Femtosecond pulse amplification by coherent addition in a passive optical cavity

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By simultaneously controlling repetition and carrier frequencies, one can achieve the phase coherent superposition of a collection of successive pulses from a mode-locked laser. An optical cavity can be used for coherent delay and constructive interference of sequential pulses until a cavity dump is enabled to switch out the amplified pulse. This approach will lead to an effective amplification process through decimation of the original pulse rate while the overall coherence from the oscillator is preserved. Detailed calculations show the limiting effects of intracavity dispersion and indicate that enhancement of sub-100-fs pulses to microjoule energies is experimentally feasible.

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Phase control of femtosecond lasers was recently achieved,[1,2] and its potentially powerful applications in extreme nonlinear optics and novel coherent processes are being actively explored.[3] Ordinarily, the peak power obtainable from pulses emitted from a simple oscillator is not sufficient to drive the high-order nonlinear processes of interest. Naturally, researchers are interested in the development of phase-controlled pulse amplification.[4] However, the use of conventional amplifiers can introduce a great deal of phase noise owing to effects such as beam pointing variation, pump power fluctuation, and amplifier medium instability. Stabilization of the carrier-envelope phase after an amplifier remains a daunting task. In this Letter we analyze a unique approach to pulse amplification without the use of an active gain medium. The technique relies on coherent superposition of successive components from a pulse train to increase the amplitude of a single pulse while reducing the repetition frequency. This procedure requires not only a suitable delay mechanism for lining up successive pulses but also the ability to control the phase evolution of the electric field lying under the pulse. These requirements are similar to those that have already been demonstrated in coherent pulse synthesis from separate femtosecond lasers.[5] In that work, precise control of both timing synchronization and carrier phase locking was achieved for successful synthesis of a single pulse from two independent pulses. An amplification scheme based on coherent addition would maintain the carrier-envelope phase coherence of the original oscillator. We no longer need an additional gain medium.

A passive optical cavity is an ideal place in which to temporarily store and coherently enhance a pulsed electric field. The operating principle of the proposed amplifier design is illustrated in Fig. 1. To ensure efficient coupling into the cavity and subsequent power buildup, the repetition rate and the carrier-envelope phase of the input pulses must match those of the pulse circulating inside the passive cavity. The equivalent frequency-domain requirement is that all frequency components that make up the pulse train be tuned to resonance with the corresponding cavity modes. The cavity decay time is directly proportional to the overall cavity finesse and is predetermined to match the desired pulse amplification factor. For example, suppose that a laser pulse train has a 100-MHz repetition rate and we wish to convert it to an output pulse train with a 1-MHz repetition rate with 100 times amplification in the peak power. We would then design the cavity finesse to be ~314, such that the cavity linewidth were 0.32 MHz and the field decay time were roughly 1 μs. Then the electric fields of roughly 100 pulses would be able to add coherently inside the cavity before being switched out.

Resonant enhancement cavities are commonly used with cw lasers to improve efficiencies in nonlinear optical interactions or to increase sensitivity in spectroscopic applications. Based on these cw techniques, similar intracavity experiments that use mode-locked lasers have been demonstrated,[6,7] and the idea of periodically dumping a laser pulse from a passive optical cavity for amplification was described in a recent patent.[8] These approaches, however, address

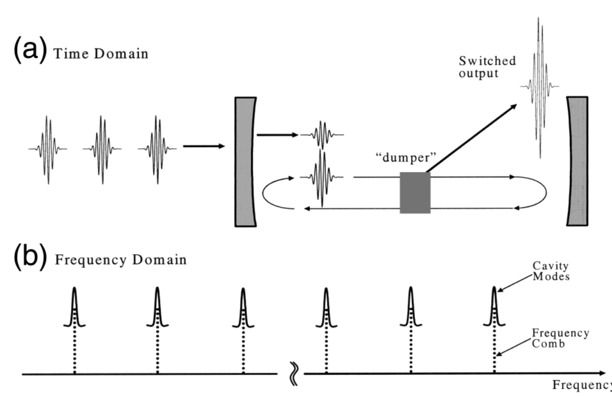

Fig. 1. Coherent pulse amplification with the aid of an optical cavity. (a) Time-domain picture showing matching of the pulse repetition period with the cavity round-trip time. The intracavity pulse is switched out when sufficient energy is built up in the cavity. Intracavity dispersion compensation is not shown. (b) Frequency-domain illustration showing the matching of the pulse comb structure with corresponding cavity modes, which ensures the efficient coupling of the pulse energy into the cavity.

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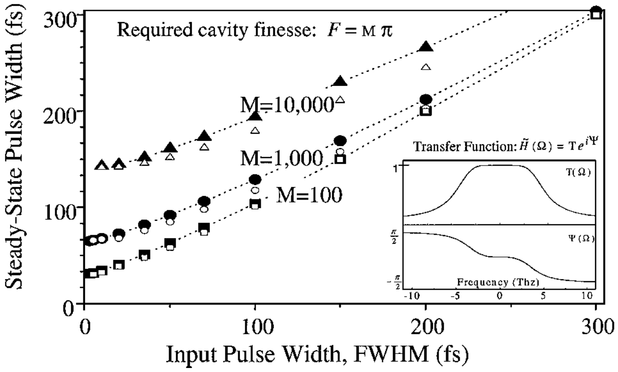

Fig. 2. Relationship between input and output (amplified) pulse widths through the cavity for three maximum cavity magnifications (M). Filled (open) points indicate results from steady-state (time-dependent) calculations. Inset, transmission and phase coefficients of the cavity transfer function for the pulse train obtained from steady-state calculations. Even for an amplification factor of 1000, output pulses well under 100 fs are achievable.

only one parameter (repetition rate or laser average frequency), whereas both are required for coherent pulse manipulation. Hence coherent superposition of successive short pulses for significant amplification would not be feasible. To efficiently couple sub-100-fs pulses into an optical cavity with a finesse sufficiently high to build up pulse energy by 100 to >1000 times, two key criteria must be met: (i) the carrier and the repetition frequency of the femtosecond (fs) laser must be simultaneously stabilized to that of the cavity and (ii) the cavity itself must be designed such that dispersion does not severely distort the intracavity pulse. The stabilization of a fs laser to an optical reference cavity that meets requirement (i) was recently carried out,[9] confirming the promise of this approach. In this Letter we calculate and clearly show the effects of cavity dispersion in limiting energy buildup and in distorting the pulse shape inside a cavity.

The inevitable dispersion inside an optical cavity that arises from intracavity elements and mirror-reflection phase shifts leads to a nonuniform cavity mode spacing throughout relevant spectral regions. This fact will place a practical limit on the spectral bandwidth (and therefore on the pulse duration) that one can employ in this scheme because the modes of the fs pulse train are rigorously equally spaced. In addition, relevant laser comb components coupled into the cavity cannot be simultaneously locked to the center of corresponding cavity modes [in contrast to the ideal case shown in Fig. 1(b)], a situation that leads to a frequency-dependent phase shift imposed on the intracavity spectrum and therefore to distortion of the pulse's temporal profile. If higher cavity finesse is desired for greater pulse enhancement, the cavity linewidth will become narrower and the increased mismatch between the cavity modes and the fs comb will lead to a further reduction in the useful bandwidth of the cavity. These facts can also be easily understood from time-domain considerations when pulses bouncing back and forth in the cavity are broadened and distorted as a result of dispersive phase shifts. As a result, the overlap of the incoming pulse envelopes with the stored pulse is reduced, and their constructive interference is compromised.

For the calculations presented below, we assume a four-mirror linear cavity with a pair of fused-silica prisms for dispersion compensation and an intracavity fused-silica Brewster-angled Bragg deflector for switching out the pulse. Two of the mirrors are used to create an intracavity focus to decrease the switching time of the Bragg deflector. It should be noted that, to reduce intracavity peak powers to avoid substantial nonlinear effects, the input pulse may be chirped and later recompressed, as is commonly practiced with traditional optical amplifiers. This operation would have no effect on the results shown here. The input mirror should have a transmission coefficient matched to the remaining part of the total cavity loss (impedance matching). The maximum finesse, and hence the maximum pulse magnification, will then be limited by scattering losses in the fused silica, residual losses at the Brewster-angled surfaces, and reflection loss at the remaining cavity mirrors. We expect that a cavity finesses of greater than 1000 will be experimentally feasible.

The round-trip phase shift inside the cavity can be expressed in a power series expansion: $\Phi_{\mathrm{RT}}(\omega) = \Phi_0 + \Phi_1(\omega - \omega_0) + \Phi_2(\omega - \omega_0)^2/2! + \Phi_3(\omega - \omega_0)^3/3! + \ldots$, where ω_0 is the center angular frequency of the mirror coating. Frequency-independent phase shift Φ_0 describes the carrier-envelope phase shift per round trip of the intracavity pulse, and group delay Φ_1 determines the cavity's free spectral range (FSR) at ω_0. These terms are not important to the calculations, as the incident pulse train will be matched to these values when it is properly stabilized to the cavity. The group-delay dispersion will be set to zero at ω_0 with prism compensation. The phase shifts that are due to reflection from the dielectric mirrors depend strongly on the coating design. For these calculations we have chosen to use standard quarter-wave stack mirrors, for which dispersion characteristics are well known,[10] although better performance may be achieved with mirrors that have been custom designed for dispersion compensation. A total path length of 0.9 cm through the fused-silica components was assumed, with a 30-cm separation between the prisms. The dispersion coefficients used for the given cavity parameters are $\Phi_2 = 0$, $\Phi_3 = 400\ \mathrm{fs}^3$, and $\Phi_4 = -1600\ \mathrm{fs}^4$.

Two independent calculations were performed to model the interaction of the pulse train with the optical cavity. For the first model an infinite interaction time between the cavity and the pulse train (steady-state model) was assumed, whereas in the second model the coherent buildup of the intracavity electric field was calculated for each round trip of the pulse (time-dependent model). For the steady-state calculations, we used the intracavity dispersion to calculate the frequency-dependent cavity FSR. We then used the FSR to determine the detuning, δ, of the mth laser mode from a corresponding cavity mode. It was assumed that the laser repetition rate matches the cavity FSR at ω_0. The cavity transfer function that

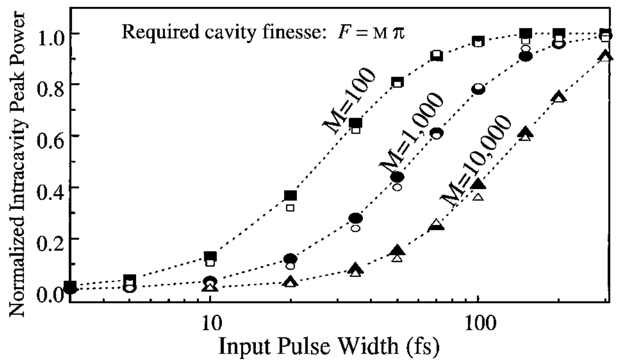

Fig. 3. Intracavity peak power normalized to the maximum achievable effective gain versus input pulse duration for different cavity magnifications. Filled (open) points, results from frequency- (time-) domain calculations. When the input pulse width is narrow and (or) the finesse is high (for large amplification), intracavity dispersion will limit the amount of coherent superposition allowed. For a 100-fs pulse with a desired amplification factor of 1000, nearly 100% of the design goal is achievable.

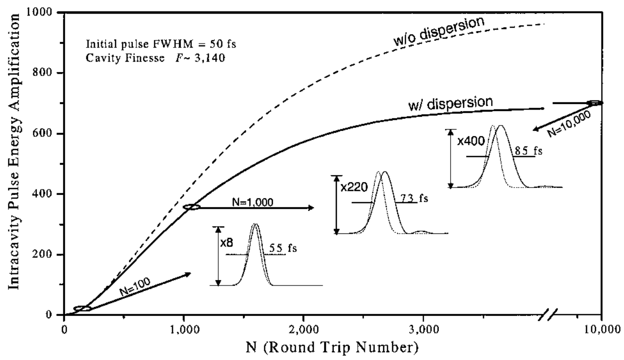

Fig. 4. Results from time-dependent calculation showing the coherent evolution of a 50-fs pulse inside the cavity. Dashed curve, ideal case of a dispersion-free cavity perfectly matched with the incident pulse train; solid curve, effect of cavity dispersion in limiting the amount of energy coupled into the cavity.

relates the transmitted ($\tilde{E}_t$) to the incident ($\tilde{E}_i$) pulse train, $\tilde{E}_t = \tilde{E}_i \tilde{H}(\omega)$, where $\tilde{H}(\omega) = Te^{i\psi}$, was then calculated based on δ and the transfer function for the individual frequencies. Figure 2 shows the resultant steady-state pulse width as a function of the input pulse for a given cavity finesse. The inset of Fig. 2 shows the cavity transmission profile, $T(\omega - \omega_0)$, and the spectral phase shift, $\Psi(\omega - \omega_0)$. One can easily see from $T(\omega - \omega_0)$ the limited bandwidth that can be employed for pulse amplification. Figure 3 shows the limits to peak power amplification that are due to the cavity dispersion. Again, the desire for greater amplification or for a shorter pulse width will be more severely affected by the cavity dispersion, leading to a lower value for the normalized intracavity peak power.

Also shown in Figs. 2 and 3 are the results of time-dependent calculations, which allowed use to visualize the evolving intracavity pulse one round trip at a time. We obtained these results by repeatedly solving for the transmitted and reflected fields at the input mirror after the pulse propagated once through the cavity. This process was continued until steady-state values were obtained for the intracavity energy. The steady-state and dynamic models are in good agreement, as shown in Figs. 2 and 3. Figure 4 illustrates the evolution of a 50-fs pulse inside a cavity with a finesses of 3140 under the conditions of zero cavity dispersion (dashed curve) and finite dispersion (solid curve). Three representative pulses at different stages of amplification are also shown. Although the 50-fs pulse is stretched by the dispersive cavity, it is not severely distorted because it is coupled with the incident pulse train. If the incident pulses become too short or the cavity finesse too high, or if the laser repetition frequency deviates significantly from the cavity FSR at ω_0, the intracavity pulse may be quickly pulled apart into several pulses, and the meaning of a single pulse width will be lost.

The results shown here demonstrate the feasibility of a pulse amplification scheme based on coherent storage and constructive interference of pulsed electric fields inside a passive optical cavity. Such a technique will preserve the carrier-envelope phase-coherence characteristics of the original pulses from the oscillator while enabling pulse energies to be increased by 2–3 orders of magnitude. This indicates that sub-100 fs pulses with microjoule energies can be obtained, given the nanojoule level of pulse energy available from current ultrafast lasers. Future cavity designs based on custom dispersion-compensating mirrors may extend the usefulness of this technique to the sub-20-fs regime.

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