Control of relative carrier-envelope phase slip in femtosecond Ti:sapphire and Cr:forsterite lasers

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We were able to control relative carrier-envelope phase slip among mode-locked Ti:sapphire and Cr:forsterite lasers by employing electronic feedback. The pulse timings of these lasers were passively synchronized with our crossing-beam technique. Since the optical-frequency ratio of Ti:sapphire and Cr:forsterite is approximately 3:2, we can observe the phase relation by superimposing the third harmonic of Cr:forsterite and the second harmonic of Ti:sapphire lasers in time and in space. The spectrum width of the locked beat note was less than 3 kHz, which corresponds to the controlled fluctuation of a cavity-length difference of less than 10 pm.

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Remarkable progress has been made in measuring and controlling the carrier-envelope offset (CEO) phase in Ti:sapphire (TiS) laser oscillators[1-3] and optical parametric oscillators.[4] The CEO phase between two TiS oscillator has also been controlled, and coherent superposition of two independent TiS lasers has been demonstrated.[5] As a time-domain application, control of the CEO phase could be used for dealing with optical-phase-sensitive phenomena such as multiphoton ionization[6] and generation of high-order harmonics.[7,8] If the CEO phases of two pulses generated from different kinds of mode-locked laser are controlled, the lasers will yield attosecond pulse generation in the visible and infrared regions by Fourier synthesis.[9] The CEO-phase relation between mode-locked TiS and erbium-doped fiber laser was controlled very recently.[10] As a frequency-domain application, the CEO phase control is useful for high-precision measurements and metrology.[11] Controlling the CEO phase between two-color lasers will generate an ultrawide frequency comb. A passively synchronized laser constructed from mode-locked TiS and Cr:forsterite (CrF) lasers[12] is an attractive candidate for a CEO-phase-controlled, multicolor femtosecond system. Such a laser generated synchronized pulse trains with very low timing jitter of less than 1 fs.[13] In addition, a synchronized laser exhibited a simple CEO-phase-relation dependence for each cavity length.[14]

In this Letter we report that we have controlled the relative CEO phase among femtosecond TiS laser pulses and CrF laser pulses generated by a dual-wavelength synchronized laser. The controlled beat signal has a spectrum width of less than 3 kHz, corresponding to a relative cavity-length difference of 10 pm.

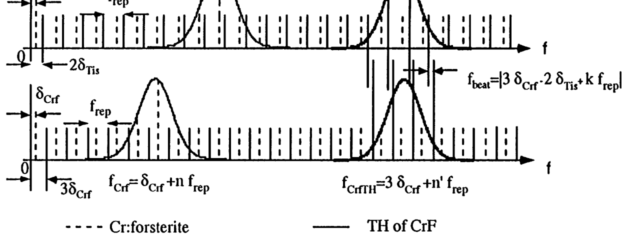

Fig. 1. Schematic of beat measurement in frequency-domain space. Dashed lines, combs of the TiS and CrF pulses; solid lines, combs of the SH of the TiS and the TH of the CrF pulses. The optical-frequency differences (beat frequencies) among the SH of the TiS pulses and the TH of the CrF pulse are $|3\delta_{\mathrm{CrF}} - 2\delta_{\mathrm{TiS}}|$, $|3\delta_{\mathrm{CrF}} - 2\delta_{\mathrm{TiS}} - f_{\mathrm{rep}}|$, $|3\delta_{\mathrm{CrF}} - 2\delta_{\mathrm{TiS}} + f_{\mathrm{rep}}|$, ...

Figure 1 illustrates schematically how to measure the phase relation among TiS and CrF pulses. The comb spacings of TiS and CrF lasers are identical because the two lasers are passively synchronized. The center wavelengths of TiS and CrF lasers are 830 and 1245 nm, respectively. In this case, we can acquire phase-relation information by using the second harmonic (SH) of the TiS laser and the third harmonic (TH) of the CrF laser, because their spectra overlap at 415 nm. The comb frequencies of the TiS and CrF pulses can be defined as $f_{\mathrm{TiS}} = \delta_{\mathrm{TiS}} + mf_{\mathrm{rep}}$ and $f_{\mathrm{CrF}} = \delta_{\mathrm{CrF}} + nf_{\mathrm{rep}}$, respectively, where δ_{TiS} and δ_{CrF} are the offset frequencies of TiS and CrF pulses, respectively, f_{rep} is the repetition frequency, and m and n are integers. The comb frequency of the SH of the TiS (f_{TiSSH}) is $f_{\mathrm{TiSSH}} = 2\delta_{\mathrm{TiS}} + m'f_{\mathrm{rep}}$, and the comb frequency of the TH of the CrF laser (f_{CrFTH}) is $f_{\mathrm{CrFTH}} = 3\delta_{\mathrm{CrF}} + n'f_{\mathrm{rep}}$, where m' and n' are integers. Thus, all observable beat frequencies (f_{beat}) generated by the SH of a TiS laser and the TH of a CrF laser can be expressed as $f_{\mathrm{beat}} = |(3\delta_{\mathrm{CrF}} - 2\delta_{\mathrm{TiS}}) + kf_{\mathrm{rep}}|$, where k is an integer. When the cavity-length difference between TiS and CrF laser oscillators (Δl) changes within the synchronization region ($\sim 3\ \mu\mathrm{m}$), the difference in the offset frequencies between the TiS and CrF lasers changes

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because the repetition frequencies (comb spacing) are passively fixed. The beat-frequency shift, Δf_{beat}, versus Δl can also be expressed as $\Delta f_{\text{beat}} = 4|\Delta l|/\lambda_{\text{TiS}} \times f_{\text{rep}}$, where λ_{TiS} is the TiS wavelength. This linear relation has been experimentally confirmed.[14] Thus, we can control the beat frequency by tuning the cavity-length difference between the TiS and CrF lasers. Because the offset frequency (δ) and the CEO-phase slip in successive pulses ($\Delta\Phi$) are related by $\Delta\Phi = 2\pi\delta/f_{\text{rep}}$, controlling the relative offset frequencies corresponds to controlling the relative CEO-phase slip, $3\Delta\Phi_{\text{CrF}} - 2\Delta\Phi_{\text{TiS}}$. Thus, we can control the relative CEO phase by tuning the cavity length.

Note that one should control both $\Delta\Phi_{\text{CrF}}$ and $\Delta\Phi_{\text{TiS}}$ into dc at the same time to realize an ideal field synthesis that is fixed to the pulse envelope. However, we consider it worthwhile to lock f_{beat} to some subharmonic frequency of the repetition frequency. When the relative offset frequency f_{beat} is locked to 1/4 of the repetition frequency, the relative phase, $3\Delta\Phi_{\text{CrF}} - 2\Delta\Phi_{\text{TiS}}$, is recovered every four pulses. We can then implement a time-domain application such as coherent superposition with appropriate pulse slicing,[4] although the synthesized field will slip in the pulse envelope. This slip will be controlled by application of a technique similar to the one used to control $\Delta\Phi_{\text{TiS}}$.

Figure 2 is a schematic of the experimental setup. A dual-wavelength laser[12] produces synchronized femtosecond TiS and CrF pulses. The optical paths of TiS and CrF pulses overlap in a TiS crystal, and a four-wave mixing process in the crystal passively locks the pulse timing. The TiS and CrF lasers output 450 and 200 mW, respectively, at a 75.4-MHz repetition frequency. The TH of the CrF laser and the SH of the TiS laser are superimposed in time and space and detected by a photomultiplier tube (Hamamatsu H6780-06). A photodiode with a bandpass filter detects the repetition frequency, f_{rep}. The reference frequency is produced by division of f_{rep} by 4. The beat signal is measured by a spectrum analyzer (Agilent E4401B). The beat frequency is compared with the reference frequency by a digital phase-frequency comparator. The displacement of the end mirror in the TiS laser cavity can be changed by a piezoelectric transducer (PZT) in accordance with the error signal produced by the comparator. When the position of the end mirror moves 0.21 μm, the beat frequency changes by 75.4 MHz. The error signal also changes the pump power of the TiS laser through an electro-optical modulator (EOM) that can also shift the beat frequency.

The signal-to-noise ratio of the obtained beat signal is ~30 dB for a 100-kHz resolution bandwidth (RBW). Without feedback, the beat frequency slowly fluctuates within a 10-MHz range because of mechanical vibrations or air turbulence, although the dual-wavelength laser is covered to prevent air flow. The frequency fluctuation corresponds to the initial cavity-length fluctuation of ~30 nm. Figure 3 depicts the rf power spectrum when the beat frequency is locked to $f_{\text{rep}}/4 = 18.8$ MHz. The RBW is 100 kHz, and more than 100 scans are averaged. The strong peak near 75.4 MHz represents the repetition frequency. The signal at 18.8 MHz ($1/4\, f_{\text{rep}}$) represents the locked beat. The beat signal also appears at 75.4–18.8 MHz ($3/4\, f_{\text{rep}}$) and 75.4 + 18.8 MHz ($5/4\, f_{\text{rep}}$). Figure 4 illustrates the beat signal at 18.8 MHz locked by only a PZT (averaged 100 times). The RBW is 10 kHz. The spectrum width of the locked beat signal is ~100 kHz. The bandwidth of the feedback loop provided by the PZT is ~3 kHz because the power spectrum of the error signal is suppressed at frequencies below 3 kHz (inset of Fig. 4). Thus, one must control the beat frequency with an EOM to compensate for the cavity fluctuation with higher speed. Figure 5 shows the beat note at 75.4–18.8 MHz with an 800 kHz span, obtained by use of both the PZT and the EOM. The RBW is 3 kHz, and more than 10 scans are averaged. The spectrum width of the locked beat is 3 kHz (approximately the RBW), which corresponds to a cavity-length fluctuation of less than 10 pm. Sidebands 100 kHz from the beat signal in Fig. 5 are observed when the gain for the EOM is high. We can then roughly estimate the bandwidth of total feedback loop to be ~100 kHz. The locking can be maintained for more than 1 h.

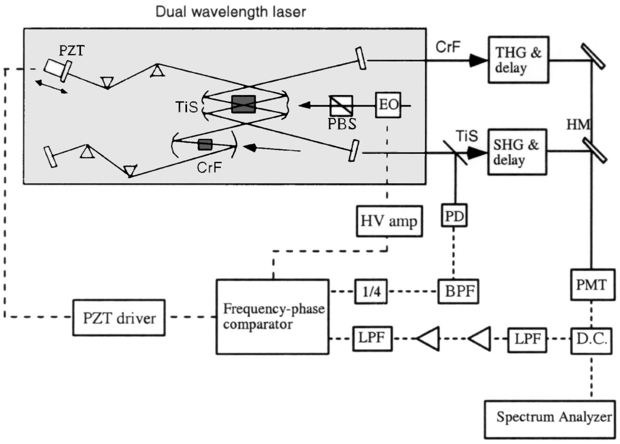

Fig. 2. Experimental setup: solid lines, optical paths; dashed lines, electrical paths. PD, p-i-n photodiode; LPFs, low-pass filters; BPF, bandpass filter; 1/4, frequency divider; HM, half-mirror; D.C., directional coupler; PBS, polarized beam splitter; HV amp, high-voltage amplifier; THG, third-harmonic generation; SHG, second-harmonic generation. Other abbreviations defined in text.

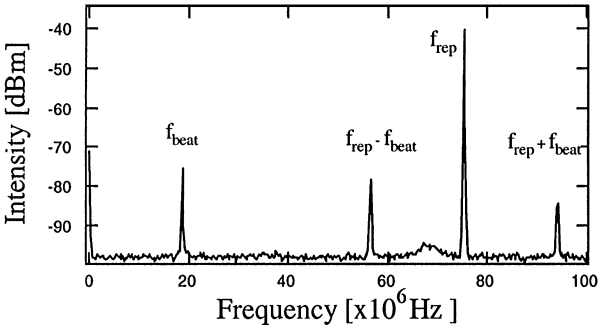

Fig. 3. rf power spectrum of a combined frequency-doubled TiS laser and a frequency-tripled CrF laser in a 100-MHz span.

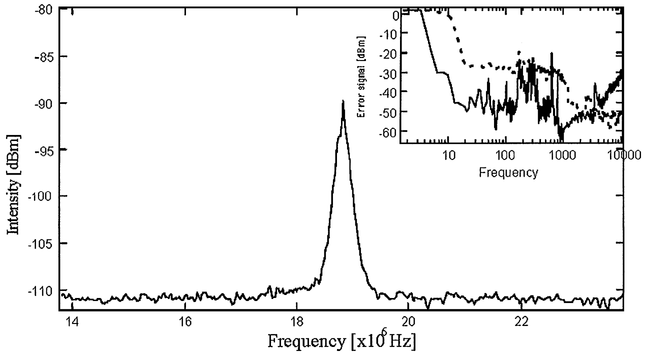

Fig. 4. Beat signal locked by only PZT in a 10-MHz span. The RBW is 10 kHz, and 100 traces are averaged. The spectrum width of the locked beat is ~100 kHz. Inset, power spectrum of the error signal with (solid curve) and without (dashed curve) feedback.

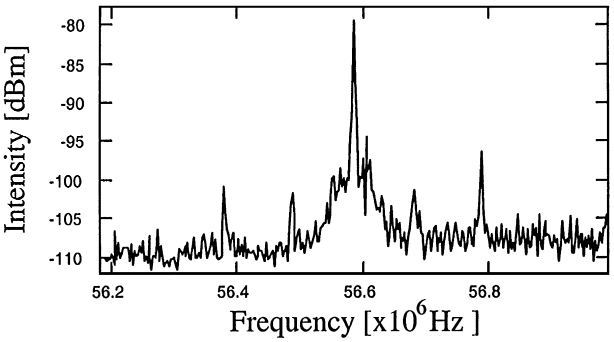

Fig. 5. rf power spectrum of the locked beat ($f_{\mathrm{beat}} = 3/4\, f_{\mathrm{rep}}$) over a 10-trace average in a 0.8-MHz span. The data acquisition time is ~2 s. The spectrum bandwidth is 3 kHz (RBW).

In this study the optical-phase relation between TiS and CrF pulses is fixed every four pulses because the beat frequency is locked to 1/4 of the repetition frequency. If a 75.4-MHz pulse train is converted to an 18.8-MHz pulse train (if one of every four pulses is selected) by a single-pulse selector, the phase relation between TiS and CrF pulses will be fixed within a coherent time. To estimate the CEO-phase variation between two lasers, one has to measure the power spectrum density of the beat signal. Although we do not have sufficient data on the fluctuation dynamics to evaluate the coherent time, the inverse of the spectrum width of the locked beat represents the lower limit of the coherent time. The obtained 3-kHz bandwidth of the beat signal suggests the feasibility of a phase-dependent, multicolor experiment using many pulses of an 18.8-MHz pulse train. In practice, the beat-locking performance, including the bandwidth of the beat, is limited by the initial cavity-length fluctuation, the signal-to-noise ratio, the gain of the feedback loop, and the bandwidth of the feedback system. Improving these factors would enable us to realize Fourier synthesis with a much longer coherence time.

In conclusion, we have measured and controlled the relative CEO-phase slip among mode-locked femtosecond TiS and CrF lasers. To our knowledge, this is the first demonstration of relative CEO phase control among independent two-color laser pulses that have no spectrum overlap. Such phase-controlled light sources are useful for coherent synthesis because the optical-frequency ratio of TiS and CrF pulses is 3:2, and it is easy to generate the sum frequency and each SH. This technique will facilitate realization of optical Fourier synthesis with multicolor femtosecond lasers.

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