Ultrafast-Laser Stabilization with Application to Pulse Amplification by Use of Passive Optical Cavities

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1 Introduction

Stabilization and control of the femtosecond laser is becoming increasingly important as novel applications utilizing the femtosecond comb are developed that require greater levels of precision. Improved stability is beneficial for both " "frequency domain" applications, where the relative quadratic phase between comb components, or "chirp", 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 nonlinear optical interactions [1]. For both types of applications, minimizing jitter in the pulse train and noise in the carrier-envelope (CE) phase is often critical to achieve the desired level of precision. The stabilization of mode-locked femtosecond lasers has played a key role in recent advances in optical frequency measurement [2, 3], carrier-envelope phase stabilization [4, 5], all-optical atomic clocks [6, 7] and coherent pulse synthesis [8]. Proper stabilization of ultrafast lasers can allow efficient coupling and temporary storage of ultrashort light pulses inside high finesse cavities [9]. This enables exciting possibilities for advancing external enhancement-cavity based techniques for short pulses, such as nonlinear frequency conversion [10], intracavity spectroscopy [11], and coherent pulse "amplification" [12, 13] to name a few. A highly stable cavity may even itself serve as a frequency and phase reference for the pulse train [14]. This provides strong motivation to further improve tools for ultrafast laser control. Here we describe efforts in both active stabilization of ultrafast lasers and in storing these pulses in high finesse passive cavities. Results are given for pulse amplification when the single intracavity pulse is switched out with a Brag cell acting as a cavity dumper.

2 Stabilization of femtosecond lasers

To tightly lock a fs laser to a high finesse cavity and take advantage of the high signal to noise ratio of the recovered resonance information requires optimizing high bandwidth servo designs. An understanding of the dominant sources of noise in mode-locked lasers is important in determining the best choice of actuators such that corrections can be made without introducing more noise in another parameter of the laser. Like their single frequency counter-parts, mode-locked lasers are perturbed by

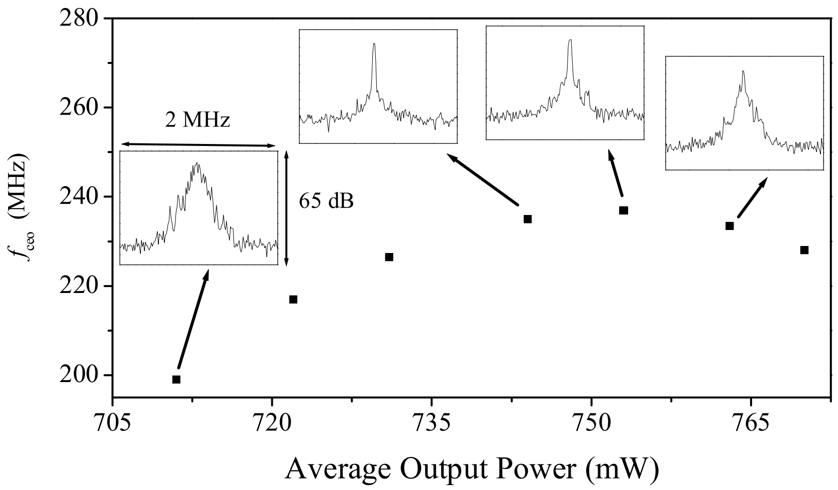

Fig. 1. Free-running linewidth of f_{ceo} near the turning point (i.e. $\Delta f_{ceo}/\Delta I \approx 0$) for the prism-less laser.

mechanical and acoustic vibrations. However, because of the higher peak intensities and the nonlinear amplitude-phase coupling, the mode-locked lasers are much more susceptible to frequency noise induced by pump amplitude fluctuations. Previous work has attributed the dominant source of noise in the CE offset frequency (f_{ceo}) to power fluctuations, explained in terms of spectral shifts [15], self-steepening, and nonlinear refraction [16]. We have investigated intensity-related dynamics in both the repetition rate (f_{rep}) and f_{ceo} for laser systems incorporating prism-based and chirped mirror dispersion compensation designs [17]. An interesting sign-reversal in the dependence of f_{rep} and f_{ceo} on the laser power is observed and found to correspond to a shift of the laser spectrum. The point of reversal also coincides with minimum free running noise of both f_{rep} and f_{ceo} (see Fig.1). We 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. [15]. 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 [20], 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.

3 External Cavity Amplification

An external passive optical cavity can be used to coherently superpose and temporarily store sequential pulses from a mode-locked laser. Equipped with a Bragg cell for cavity dumping, this approach can lead to an effective amplification process through decimation of the original pulse rate while preserving the overall coherence from the oscillator. 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]. Unlike actively dumped laser systems, pulse energy is not limited by saturation of the gain or the effective saturable absorber needed for stable mode-locking. Instead, the linear response of the external cavity allows pulse energy to build up until limited by scattering loss and dispersion. The technique is applied to picosecond and femtosecond pulses.

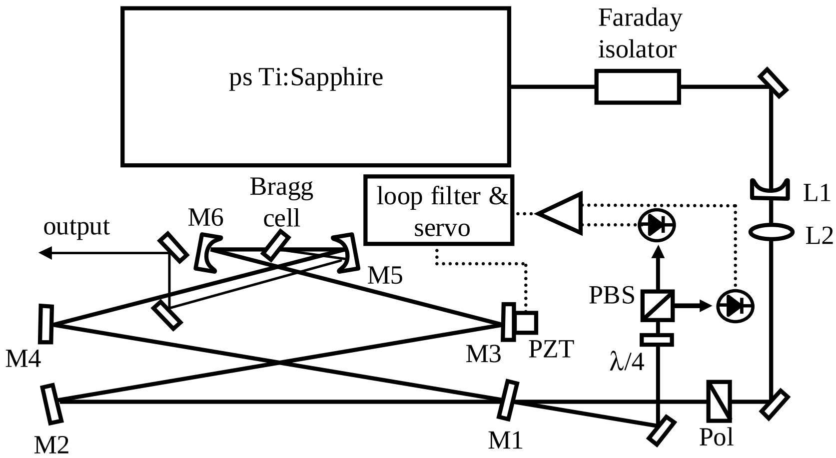

Fig. 2. Schematics of the passive optical amplifier. The Ti:sapphire laser is pumped by a 5W, 532 nm laser ; L1: Concave lens r = -75 mm; L2: Convex lens f = 125 mm; Pol: Polarizer; M1: output coupler 2% at 800 nm ; M2-M4: Low loss (¿ 30 ppm) high reflectors ; M5-M6: Low loss (>30 ppm) concave mirrors r = -100 mm ; Bragg cell: 3-mm fused silica cavity dumper; PBS: Polarizing beam splitter; $\lambda/4$: Quarter waveplate.

Initial experiments focused on amplification of ps pulses for immediate application in CARS microscopy. The use of ps pulses also allows us to separate out complications arising from intra-cavity dispersion and nonlinear effects from the higher peak intensities of femtosecond pulses. The layout of the amplifier is depicted in Fig. 2. The 835 nm output of a mode-locked 3.4-ps Ti:sapphire laser is fed into a six-mirror folded ring cavity. A mirror with 0.95% transmission is used as the coupling mirror. In order not to compromise the cavity finesse, all the other intra-cavity mirrors have reflectivity greater than 99.997%. The passive resonator incorporates a 3-mm fused silica Bragg cell placed under Brewster's angle, which acts as an acousto-optic cavity dumper. The FSR of the cavity is set to the 76 MHz repetition rate of the pump laser while the cavity resonances are actively locked to the average frequency of the laser. The error signal for the feedback loop is derived from the polarization sensitive detection scheme of Hänsch and Couillaud [19], and used to drive a PZT transducer attached to one of the cavity mirrors.

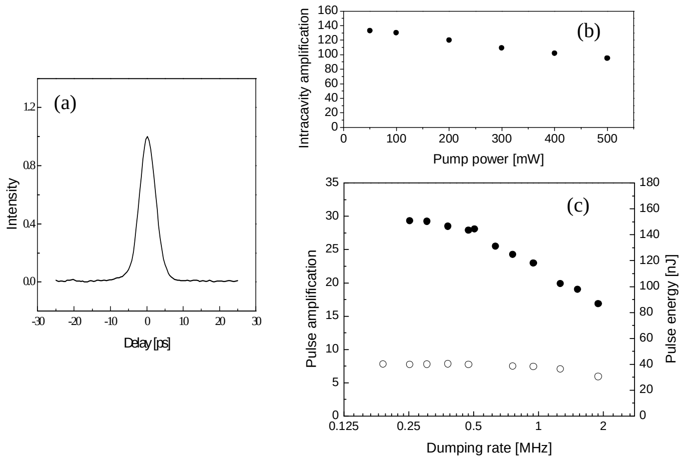

Fig. 3. Pulse amplification with the passive optical amplifier. a) Autocorrelation of 140 nJ amplified pulses at 475 kHz. Pulse width amounts to 3.4 ps, assuming a Gaussian envelope. b) Intra-cavity enhancement for various average powers of the incoming pulse train. c) Pulse amplification as a function of dumping frequency with single pass dumping efficiencies of 7.5% (open circles) and 30% (solid circles). Pulse energies (right axis) are obtained when seeding the amplifier with 400 mW from the Ti:sapphire laser. Note that dumping at frequencies beyond 2 MHz is limited by dumper electronics rather than by optical constraints.

Results with 3.4 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 μJ range. This technique offers the additional practical benefits of being simple to implement with pre-existing commercial systems and providing all the pulse energy in a filtered spatial 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, the carrier and repetition frequency of the fs laser must be simultaneously stabilized to that of the cavity [14], and cavity dispersion must not distort the intracavity pulse. Stabilizing both degrees of freedom of the fs laser becomes increasingly important with shorter pulse durations and longer cavity lifetimes.

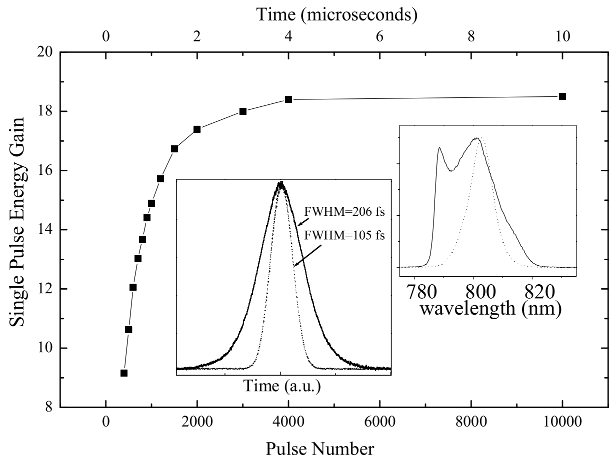

Fig. 4. External cavity amplification of single pulse energy versus number of pulses incident on cavity. Inset shows autocorrelation and spectrum of incident (dots) and dumped (solid) pulses.

Preliminary results in enhancing low individual pulse energies for ≈75 fs pulses are shown in Fig. 4. The external cavity setup is similar to that shown in Fig. 2. The external enhancement cavity used incorporated specially designed negative GDD low loss mirrors to simultaneously compensate for the Bragg cell's 3 mm of fused silica and provide a high finesse. The input coupling mirror transmission was ≈0.8 %. From the buildup time of the pulses, a finesse of 440 is determined. An intracavity energy buildup of 163 is therefore expected, resulting in a single pulse amplification of approximately 65 for the current setup, given the 40% dumping efficiency of our Bragg cell. The negative dispersion mirrors were designed to only partially compensate for the total cavity dispersion. The remaining cavity GDD was estimated at +20-30 fs^2. The excess dispersion results in pulse broadening and a nonuniform filtering of the transmitted pulse spectrum, as shown in the inset of Fig. 4. The experimental results are in good agreement with independent numerical calculations predicting the observed transmission spectrum for a cavity with a net positive GDD of 26 fs^2. The observed amplification of only 18 times is therefore not surprising as the achievable pulse enhancement is limited by the lack of perfect resonance between the fs comb and the external cavity. Reducing the net cavity GDD by lowering the cavity air pressure 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 minimum pulse duration achievable will crucially depend on the availability of low loss, broad bandwidth and dispersion tailored mirror technology.

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