Intracavity pulse compression with glass: a new method of generating pulses shorter than 60 fsec

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The introduction of a glass prism in a ring dye laser is shown to provide simultaneous wavelength selection and pulse compression.

Significant progress has been made in the last decade in the generation of ultrashort dye-laser pulses. Subtle changes in cavity configuration resulted in dramatic changes in laser operation, which explains the somewhat erratic pace of progress in this field.

Pulses of 0.5-psec duration were generated in a linear configuration with two dye jets by Shank and Ippen.[1] The cavity loss modulation responsible for mode locking is obtained by saturation of the absorption in the dye diethyloxadicarbocyanine iodide (DODCI). The saturable absorber is flown through a jet located near the cavity end opposite the gain medium (Rh6G pumped by a cw argon laser). Pulse compression down to 0.3 psec was obtained with a pair of gratings.[2] By positioning the saturable absorber [diethylquinolyloxacarbocyanine iodide (DQOCI) in a dye cell] where the ultrashort laser pulse collides with itself at the cavity end mirror, Ruddock and Bradley[3] directly produced pulses of 0.3-psec duration. Diels *et al.*[4] choose a simpler configuration in which all the nonlinear elements (saturable absorber and gain medium) are mixed in the same dye jet. By a careful optimization of the dye mixture and cavity bandwidth (by eliminating all intracavity bandwidth-limiting elements and using carefully profiled mirror spectra), they obtained pulses as short as 120 fsec.[5] With a similar cavity configuration but using synchronous pumping and DQOCI, Mourou and Sizer produced pulses as short as 70 fsec (Ref. 6) with an exceptionally high conversion efficiency (10%). Instead of causing the pulse to collide with itself at the end of a linear cavity,[3] Fork *et al.*[7] used a ring-laser configuration in which the counterpropagating pulses collided in a thin saturable-absorber dye jet. The use of an absorbing-medium thickness as short as 10 μm resulted in a pulse duration of 90 fsec.[7] Shorter pulses (65 fsec) were reported[8] after optimization of the mirror spectra as in Ref. 5.

It is generally believed that the introduction of any dispersive intracavity element will produce a significant pulse broadening. Shank[8] reported an increase of pulse duration from 90 to 200 fsec by introduction of a microscope slide in the cavity. We demonstrate instead that, for a particular dye composition and wavelength, there is an optimal thickness of glass in the cavity that leads to the generation of the shortest pulses. For example, with a 2-mm thickness of BK7 inserted in our cavity, we recorded the second-order autocorrelation trace shown in Fig. 1, corresponding to a sech^2-shaped pulse of 53-fsec duration.

The laser configuration (Fig. 2) is similar to the one reported earlier by one of us.[9] All mirrors have maximum reflectivity coatings centered at 600 nm. A dispersive prism of BK7 or flint glass is used. Rotation and translation of the prism provide for independent control of the laser wavelength and the optical pathlength in glass, respectively. A standard coherent-radiation jet nozzle is used for the gain medium (100-μm thickness). The absorber jet is of a fanned-out type to provide for a thickness decreasing with distance from the nozzle, to a minimum of about 50 μm. It appears that, for our cavity configuration, the thickness of the jet is not of critical importance. The laser is pumped using all the lines of a Spectra-Physics Model 165-08

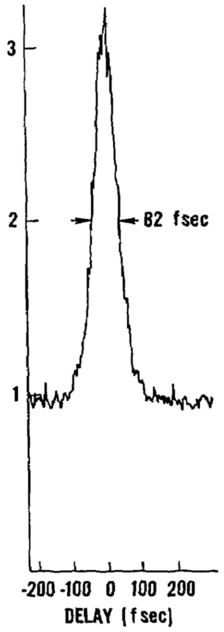

Fig. 1. Second-order autocorrelation of the pulse train, with peak-to-background ratio of 3 to 1. The autocorrelation width of 82 *fsec corresponds to a sech^2 pulse duration of* 53 fsec.

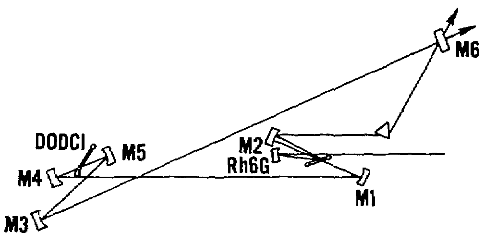

Fig. 2. Cavity configuration. The argon-laser pump mirror has a radius of curvature of 3 cm. The focusing mirrors around the amplifying and absorbing jets are, respectively, M1 and M2 (= 5 cm) and M4 and M5 (= 3 cm). The cavity mirror M3 has a radius of curvature of 1 m. The perimeter of the resonator is 3.6 m.

argon laser. The cw lasing threshold, in the absence of an absorber jet, is 80 mW. The DODCI solution with a concentration of 10^{-3} *M*/liter increased the threshold up to 4 W.

Two types of autocorrelator were used to monitor the laser output. The trace shown in Fig. 1 was recorded with an instrument using pellicle beam splitters to minimize the pathway in glass and collinear second-harmonic generation in a 0.3-mm-thick KDP crystal. The total pathway in glass, including the transmission through the output laser mirror, is 2.5 cm. Background-free autocorrelation traces, as in Fig. 3, were taken using polarizing beam splitters and type II second-harmonic generation in urea.[10] Two mutually delayed orthogonally polarized equal fractions of the laser beam are focused into the urea crystal. The measured autocorrelation width of 100 fsec (sech^2 pulse of 65 fsec FWHM) is remarkably short in view of the large thickness of glass (a total of 5 cm) traversed by the pulses between the laser and the second-harmonic-generating urea crystal. The measurement of Fig. 3 indicates that a resolution of tens of femtoseconds is possible for applications in time-resolved spectroscopy and fluorescence, or a resolution of the order of several micrometers for time-domain reflectometry[11] and optical imaging.[12]

The dependence of pulse duration on the optical pathway in glass is shown in Fig. 4. The pulse wavelength is maintained constant near 605 nm. For the measurement of Fig. 4, the prism of BK7 (n = 1.515) was replaced by a more-dispersive prism of flint glass (n = 1.62). It should be noted that qualitatively a similar pulse-width dependence can be measured at various wavelengths. However, the optimum glass thickness can vary by more than 1 order of magnitude with the laser wavelength. The wavelength dependence of the glass thickness at minimum pulse duration is not monotonic.[13] The various parameters of the laser (concentration, temperature, and age of the DODCI solution) have to be adjusted for each wavelength. If the dispersive prism is adjusted for minimum losses for each concentration of DODCI, a tuning curve (wavelength versus dye concentration) can be established.[13] The observed dependence is consistent with the recent observation[9] of *extracavity* pulse compression by passage of the pulse through a certain thickness of glass. The implication is that the nonlinearities in the absorbing (or amplifying) medium induce a downchirp.[9] Work is in progress to establish a theoretical model to match quantitatively the wavelength dependence of the observed downchirp. Pulses with such a frequency decreasing with time can be shortened by passage through a medium with normal dispersion (e.g., glass) since the training edge (seeing a smaller index) will catch up with the slower leading edge of the pulse. A compression by a factor of 1.5 was observed after transmission of 0.3-psec pulses through 17 cm of BK7

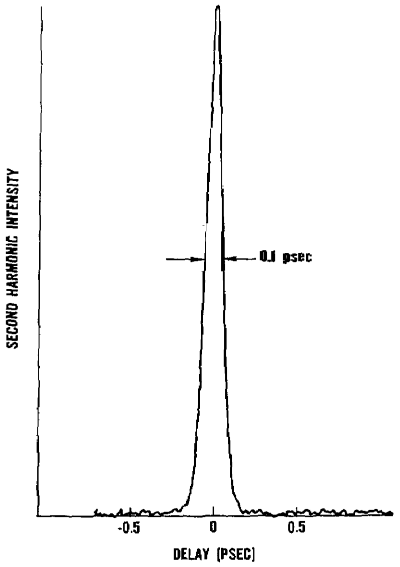

Fig. 3. Background-free autocorrelation recorded by type II second-harmonic generation in urea. The experimental arrangement is detailed in Ref. 10. The autocorrelation width of 100 fsec corresponds to a sech^2 pulse duration of 65 fsec. Spectral measurements indicate that the pulses are nearly bandwidth limited (6-nm bandwidth).

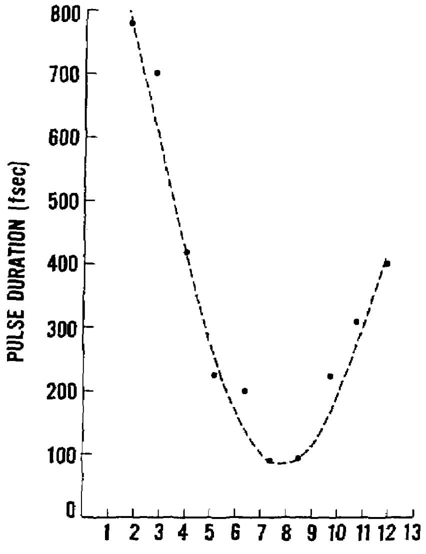

Fig. 4. Pulse duration versus thickness of glass (flint F2, n = 1.62) in the cavity for a particular wavelength (605 nm).

glass. However, the intensity autocorrelation of pulses of 0.15 psec remained unchanged, whereas a broadening by a factor of 2.3 was observed for 0.1-psec pulses.[9] Similar observations were reported by Mourou and Sizer for the synchronously passively mode-locked laser.[6] In the case of the cavity used in this work (Fig. 2), an intracavity pulse-compression mechanism takes place through successive passages through the absorbing and amplifying media (inducing down-frequency chirping) followed by transmission through glass.

In conclusion, we have demonstrated a laser that combines the above-mentioned intracavity compression mechanism with the stability of colliding pulse mode locking. The latter can be attributed to a stabilization mechanism introduced by a four-wave-mixing type of interaction in the absorber jet.[14]

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