TuC2.4 (Invited)
11:30 am – 12:00 pm

Femtosecond Laser Stabilization: Time and Frequency Domain Applications

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Abstract: Reducing noise in femtosecond laser systems becomes increasingly important as new applications are developed demanding improved levels of performance. Current stabilization techniques and applications from frequency metrology to coherent pulse synchronization will be discussed.

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 modes of the femtosecond laser becomes increasingly important as novel applications utilizing the fs comb are developed demanding 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 is often critical to achieve the desired level 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 coherent interactions between two pulse trains, or between one pulse train and an atomic ensemble, the timing jitter and CE phase of each pulse needs to be well defined. This provides strong motivation to further improve tools for ultrafast laser stabilization.

Understanding the dominant sources of noise in mode-locked lasers is important in determining the best choice of actuators and 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 intensities, they 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 [9], self-steepening, and nonlinear refraction [10]. In this work experimental investigations of intensity-related dynamics in both the repetition rate (f_{rep}) and f_{ceo} are investigated. An interesting sign-reversal in the dependence of f_{rep} and f_{ceo} on the laser power is observed. These dynamics are well accounted for by a corresponding shift of the laser pulse spectrum. Mode-locking conditions can be found under which the intensity-related spectral shift is minimized, leading to minimum noise of both f_{rep} and f_{ceo}. This understanding has implications on the optimal use of power control for the femtosecond laser. The actuators commonly used to stabilize femtosecond lasers are usually limited to ~50 kHz (piezoelectric translation) for control of the cavity length to ~200 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.

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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 [11], nonlinear frequency conversion [12], intracavity spectroscopy [13], and coherent pulse "amplification" [14, 15]. 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 [16] or in the UV from harmonic generation. 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 technique is applied to picosecond and femtosecond pulses. Experimental results demonstrate pulse energies greater than that achievable by active cavity dumping of conventional oscillators. Requirements for coupling pulse trains into high finesse cavities and detailed calculations showing the limiting effects of intra-cavity dispersion will be given. Investigations of broadband, dispersion compensated high finesse mirror coatings needed for these applications will also be presented. Novel experiments utilizing mode-locked pulse trains locked to high finesse cavities will be discussed.

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