Femtosecond Laser Stabilization: Time and Frequency Domain Applications

R. Jason Jones, Kevin Holman, and Jun Ye
JILA/ NIST and University of Colorado, 440 UCB, Boulder CO 80309
Phone: (303)492-5237, Fax: (303)492-5235, e-mail address: rjjones@jilau1.colorado.edu

Eric Potma and X. Sunney Xie
Harvard University,12 Oxford Street, Cambridge, MA 02138

Abstract: Noise reduction in femtosecond laser systems becomes increasingly important as new experiments evolve requiring improved levels of performance. Stabilized ultrashort pulses can now be coherently coupled and stored inside high finesse passive optical cavities. These optical storage cavities can be used for a variety of applications, including stabilization of the pulse train itself, sensitive spectroscopy, enhancement of nonlinear frequency conversion, and coherent pulse amplification.

The stabilization of mode-locked femtosecond lasers has played a key role in recent advances in optical frequency measurement [1,2] carrier-envelope phase stabilization [3,4], all-optical atomic clocks [5,6] and coherent pulse synthesis [7]. The ability to stabilize and control the discrete comb of frequencies that comprise the train of optical pulses becomes increasingly important as novel applications utilizing the "femtosecond comb" are developed that demand greater levels of precision. Improved performance will benefit both "frequency domain" applications, where the relative phase or "chirp" between comb components is unimportant (e.g. optical frequency metrology), as well as "time domain" applications where the pulse shape and/or duration is vital, such as in extreme nonlinear optical interactions [8]. For both types of applications, minimizing the jitter in the pulse train and noise in the carrier-envelope (CE) phase[1] is often critical to achieve the desired level of precision. In many metrological experiments, frequencies are counted with relatively long gate times (usually on the order of a second), allowing fast noise processes to average out. However, for many time domain applications, the requirement on the timing jitter and CE phase noise is more stringent owing to the large signal processing bandwidth. This provides strong motivation to further improve tools for ultrafast laser stabilization.

There are two degrees of freedom that must be controlled in order to stabilize ultrashort pulse trains. One way to express these requirements is in terms of the laser repetition frequency (f_{rep}) and the CE offset frequency (f_{ceo}), where $f_{rep} = v_g/l_c$ and $f_{ceo} = (\omega_c/2\pi)(1 - v_g/v_p)$. ω_c is the spectrally-weighted center frequency, l_c is the round-trip cavity length, and v_g (v_p) is the average group (phase) velocity inside the laser cavity. In a time domain representation, the pulse-to-pulse change in the CE phase is responsible for the offset frequency of the fs comb and can be expressed as $\Delta\phi = 2\pi\, f_{ceo} / f_{rep} = \omega_c\, l_c\, (1/ v_g - 1/ v_p)$. Understanding the dominant sources of noise in mode-locked lasers is important in determining the best choice of actuators and in optimizing servo designs for active stabilization. Like their single frequency counter-parts, mode-locked lasers are perturbed by mechanical and acoustic vibrations. However, because of the higher peak

[1] The CE phase can be defined as the phase difference between the peak of the electric field envelope of the pulse and that of the carrier frequency.

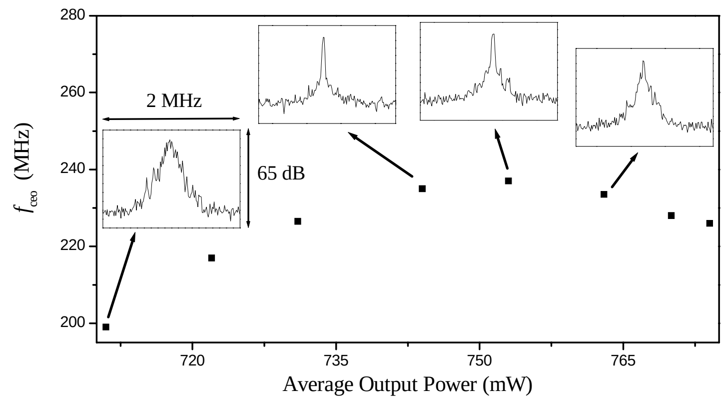

Fig. 1. Absolute value of f_{ceo} and its free-running linewidth (inset) versus average laser power.

intensities of femtosecond pulses and the dynamics of the mode-locking process itself, they are much more susceptible to frequency noise induced by pump amplitude fluctuations. We have investigated intensity-related dynamics in both f_{rep} and f_{ceo} for laser systems incorporating prism-based and/orchirped mirror dispersion compensation designs [9]. Previous work has attributed the dominant source of noise in the CE offset frequency to power fluctuations, explained in terms of spectral shifts [10], self-steepening, and nonlinear refraction [11]. Figure 1 shows the values of f_{ceo} measured with a spectrum analyzer as the average laser power is increased. The local slope of the curve (df_{ceo}/dI) determines the sensitivity of the CE offset frequency to intensity fluctuations. An interesting sign-reversal in the dependence of f_{ceo} on the laser power is observed, at which point df_{ceo}/dI goes to zero. It is at this point that the free-running linewidth (shown in insets) also reaches a minimum, indicating that fluctuations in the pump amplitude are the dominate source of perturbations of the CE phase. Simultaneously measuring the spectrum of the laser reveals that the intensity dependence of f_{ceo} is well accounted for by a corresponding shift of the laser pulse spectrum. This intensity-related spectral shift ($\partial \omega_c/\partial I$) reaches a minimum at the same point as df_{ceo}/dI. A coupling between spectral shifts and changes in f_{ceo} can be understood due to residual net cavity group-delay dispersion in mode-locked lasers: a slight change in the average frequency of the laser results in different group and phase velocities for the circulating intracavity pulse, thereby changing the value of f_{ceo}. We therefore find that in Ti:sapphire fs lasers with significant negative group delay dispersion (GDD), the dominant source of noise in f_{ceo} is due to power induced spectral shifts, in agreement with the findings of Xu et. al. [9]. This dependence is minimized with a decrease in the magnitude of the intensity dependent spectral shift and/or net cavity GDD, thereby minimizing the corresponding free-running linewidth of f_{ceo} and f_{rep}. An extremely broad bandwidth laser with near-zero net cavity GDD, such as that described by the dispersion-managed mode-locked model [12], is least susceptible to intensity fluctuations. In such cases other (smaller) noise mechanisms may dominate, and the use of power control to stabilize f_{ceo} may not be ideal. Actuators commonly used to stabilize femtosecond lasers are usually limited to ~50 kHz (piezoelectric translation) for control of the cavity length to ~100 kHz (modulation of the pump beam intensity via acousto-optic modulation) for control of the carrier and offset frequencies. Actuators with improved bandwidth are being pursued to improve stabilization performance.

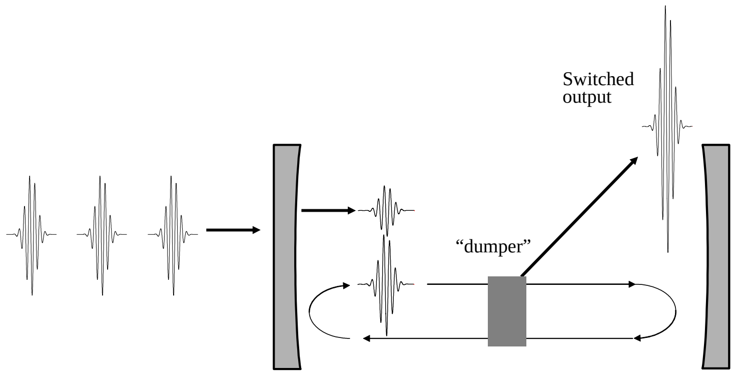

Fig. 2. Principle of coherent pulse amplification scheme with the aid of an optical cavity.

The ability to stabilize and precisely control an ultrashort pulse train opens up, among other things, opportunities for coherently coupling and enhancing ultrashort pulses in external high finesse optical cavities. A passive optical cavity can be used to coherently superpose and temporarily store sequential pulses from a mode-locked laser. The resulting intracavity pulse can be used for stabilization of femtosecond lasers [13], nonlinear frequency conversion [14], intracavity spectroscopy [15], and coherent pulse "amplification" [16, 17] when the cavity is equipped with a Bragg cell for pulse picking (see Fig. 2). This approach leads to an effective amplification process through decimation of the original pulse rate while preserving the original CE phase coherence from the oscillator. Unlike actively dumped laser systems, the pulse energy is not limited by the saturation of a gain medium or saturable absorber. Instead, the pulse energy can continue to build up inside the passive storage cavity until limited by scattering loss and dispersion. The use of a passive cavity also enables amplification of short pulses where no suitable active gain medium may exist, such as in pulse trains generated in the infrared from difference-frequency mixing [18] or in the UV from harmonic generation.

The maximum energy that can be stored in the cavity depends on the total cavity losses (*L)* and the transmission of the coupling mirror *(T)*. When the cavity modes are properly locked to the frequency comb of the incoming pulse train, the intra-cavity pulse amplification factor *N*, in the absence of dispersion effects, can be expressed as:

$$\boldsymbol{N} = \frac{4\boldsymbol{T}}{\boldsymbol{L}^2} = 4\boldsymbol{T}\left(\frac{\boldsymbol{F}}{2\pi}\right)^2$$

where *F* is the cavity finesse. Efficient intra-cavity pulse amplification results when the transmission of the input-coupling mirror matches that of the remaining cavity losses (impedance matching). In this case the intra-cavity enhancement reduces to $\boldsymbol{N} = \boldsymbol{F} / \pi$ and the maximum amplification is in theory limited only by the attainable cavity finesse one can achieve. In the picosecond (ps) enhancement cavity, losses are primarily introduced by scattering and/or absorption in the coupling mirror and Bragg cell. We have found that losses inside our Bragg

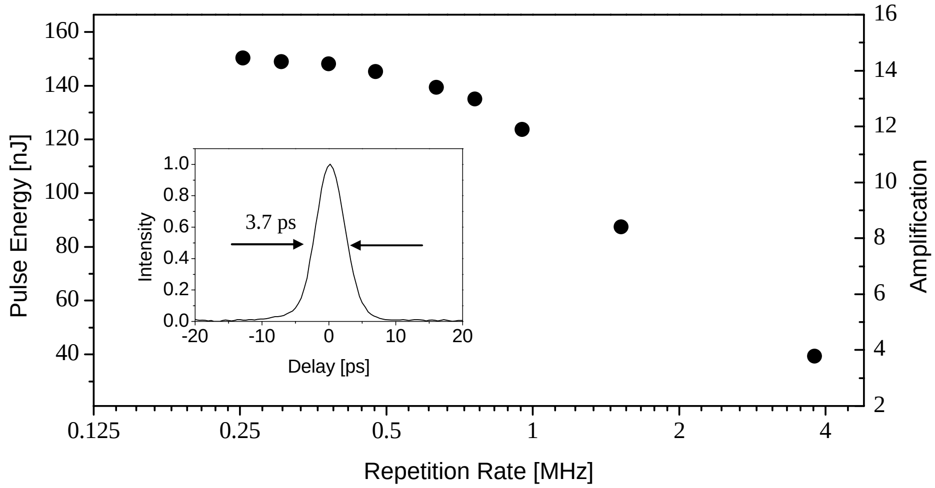

Fig. 3. Pulse energy from picosecond "amplifier" as a function of dumping rate. Input pulse energy is 10.4 nJ at 76 MHz. Coupling mirror has 2% transmission.

cell and at its faces are at least 0.2%, which could in principle be suppressed by selecting a higher quality cell with super polished surfaces.

Experimental results with ps pulses demonstrate pulse energies greater than that achievable by active cavity dumping of conventional oscillators. The use of ps pulses also allows us to separate out complications arising from intra-cavity dispersion. Results with ~3.7 ps pulse durations emitted from a mode-locked Ti:sapphire laser are shown in Fig. 3. Based on measurements of the intra-cavity energy build up, a finesse of 349 is estimated, limited most likely due to loss in the input coupler. Output pulse enhancements of 30 times are obtained at 253 kHz, yielding pulse energies greater than 150 nJ. The present pulse amplification is about three times better than what can be achieved by direct cavity dumping from a mode-locked laser while still maintaining relatively high repetition rates (hundreds of kilohertz). With optimization of the cavity finesse, we expect that amplifications greater than a hundred times are feasible, bringing pulse energies into the hundreds of microjoule to few millijoule ranges. This technique offers the additional practical benefits of being simple to implement with pre-existing commercial systems and delivering all the pulse energy in a filtered spatio-temporal mode.

To efficiently couple sub-100 femtosecond pulses into an optical cavity with a finesse sufficiently high to build up pulse energy by several orders, two key criteria must be met: (i) the carrier *and* repetition frequency of the fs laser must be simultaneously stabilized to that of the cavity, and (ii) the cavity dispersion must not severely distort the intracavity pulse. Stabilizing both degrees of freedom of the fs laser becomes increasingly important with shorter pulse durations. Preliminary work with 75 fs pulses reveal significant pulse distortion and spectral filtering when the net cavity group-delay dispersion is as little as +25 fs^2 , limiting the pulse enhancement from a possible 65 times to only 15 times the incident pulse energy. These preliminary results are in good agreement with independent numerical calculations predicting the observed transmission spectrum for a cavity with a net positive GDD of 25 fs^2. The next step will be to precisely adjust the cavity GDD to zero by lowering the cavity air pressure. This will allow us to efficiently couple the entire pulse spectrum into the external cavity and enhance the pulse distortion free. The amount of external cavity amplification and the minimum pulse duration achievable will crucially depend on the availability of low loss, broad bandwidth and dispersion tailored mirror technology.

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