Relative carrier-envelope phase dynamics between passively synchronized Ti:sapphire and Cr:forsterite lasers

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We observed and measured the relative carrier-envelope phase difference per round trip between synchronized femtosecond Ti:sapphire and Cr:forsterite mode-locked lasers. The relative carrier-envelope phase slip was directly recorded by heterodyning of the Cr:forsterite laser with the supercontinuum from the Ti:sapphire laser. We also obtained another phase relation by superimposing the third harmonic of the Cr:forsterite laser with the second harmonic of the Ti:sapphire laser. In the latter case we obtained a stable beat signal with a signal-to-noise ratio larger than 30 dB and found a dependence of the beat frequency on the cavity length. © 2002 Optical Society of America

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The technique of carrier-phase control recently became a prominent scientific theme in research on solid-state femtosecond lasers. Since Xu *et al.*[1] observed a round-trip phase slipping in a mode-locked Ti:sapphire laser and Telle *et al.*[2] proposed methods of measuring the carrier-envelope offset (CEO) phase, remarkable progress has been made in measuring and controlling the CEO of femtosecond lasers. Self-referencing techniques were successfully used by several groups[3,4] to lock the CEO, which resulted in unprecedented achievements in both optical frequency metrology and ultrafast laser science. More recently, Shelton *et al.*[5] generated a coherently synthesized optical pulse based on two synchronized and phase-locked Ti:sapphire lasers, and Kobayashi and Torizuka[6] measured and stabilized the phase relation among the subharmonics generated by a femtosecond optical parametric oscillator. These rapid developments may make possible optical clocks and generation of attosecond single-cycle pulses.

We developed a passive synchronized dual-wavelength laser based on cross-phase modulation between Ti:sapphire and Cr:forsterite lasers.[7] Stable two-color femtosecond pulses near the central wavelengths of 820 and 1250 nm were obtained. Compared with the conventional schemes of optical parametric oscillators and synchronized Ti:sapphire lasers, our design not only generates wavelengths with related subharmonics but has also shown superior robustness and subfemtosecond timing jitter,[8] which enable us to pursue attosecond single-cycle pulses and an ultrabroad optical frequency comb by coherent subharmonic synthesis in a more feasible way. For this purpose, the carrier phase between the Ti:sapphire and Cr:forsterite lasers must be measured and controlled.

In this Letter we present the observation and measurement of relative carrier-envelope phase difference per round trip between Ti:sapphire and Cr:forsterite lasers within the synchronized regime. The laser layout is basically the same as in our recent improved experiment.[9] To observe the relative carrier-phase slipping we used two approaches. One approach is beat measurement by injection of the Ti:sapphire laser into a photonic crystal fiber (PCF).[10] The other approach is beat measurement using nonlinear optical crystals; a similar technique was used by Morgner *et al.* in the beat measurement of a Ti:sapphire laser.[11] In our case, we heterodyned the second harmonic (SH) of the Ti:sapphire laser with the third harmonic (TH) of the Cr:forsterite laser.

Our first approach is similar to the standard technique for a single femtosecond laser that converts the carrier phase into the beat frequency by using a supercontinuum with a bandwidth of more than one octave[4]; the experimental setup is shown in Fig. 1(a). To heterodyne both lasers we injected the Ti:sapphire laser into a 25-cm-long PCF with a core diameter of 1.8 μm to broaden the spectrum to cover the wavelength 1250 nm. After the delay line, M1–M3, for the Cr:forsterite laser we carefully superimposed both lasers by use of a metal beam splitter (PSCH, Sigma KOKI). Following a long-pass optical filter and a lens, an infrared p-i-n diode and a spectrum analyzer

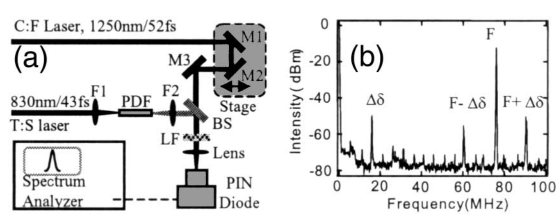

Fig. 1. (a) Experimental setup for heterodyning the Cr:forsterite (C:F) laser with the continuum from the Ti:sapphire (T:S) laser: PDF, 25-cm PCF with a 1.8-μm core diameter; F1, F2, 40× objective lenses; BS, metal beam splitter; LF, optical filter. M1–M3, gold mirrors. (b) Observed beat signal.

(Hewlett-Packard HP-8563E) were used to detect the beat signals. Figure 1(b) shows the typical beat spectrum with a log vertical axis scale; the resolution bandwidth is 100 kHz, and the sweep time is 50 ms.

A femtosecond laser can be described as a comb of optical frequencies separated by the repetition rate, F, in the frequency domain. The time–frequency relation between the offset frequency, δ, and the carrier phase slip, $\Delta\phi$, in the successive pulses has been well discussed and corresponds to $\Delta\phi = 2\pi\delta/F$. For our synchronized two-color lasers, the frequencies of the Ti:sapphire and Cr:forsterite lasers can be written as $f_{\mathrm{TS}} = \delta_1 + mF$ and $f_{\mathrm{CF}} = \delta_2 + nF$, respectively. Therefore, the component of the supercontinuum near 1250 nm will be $f_{\mathrm{SC}} = \delta_1 + n'F$, where δ_1 and δ_2 are the offset frequencies ($\delta_1, \delta_2 < F$) and m, n, and n' are integer numbers ($\sim 10^6$) with the approximate relations of $m{:}n \sim 3{:}2$ and $n \sim n'$. The supercontinuum mixed with the Cr:forsterite laser will yield the heterodyne beat $f = \pm(kF + \Delta\delta)$, where $k = n - n'$ and $\Delta\delta = \delta_2 - \delta_1$. Obviously, beside the peak frequency F near 75 MHz the other three signals in Fig. 1(b) correspond to the beat frequencies $\Delta\delta$, $F - \Delta\delta$, and $F + \Delta\delta$, respectively. Although $\Delta\delta$ directly reflects the carrier-phase relation between two lasers, unfortunately the observed beat signal with this approach showed worse stability and a lower signal-to-noise ratio. We think the possible reasons for this may be the weak component the of PCF-generated spectrum near 1250 nm and air fluctuation near the PCF. For these problems, we further measured the beat frequency and the relative carrier-envelope phase dynamics with the second approach described above. A schematic of the experiment setup is shown in Fig. 2; a detailed description is given below.

To generate a TH from the Cr:forsterite laser efficiently we improved the output power to 210 mW by increasing the pump to 9.5 W and replacing the output coupler with 4% transmission. By optimizing the orientation of C1, we first obtained 8-mW SH power from the Cr:forsterite laser. After separating the SH from the fundamental wave with a dichroic mirror and passing it through a delay stage, we then noncollinearly focused both the 625- and the 1250-nm lasers into C2 to produce a TH laser. To match the polarization of the Ti:sapphire laser we set the nonlinear process at type II phase matching ($o + e \rightarrow e$), and a TH laser with submilliwatt power was generated by fine adjustment of the crystal orientation and the spatial and temporal overlap inside the BBO crystals. Finally, an aperture was used to block both the fundamental and the SH waves but pass the blue TH laser.

The Ti:sapphire laser was directly frequency doubled with crystal C3 after the laser was passed through another delay stage. A blue SH laser with similar wavelength and intensity as the TH of the Cr:forsterite laser was generated with the simple setup. Based on the harmonics, we used the same beam splitter to superimpose both the SH and the TH for spatial overlap. Unlike with the first approach presented above, we blocked the remaining longer wavelength with a short-pass optical filter and detected the beat signal with a fast photomultiplier (Hamamatsu Photonics H6780). By optimizing the temporal overlap with the second delay stage, we observed a stable beat spectrum with a signal-to-noise ratio of 30 dB, as shown in Fig. 3, which corresponds to a beat frequency of $f = \pm(lF + \Delta\delta^*)$ if we define $l = 3n - 2m$ and $\Delta\delta^* = 3\delta_2 - 2\delta_1$. Although $\Delta\delta^*$ does not directly reveal the offset frequency difference between the two lasers as in the first approach discussed above, it still supplies a kind of mutual relation between the carrier-envelope phases of two lasers. Unlike the CEO measurement in the single Ti:sapphire laser, the beat signal, $\Delta\delta^*$, observed in this experiment was very sensitive to random fluctuation of two cavity lengths. For example, the beat signal in Fig. 3 fluctuated within a bandwidth of 10 MHz. Based on self-referencing techniques for controlling the carrier-envelope phase slip in a single laser, further locking $\Delta\delta^*$ at given value will enable us to generate a new coherently synthesized optical pulse and a wide frequency comb.

The mutual relation of the carrier-envelope phase slip between the Ti:sapphire and Cr:forsterite lasers can be directly derived from the beat frequency. For the measurement in the second approach, we can define the relative phase slip $\Delta\Phi$ after one round trip as

$$\Delta\Phi = 3\Delta\phi_2 - 2\Delta\phi_1 = 2\pi\Delta\delta^*/F\,, \qquad (1)$$

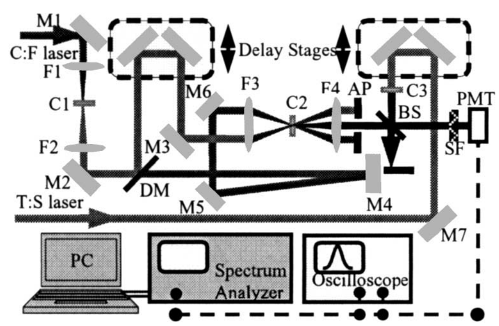

Fig. 2. Schematic of beat signal measurement with nonlinear optical crystals: M1–M7, gold-coated mirrors; F1–F4, $f = 100$ mm focus lens; C1–C3, 1-mm-thick BBO crystals cut to $\theta = 29°$ (C1 and C3 are type I for the SHGs of 1250 and 830 nm, respectively; C2 is type II for the THG of 1250 nm); DM, dichroic mirror coated for high transmission (600 nm) and high reflection (1250 nm); AP, aperture; BS, metal beam splitter with $R \sim T \approx 40\%$; SF, optical filter; PMT, photomultiplier.

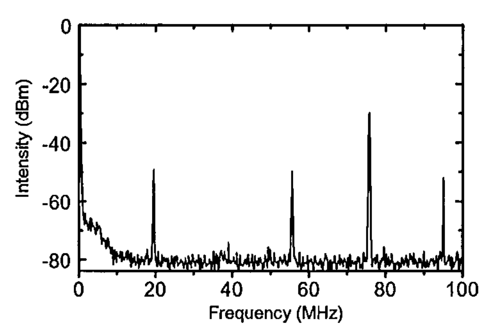

Fig. 3. Frequency spectrum obtained by heterodyning of the SH of the Ti:sapphire laser with the TH of Cr:forsterite lasers.

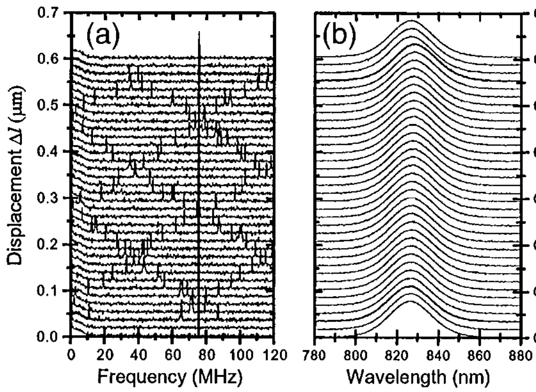

Fig. 4. (a) Beat signals acquired by shifting of the mirror displacement and (b) corresponding spectra of the Ti:sapphire laser.

where $\Delta\phi_1$ and $\Delta\phi_2$ denote the carrier-phase slips for one round trip of the Ti:sapphire and the Cr:forsterite laser, respectively. In general, the relative phase slip, $\Delta\Phi$, varies with the difference in cavity lengths between the two lasers. Δl is defined as the displacement of the Ti:sapphire laser end mirror from the position where the measurement starts. We can then infer the relation as[6]

$$\Delta\Phi = 8\pi\Delta l/\lambda_{\mathrm{TS}}, \quad (2)$$

where λ_{TS} is the wavelength of the Ti:sapphire laser.

Figure 4(a) shows the shift of the beat frequency as we tune the Ti:sapphire laser cavity length by driving the piezoelectric transducer (PZT). To reduce the fluctuation and drift of the beat frequency we covered the laser cavity with a box to eliminate the airflow and rapidly collected the data with the PZT controlled by a portable computer. With the self-edited program, the computer drove a function generator (Hewlett-Packard HP-33120A) that supplied a monotonically increasing voltage to the PZT. In synchronization with the mirror movement, the computer recorded the beat signals and the laser spectra from the spectrum analyzer and spectrometer. For each measurement, we preset the PZT at the longer edge of the synchronized regime of the two lasers. Starting this program will permit the PZT to cross the regime and stop at the shorter edge; the sustained time is less than 1 min. This fast measuring technique greatly reduces the possible error arising from the cavity length fluctuation with time. We calibrated the displacement of the PZT-controlled mirror by the shift of repetition rates. The results shown in Fig. 4(a) clearly reveal that the beat signal varies linearly with the mirror displacement and shifts with a period of $\sim 0.19\ \mu$m, which is in agreement with the calculation based on Eq. (2). Unlike in the case of the optical parametric oscillator,[6] the observed spectra in this experiment do not exhibit any obvious changes, except the pull effects at the boundaries of the synchronized regime,[9] as shown in Fig. 4(b). The spectrum of the Cr:forsterite laser also exhibited similar behavior but was pulled in the opposite direction at the boundaries. The power of both lasers remained unchanged during the measurement.

Beat-frequency measurements with high signal-to-noise ratios will provide information about the mechanism of the passively synchronized mode-locked laser and open new possibilities to control their carrier phases. This will provide a novel way of generating a wide frequency comb and coherent synthesis of ultrashort optical pulses.

In summary, we have observed the relative carrier-phase slip between synchronized Ti:sapphire and Cr:forsterite lasers by measuring the corresponding beat signal. A signal-to-noise ratio as high as 30 dB was obtained from the interference of overlapped SH and TH beams from each laser.

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