MERGING TWO INDEPENDENT FEMTOSECOND LASERS INTO ONE

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Two independent mode-locked femtosecond lasers are synchronized and phase-locked to an unprecedented precision. The timing jitter between the two fs lasers is less than 5 fs rms, observed within a 160-Hz bandwidth over minutes. The beat frequency between the two synchronized fs lasers has a standard deviation of 0.15 Hz at 1-s averaging time under phase-locked conditions. Coherence between the two lasers is demonstrated via spectral interferometry and second order field cross-correlation when the two fs lasers are tightly synchronized and phase-locked. The auto-correlation measurement of the combined pulse reveals a narrower and larger amplitude "synthesized' pulse.

1 Introduction

Precision control of CW laser light in the frequency domain has been a prominent area for atomic, molecular, solid-state physics and fundamental measurements in physics. It has improved spectral resolution to the sub-Hertz level and the detection sensitivity of weak absorption to the $< 10^{-12}$ level. In recent years, the precision control of the repetition rate and phase of femtosecond lasers has improved so much that the fs laser comb has became a superior technique [1-4] for optical frequency metrology, carrier-envelope phase control and for implementing an optical clock. Many exciting areas of current research stimulate us to make greater efforts to synchronize and phase lock two independent femtosecond lasers. For example, one exciting field is "coherent control". Light pulses that have been precisely shaped in amplitude and phase can selectively "drive" a chemical reaction [5,6], molecular vibration [7], or other process such as the nonlinear-optical conversion of light into the extreme ultraviolet region of the spectrum [8]. Often the quantum transitions for a process of interest in coherent control are concentrated in a few disparate regions of the spectrum. In this case, it would be desirable to be able take two separate laser systems, generating light with distinct optical properties, and precisely synchronize the output of both lasers, essentially generating a single, composite coherent light field from two separate sources. Clearly, the ability to precisely synchronize separate pulsed laser sources is an important step in the road toward the ultimate, 'arbitrary light wave-form generator'. It is also important for a number of other technologies, such as mid-infrared light generation through difference frequency mixing, and for experiments requiring synchronized laser light and x-rays or electron beams.

To date, previous work in synchronizing separate mode-locked Ti:Sapphire lasers has demonstrated a timing jitter of at best a few hundred femtoseconds (fs) [9]. In addition, to our knowledge, there has been no report of phase locking between two separate fs lasers. In this paper, we demonstrate robust synchronization of pulse trains from two separate fs lasers, with a timing jitter of < 5 fs, at a bandwidth of 160 Hz, observed over an interval of one minute. Due to our precision synchronization of two independent fs lasers, we are now able to tightly phase lock the two lasers to each other. Measuring the beat frequency between two fs lasers gives us a standard deviation of 0.15 Hz at 1-s averaging time. Coherence between the two lasers is demonstrated via spectral interferometry and second order field cross-correlation when the two fs lasers are tightly synchronized and phase-locked. The auto-correlation measurement of the combined pulse reveals the "synthesized" pulse to be narrower and of larger amplitude.

2 Experimental setup and results

The experimental configuration is shown in Figure 1. Two independent mode-locked Ti:Sapphire lasers operate at 760 nm and 810 nm respectively [10], with ~ 100 MHz repetition rates. Two separate pump lasers are used. Our synchronization and phase-locking setup employs two high-speed photo-diodes to detect the two pulse trains from their respective lasers. There are four phase locked loops (PLL) in the system that establish synchronization and phase locking between the two fs lasers. We synchronize the repetition rate of laser #1 to a stable RF source using the first PLL, while laser #2 is synchronized to laser #1 using a second PLL. This second PLL compares and locks the fundamental frequencies of the two lasers at 100 MHz. The phase shift between the two 100 MHz signals can be used to control the timing offset between the two pulse trains. The third PLL at 8 GHz compares the phases of the 80th harmonics of the two repetition frequencies. When the two pulse trains are nearly overlapped, the third PLL at 8 GHz is gradually activated while the second PLL at 100 MHz is gradually deactivated. This represents an electronic realization of a "differential micrometer" -- the 100 MHz loop provides the full dynamic range of timing offset between two pulse trains, while the 8 GHz loop produces enhanced phase stability of the repetition frequency. The two PLL loops at 8 GHz actuate fast piezo-transducers (PZT) mounted to the laser end-mirrors. We use a combination of a fast, small PZT and a slow, long PZT to achieve a high servo bandwidth (> 50 KHz) and a large tuning range. To further characterize the timing jitter of our system, we focus the two pulse trains so that they can cross in a 500 micrometer thick, room temperature, BBO crystal for nonlinear frequency generation (Type-I). When the two pulses are overlapped in space and time, sum frequency generation (SFG) is enabled. We can thus use the

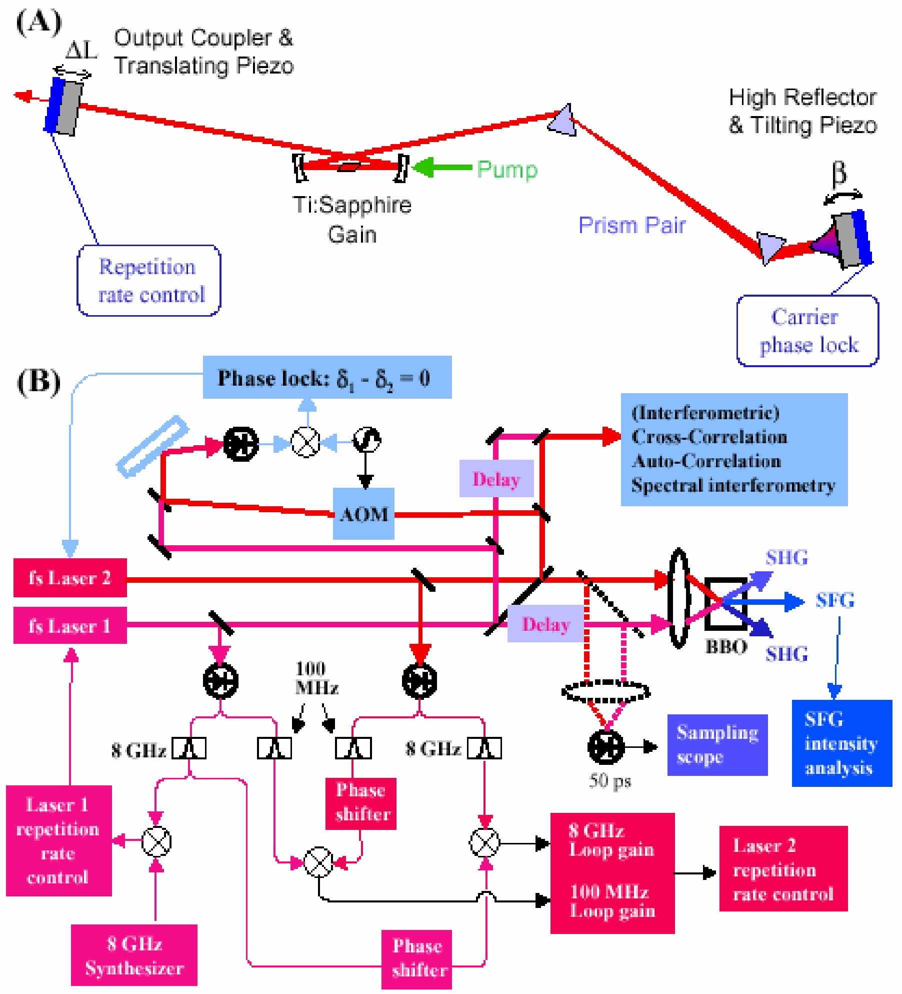

Figure 1. Experimental setup for timing synchronization and phase locking of two fs lasers. (A) Femtosecond laser and its control elements. (B) The phase locked loops for synchronization, along with the signal analysis scheme. Another phase locked loop is used to track the two carrier frequencies.

SFG intensity as a diagnostic tool to study our system performance. The SFG intensity fluctuation is proportional to the timing jitter, particularly when the two pulses are offset in time by ~ ½ the pulse width. Using this method, the timing jitter between the two independent fs lasers is estimated to be 4.3 fs rms observed within a 160 Hz bandwidth [11]. When the two lasers are well synchronized and phase shift in the synchronization lock loop is adjusted to have the two pulses optimally overlapped temporally at the heterodyne detection to produce the maximum beat signal, the beat between the two corresponding sets of combs can be recovered with a signal-to-noise ratio (*S/N*) of 60 dB in a 100 kHz bandwidth. The beat detection effectively measures the difference in the offset frequency between two fs combs. By stabilizing the beat frequency to a mean value of zero Hertz, the carrier-envelop phase evolution dynamics of one laser will be closely matched by the second laser. Locking of this beat frequency to zero Hz can be conveniently implemented using an acousto-optic modulator (AOM). One laser beam passes through the AOM, picking up the AOM's frequency offset. The beat is then phase locked to the AOM's drive frequency, effectively removing the AOM frequency from the beat. Measuring the beat frequency gives us a standard deviation of 0.15 Hz with an averaging time of 1-s [12]. When the phase lock loop is not active, the standard deviation goes up to a few MHz. When the two independent fs lasers are synchronized and phase locked, the coherent effects between the two fs lasers are clearly observed by the techniques of cross-correlation, auto-correlation, and spectral interferometry [12]. The auto-correlation measurement of the combined pulses reveals a narrower and larger amplitude "synthesized" pulse. This work represents a new and flexible approach to the synthesis of coherent light.

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