Controlling the phase of a femtosecond optical parametric oscillator via coherent mixing of the pump-generated supercontinuum and an OPO subharmonic

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Recent work has been successful in carrier-envelope offset phase control [1,2] in a mode-locked Ti:sapphire laser and also in the control of the phase relation among subharmonics generated by a femtosecond optical parametric oscillator (OPO) [3]. In our efforts to examine the stability of the supercontinuum (SC) generated by a microstructure fiber [4] at extreme wavelength shifts (> 500 nm) it is useful to establish long term locking of the phase difference between the OPO signal (ω_s) and the pump (ω_p). Furthermore, phase locking is needed for two-color coherent measurements that average over many pulses. For a synchronously pumped OPO, the round trip group delay of the OPO cavity must match that of the pump cavity. Additionally, the phase velocity of the OPO must be controlled such that the round trip phase accumulation has a fixed relation to the phase accumulation of the pump cavity for locking to the pump. That is, the extended frequency comb of the Ti:sapphire must exactly coincide with the frequency comb of the OPO. Note that the phase of the OPO signal is not established by the pump due to the extra degree of freedom allowed by the idler.

The phase relation between the signal and pump is apparent in the RF beat frequency produced between the second-harmonic of the OPO signal ($2\omega_s$) and the like frequencies of the SC. Since the Ti:sapphire frequency comb is transferred to the SC [2] the interference between the $2\omega_s$ subharmonic and the SC at $2\omega_s$ will reveal the phase slip between the pump and signal. We define $\Delta\theta_p$ and $\Delta\theta_s$ to be the phase slip per cavity round trip for the pump and OPO signal respectively, referenced to the corresponding envelope. Since the pulse envelopes remained locked, the beat frequency f is given by $f = F\,(2\Delta\theta_s - \Delta\theta_p)/2\pi$ where F is the repetition rate.

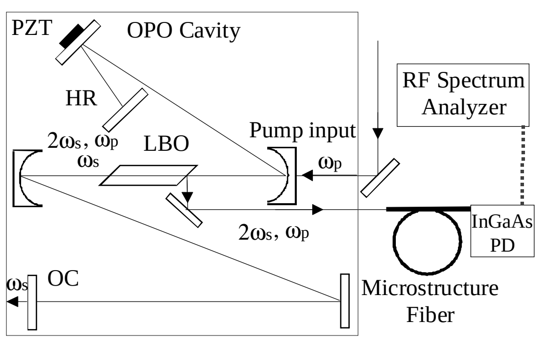


Fig. 1. The OPO cavity showing the pump and $2\omega_s$ subharmonic reflected from the LBO crystal. Both $2\omega_s$ and ω_p are coupled into the microstructure fiber. The supercontinuum generated by ω_p mixes with $2\omega_s$, which causes frequency beating measured in the combined signal RF spectrum. HR: High reflector; OC: Output coupler; PZT: Piezoelectric transducer.

A tunable OPO is pumped with the Ti:sapphire input (100 fs) at 810 nm that generates ω_s, and due to additional nonlinear processes in the LBO crystal also generates $2\omega_s$ (Fig. 1). The residual Ti:sapphire pump is coupled into the microstructure fiber together with the $2\omega_s$ subharmonic (Fig. 2). It is important to note that the ω_p and $2\omega_s$ signals are intrinsically temporally aligned. The strong pump generates a SC from ~400 nm to 1500 nm and the $2\omega_s$ mixes with the corresponding wavelengths of the SC. The combined signal is then detected with a 125-MHz InGaAs photodiode and the beat frequency is recorded with an RF spectrum analyzer. We verified that the beat frequency results from mixing of the $2\omega_s$ subharmonic and the SC by observing that the beat disappears when OPO oscillation is prevented or when the $2\omega_s$ component is filtered before the fiber. Importantly, the beat frequency was observed continuously as the OPO signal was tuned from 1430 nm to 1500 nm establishing the ability to control the phase slip over the OPO tuning range.

Control of the beat frequency was obtained by making slight variations in the OPO cavity length, via a piezoelectric crystal attached to a cavity mirror, while maintaining OPO oscillation. Ideally, the beat frequency is linearly dependent on the change in cavity length [3]. Figure 3 shows the control of the beat frequency at the OPO signal wavelengths of 1440 nm and 1450 nm. Indeed, observation of the relative phase shift for different

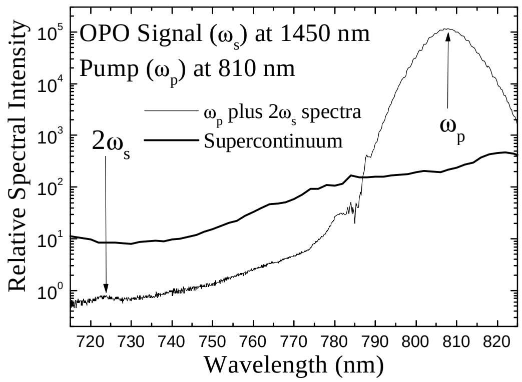
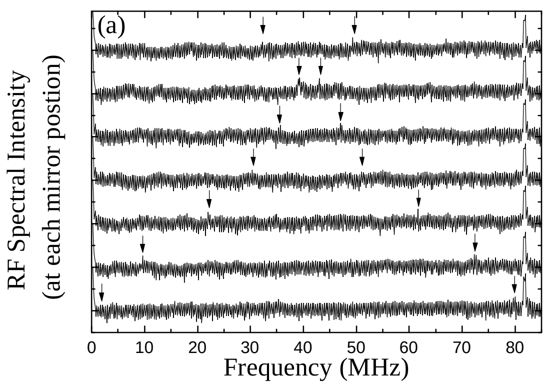


Fig. 2. The input spectrum coupled into the microstructure fiber along with the supercontinuum generated. Although the magnitude of $2\omega_s$ is five orders of magnitude smaller than of ω_p, the mixing of the supercontinuum and $2\omega_s$ generates a strong beat frequency. The $2\omega_s$ feature in the above spectrum disappears when the OPO stops oscillating.

wavelengths allows the examination of the fundamental phase behavior of parametric generation processes and OPO cavities. The cavity deviations are accompanied by spectral changes since the oscillator seeks wavelengths that have the appropriate group delay. Due to this effect, the beat frequency is not a linear function of the cavity detuning.



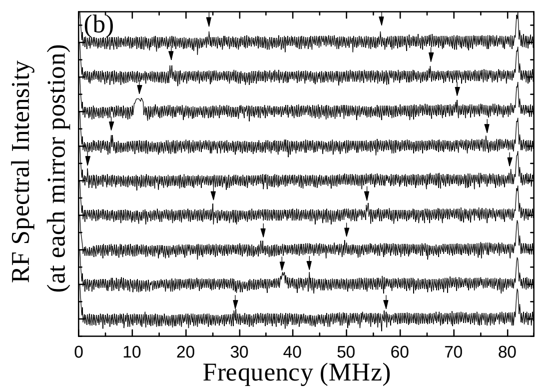


Fig. 3. Control of the beat frequency for OPO signal operation at (a) 1440 nm and (b) 1450 nm. The arrows indicate the location of the beat frequency *f* and the sideband *f-F* where *F* is the repetition rate of the laser (*F*=82 MHz). Each of the successive RF spectra was taken as the mirror position was changed by 0.1 μm.

In conclusion, we have shown by measuring the beat frequency between the SC and the OPO $2\omega_s$ subharmonic we can observe and control the relative phase slip between the pump and signal. The relative phase slip can be controlled for a large OPO signal range since the $2\omega_s$ subharmonic is mixed with the SC. It is possible to use the SC to extend carrier-envelope locking so that both the Ti:sapphire pulse and OPO signal are locked to an absolute reference. Further, we expect that the OPO signal can be readily mixed with the extreme wavelengths of the SC further extending the usefulness of this technique.

References:

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