High-repetition-rate coherent femtosecond pulse amplification with an external passive optical cavity

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We demonstrate a general technique for enhancement of femtosecond pulses from a pulse train through their coherent buildup inside a high-finesse cavity. Periodic extraction of the intracavity pulse by means of a fast switch provides a net energy gain of 42 to >70 times for 38–58-fs pulse durations. Starting with an actively stabilized but otherwise standard mode-locked laser system, we demonstrate pulses of >200-nJ energy.

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Recent advances in high-energy femtosecond (fs) oscillators permit pulse energies of hundreds of nanojoules to be obtained directly from the laser oscillator.[1,2] One motivating factor behind such work is the drive to develop simple laser systems that can provide access to increased field strengths while they operate at repetition rates higher than those of standard amplified systems. There is a range of applications that can benefit from simple, cost-effective systems that are capable of producing pulse energies in the 1–100-μJ range. Many applications would also benefit from higher repetition rates for enhanced signal-acquisition capabilities. We present a flexible and general technique for enhancement of fs pulse energies by more than 2 orders of magnitude that is applicable to ultrashort pulse trains in any spectral region where appropriate mirrors can be produced. This approach also facilitates generation of pulse energies of hundreds of nanojoules by use of common fs laser designs and can also be used to complement recent high-energy fs oscillators to produce pulse energies potentially >10 μJ.

We previously proposed the use of high-finesse enhancement cavities specifically designed to compensate for linear dispersion to coherently accumulate pulses until a fast switch was enabled to eject a single amplified pulse.[3] Active control and stabilization of a fs laser's two degrees of freedom facilitates the buildup and storage of ultrashort pulses in high-finesse optical cavities. The stored intracavity field is the result of the coherent addition of pulses accumulated over the lifetime of the cavity. An acousto-optic modulator (AOM) can be used to switch out the enhanced pulse. Greater single-pulse amplifications are achieved with higher-finesse cavities, at the expense of a reduction in the pulse repetition rate. This concept was recently demonstrated with picosecond pulses,[4,5] in which the limiting effects of cavity dispersion did not play a significant role. In this Letter we describe extending this technique to the fs regime for the first time to our knowledge by using carefully designed fs enhancement cavities to store and enhance pulses as short as 38 fs. Besides this more conventional aspect of pulse amplification, the passive fs buildup cavity opens a new, exciting opportunity to explore nonlinear optical interactions in an intracavity environment at the laser's original high repetition rate.

The experimental layout of the buildup cavity is similar to that given previously.[4] A simplified schematic for enhancement of fs pulses is shown in Fig. 1. Here we focus on the requirements of the system needed to achieve effective amplification in the fs regime. The pulse train is mode matched to the fs enhancement cavity. We obtain error signals by detecting the reflected light and use them to lock the two degrees of freedom of the fs laser relative to the enhancement cavity.[6,7] The first error signal (e_1) is sent to the enhancement cavity to keep the phase or frequency of the stored pulse resonant with the incident pulse train. The second error signal (e_2) is fed back to the laser to lock the pulse repetition rate to the cavity. With both locks on, the intracavity power coherently builds up until it reaches its steady-state value or until it is switched out by the AOM. This periodic cavity dumping results in an overall reduction in the repetition rate by n times and in a single-pulse energy gain G.

The maximum bandwidth (i.e., the shortest pulse) that can be coupled into the cavity is limited by the net cavity group-delay dispersion (GDD), as was discussed previously.[3] The higher the cavity finesse, the more severe the effects of nonzero GDD, owing to the increased average number of

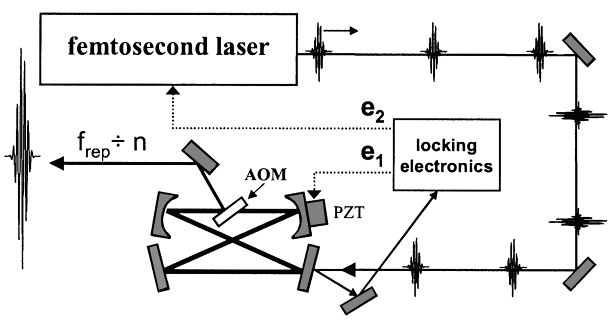

Fig. 1. Simplified schematic of pulse amplification with a fs enhancement cavity. Coherent accumulation and subsequent dumping of the passive cavity results in amplified pulse energies at repetition rates reduced n times. PZT, piezoelectric transducer.

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round trips of the pulse inside the cavity. To compensate for the dispersion of the 3.8 mm of fused silica from the intracavity AOM, we used negative GDD mirrors based on a double Gires–Tournois interferometer design[8] to construct the cavity. Three bounces per round trip from these mirrors provided approximately $-120\ \mathrm{fs}^2$ of GDD compensation. We accomplished fine tuning of the cavity dispersion by adjusting the air pressure in the chamber containing the fs enhancement cavity. This provided $\approx 60\ \mathrm{fs}^2$ of tunability when the air pressure was changed from atmospheric pressure to <1 Torr and was crucial for coupling the shortest pulses into the cavity.

The cavity pressure was adjusted to produce zero GDD at ≈ 820 nm. Figure 2 shows the intracavity buildup (normalized to its steady-state value) as a function of n. When the pulse is switched out faster than the cavity lifetime, the intracavity field does not have time to build up fully to its steady-state value. This results in a decrease of the average intracavity power. Curve (a) of the inset shows the pulse spectrum going into the cavity, and curves (b) and (c) show the intracavity spectrum for two different pulse dumping rates. The bandwidth of the transmitted spectrum is reduced as a result of uncompensated higher-order dispersion inside the cavity [e.g., third-order dispersion (TOD)]. At smaller values of n, the stored pulse makes on average fewer round trips in the cavity; the effects of the uncompensated dispersion are thus reduced. The resultant effect on the allowed pulse bandwidth can be seen by comparison of curves (b) and (c) of Fig. 2. The spectrum of curve (c) corresponds to a Fourier-transform-limited (FTL) pulse width of 40 fs when $n = 500$. However, when the pulse is switched out after 40 round trips [curve (b)], a FTL pulse width of 34 fs is maintained in the cavity. Figure 2 therefore demonstrates the spectral filtering of the cavity that is due to the combined effects of cavity dispersion and lifetime. It also illustrates the inherent trade-off among net energy gained, pulse duration, and repetition rates that can be maintained with this technique.

A second limitation on the enhancement of fs pulses arises from the nonlinear interaction of the focused pulse during its passage through the intracavity AOM. The high intracavity peak intensity results in self-phase modulation of the pulse. Consequently, intracavity enhancement N decreases from its low-energy limit as the incident energy per pulse is increased beyond a certain threshold level. This level is determined by the intracavity intensity achieved at the AOM. As the incident energy is increased, the intracavity pulse (and spectrum) eventually becomes severely distorted. Figure 3 shows the incident and intracavity pulse spectra obtained when the pulse intensity is well beyond this threshold level. In this case N has decreased by 45% from its small energy value. In contrast, with the same average power, no change of the intracavity spectrum or decrease in enhancement is seen when we significantly reduce the pulse peak power by prestretching the incident pulses to more than 100 ps. The nonlinear phase shift acquired by the intracavity pulse causes deterioration of the degree of complete constructive interference maintained with this incident pulse train owing to modifications of the pulse's spectral phase and distribution during its lifetime in the cavity. For our experiments, we estimate that the threshold for a decrease in N occurs when the peak intracavity intensity exceeds $\approx 1 \times 10^{10}\ \mathrm{W/cm}^2$, corresponding to a maximum nonlinear phase shift of ≈ 0.1 rad in the fused-silica AOM. The use of zero GDD fs enhancement cavities therefore offers the additional unique capability to study nonlinear interactions between fs pulses and intracavity samples at the full repetition rate of the oscillator, without the need for active amplification. The nonlinear response of the fs enhancement cavity is the subject of current research.

As with the ps enhancement cavity,[4] the overall gain depends on intracavity losses, impedance and mode matching, dumping efficiency of the intracavity AOM, and the pulse dumping rate for a given cavity finesse. Faster switching times easily allow the generation of greater than 1-MHz pulse trains at the expense of decreased gain but are not optimum with our cavity design owing to the >1-μs cavity lifetime (Fig. 2). A decreased gain also accompanies shorter pulses as a consequence of the less restrictive spectral filtering by the cavity. With a 0.9% input coupler at 800 nm and a pulse dumping efficiency of $\approx 40\%$, the overall gain obtained with the fs enhancement cavity varied from 42× with 39-fs pulses to greater than 70× with 52-fs pulses for dumping rates below

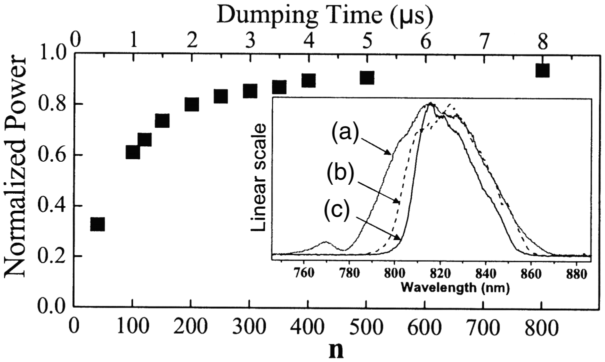

Fig. 2. Intracavity power normalized to its steady-state value versus reduction in pulse repetition rate (n). Top axis, corresponding time between pulse dumping events. Inset, spectra of (a) the incident and dumped pulses for (b) $n = 40$ and (c) $n = 500$.

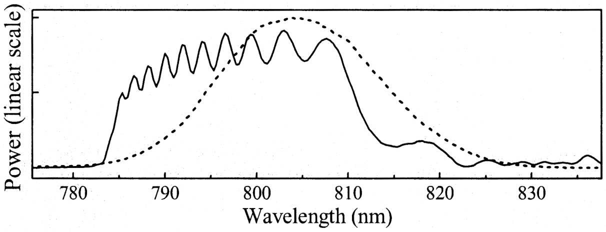

Fig. 3. Normalized incident (dotted curve) and intracavity (solid curve) pulse spectra, demonstrating the nonlinear response of the fs enhancement cavity. The integrated spectral power of the intracavity pulse was reduced 50×.

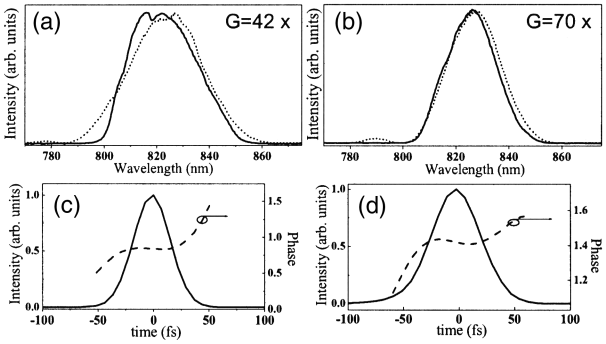

Fig. 4. Pulse spectrum and recompressed pulse intensity and phase measured by after cavity enhancement. (a), (c) incident (dotted curves) and intracavity (solid curves) pulse spectra for two incident-pulse bandwidths. (b), (d) Corresponding pulse measurements of 39- and 52-fs pulses (FWHM).

500 kHz. Greater pulse enhancements are possible with reduced intracavity losses (currently ≲0.5%) and improved impedance matching.

Measurements of fs pulse enhancement for this range are shown in Fig. 4. An ~200-kHz pulse train was generated from the 100-MHz laser. The input (output) spectra for two pulse trains with different spectral bandwidths are indicated by the dotted (solid) curves in Figs. 4(a) and 4(b). The pulse was stretched (compressed) with a grating-based system before (after) the enhancement cavity to minimize the intracavity nonlinear response. The efficiency of the stretcher–compressor was only ≈45% each. The recompressed pulse switched out of the cavity was measured with a frequency-resolved-optical-gating-based system. Figures 4(c) and 4(d) show the measured pulses that correspond to the spectra of Figs. 4(a) and 4(b), respectively. With the pulses stretched to more than 100 ps, the only limitation on the achieved energy per pulse was due to the inefficiency of the gratings and to the limited power available from the Ti:sapphire laser. For Figs. 4(b) and 4(d) the incident pulse energy of 2.5 nJ was increased 70× to 175 nJ before recompression. When the laser was adjusted to produce 58-fs pulses, the incident pulse energy available increased to 3 nJ, resulting in enhanced pulse energies of 210 nJ from the cavity before recompression back to 58 fs. A prism-based stretcher–compressor system[9] provides much higher throughput and will make more-efficient use of the power available from the laser, enabling pulse energies greater than 400 nJ to be achieved, starting with only conventional oscillators.

The current limitation on efficient enhancement of shorter pulses is consistent with that expected from the TOD of the AOM, given our current cavity finesse. Numerical calculations that take only the TOD of the intracavity fused silica into account and assume an incident spectrum as shown in Fig. 4(a), predict an intracavity bandwidth supporting an ≈38-fs FTL pulse duration, similar to that actually measured in Fig. 4(c). This modeling indicates that it will be possible to enhance sub-30-fs pulses by comparable amounts when TOD is taken into account in the overall cavity design.

In conclusion, we have demonstrated the use of enhancement cavities for amplifying fs pulse energies through coherent addition of multiple pulses in a high-finesse cavity. We have identified limitations (solutions) to achievement of better performance in terms of both peak power (pulse stretching and recompression) and intracavity dispersion (higher-order compensation). We can already provide >200-nJ pulse energies by using commonly available oscillators. When these oscillators are combined with recently tested low-repetition-rate oscillators (e.g., stretched pulse lasers[1]), one can expect to reach microjoule energies without the need for active amplification. Intracavity investigations of nonlinear interactions between fs pulses and various samples are also to be studied. With 3.8 mm of fused silica inside the cavity we have already achieved an intracavity pulse buildup exceeding 170. Greater enhancements (factors of 10^2 to more than 10^3) that lead to much higher field strengths should be obtainable when more-dilute intracavity samples replace the fused-silica plate.

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Note added in proof: Subsequent numerical modeling of the intracavity nonlinearity in fused silica shows good qualitative agreement with the features shown in Fig. 3.

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