.

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The use of passive mode-locking of cw dye lasers[1,2] to generate subpicosecond optical pulses is now a well-established technique. We report here a new technique for passive mode locking a dye laser utilizing the interaction of two oppositely directed pulses in a thin, saturable absorber. We refer to this process as colliding pulse modelocking (CPM) because of the important role played by interaction or "collision" between the counterpropagating pulses. We observe stable continuous pulse trains with pulses as short as 90 fsec from our CPM mode-locked Rhodamine 6-G dye laser with pulse envelope fluctuations limited to the order of the noise on the pump argon laser (~ 1% rms). In contrast to the previous notion that the shortest optical pulses are obtained with a single pulse in the resonator,[3] CPM requires two or more pulses in the resonator. Interaction of the counterpropagating pulses creates a transient grating in the population of absorber molecules, which synchronizes, stabilizes, and shortens the pulses in both counterpropagating trains in a surprisingly effective way.

The process of saturating a nonlinear absorber by two "colliding" pulses bears some resemblance to the case of standing-wave saturation by a single pulse when the absorber is optically contacted with an end mirror.[4] However, the two-pulse case has a number of advantages. First, the fabrication problems associated with having the absorber in optical contact with the cavity and mirror are avoided. Second, with colliding pulses the absorber provides a synchronizing function and yields shorter, more stable pulses than reported previously.[5] Also, the pronounced relaxation oscillations and associated instabilities observed previously with some passively mode-locked dye-laser configurations[6] are eliminated in our new configuration.

The principal requirement for CPM is a laser structure in which the difference in arrival time of the two interfering pulses is small compared to the pulse duration. In addition, it is necessary that the saturable absorber be sufficiently thin that the optical path in the absorber is of the order of or less than the desired pulse width. The above conditions are satisfied, e.g., in the ring laser configuration shown in Fig. 1. The saturable absorber is 3,3′-Diethyloxadicarbocyanine iodide dissolved in ethylene glycol with a small-signal loss of ~20%. A special nozzle was used to generate a dye stream approximately 10 μ thick. The dye laser was pumped with a cw argon laser using 3–7 W at 5145 Å.

The optical pulse width was measured using the background-free autocorrelation method with KDP described previously.[7] The result is shown in Fig. 2. The autocorrelation half-width is 0.14 psec. This corresponds to an optical pulse FWHM, τ_p of less than 0.1 psec. If we assume a sech^2 pulse shape we obtain a pulse width of 90 fsec. The spectral width was measured to be 50 ± 10 Å depending on resonator adjustments, which is close to the transform limit for a 90-fsec pulse. We found it unnecessary to limit the resonator bandwidth with an intracavity prism. A thin uncoated pellice etalon approximately 2 μ thick inserted into the resonator slightly decreased the wings of the pulse. The average output power was 50 mW from each of the two counterpropagating beams for a 3% output coupler. The pump power could be varied from 5 to 7 W with little change in pulse width.

Synchronization of two counterpropagating pulses in our ring laser occurs because the minimum energy is lost to the saturable absorber when the two pulses meet in the thin absorber stream. We can gain insight into this process by calculating[8] the energy lost in a thin absorber compared to the pulse width as a function of the difference in arrival time of the two pulses at the saturable absorber. In Fig. 3 we plot the ratio $W(\Delta t)/W(\infty)$ vs Δt, where $W(\Delta t)$ is the pulse energy lost to the absorber for a difference in pulse arrival time Δt, and $W(\infty)$ is the energy absorbed for Δt much greater than the absorber recovery time. Curves are given for various saturation energies defined by the parameter $\beta = 2\sigma U_0$, where σ is the absorber cross section and U_0 is the

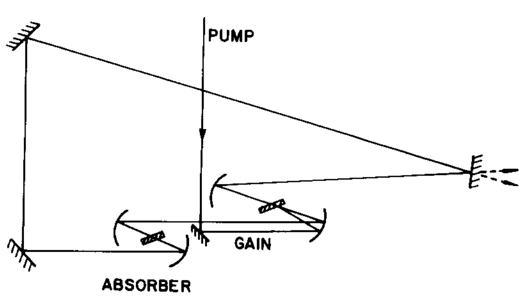

FIG. 1. Schematic diagram of ring laser used for CPM. The focusing mirrors for the gain region have a 10-cm radius and those for the absorber have a 5-cm radius. Cavity roung-trip time was 10 nsec.

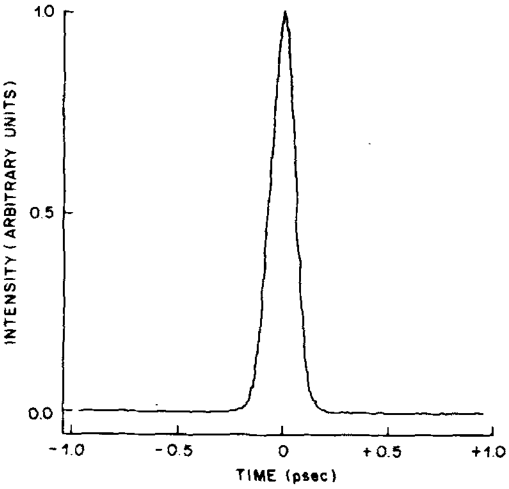

FIG. 2. Autocorrelation function of the optical pulse.

pulse energy per cm^2. Note that $W(\Delta t)/W(\infty)$ is a minimum at $\Delta t = 0$ or at precise pulse overlap. The minimum near $\Delta t = 0$ is most pronouned at intermediate energies where $\beta \sim 1$, which is close to the present experimental condition.

When the absorber stream thickness is on the order of the pulse width additional pulse forming mechanisms may occur. For example, the trailing edge of the pulse may experience additional loss relative to the peak, since the standing-wave contrast is reduced when the trailing edges of the two pulses overlap. Also, it may be necessary to take into account the coupling between the two pulses, which arises from the absorption grating created by the standing-wave saturation.[9]

We have also observed CPM in conventional (nonring) lasers. In this case the absorber must be placed precisely at a submultiple m of the cavity length from one end mirror. In addition, the laser dynamics must be such that m pulses oscillate in the cavity. We have observed CPM for the cases $m = 2, 3$, and 4. The optical pulsewidths (0.15–0.20 psec) determined for the above conditions were somewhat longer than for the ring cavity.

In conclusion, we have used a new mode-locking technique to generate the first optical pulses shorter than 0.1 psec. Perhaps equally significatnt is the increased stability, high average output power, and insensitivity of pulse width

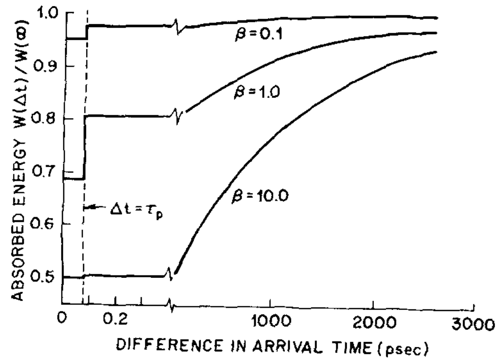

FIG. 3. Energy absorbed in the saturable absorber plotted vs difference in pulse arrival time for three values of the saturation parameter β.

to pump power. An analysis of CPM to clarify the pulse shortening mechanisms and the stabilzation process is underway. Finally, we anticipate that these concepts will be extended to other types of lasers such as semiconductor lasers.

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