Self-phase-locked degenerate femtosecond optical parametric oscillator

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We demonstrated a stable degenerate synchronously pumped femtosecond optical parametric oscillator (SPOPO) as a divide-by-2 subharmonic generator. The SPOPO exhibited passive all-optical self-phase-locking between the pump and signal/idler and thus required no external electronic feedback to produce the phase-locked subharmonic. We employed a type I phase-matched, 1-mm-long, periodically poled MgO:LiNbO$_3$ crystal as the nonlinear gain element and an 80 MHz mode-locked Ti:sapphire laser with 180 fs pulses tuned at 775 nm as the pump. The SPOPO generated transform-limited 70 fs phase-locked output pulses centered at 1550 nm. The self-phase-locking operation was confirmed by separate beat-note measurement techniques with respect to the pump laser and with respect to an external cw laser. © 2008 Optical Society of America

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Extension of the optical frequency comb toward shorter wavelengths has pushed ultrafast science and is thus revolutionizing atomic physics [1]. While extension of the optical comb toward longer wavelengths in the mid- and far-IR spectrum is less developed, it is critical to new technologies that require optical phase control in the IR, such as vacuum-based laser-driven particle acceleration [2]. Important work in this direction has been done with type II phase-matched divide-by-2 [3,4] and divide-by-3 [5–7] cw optical-parametric-oscillator (OPO) systems. Phase control between subharmonic pulses in synchronously pumped femtosecond OPOs (SPOPOs) has been accomplished [8], and a mid-IR frequency comb generated with an SPOPO has recently been reported [9]. We focus on the divide-by-2 scheme that is based on type I phase matching, which exploits the strongest nonlinear coefficient and generates signal and idler waves with the same polarization. This allows direct mixing and leads to all-optical self-phase-locking in a simple cavity without external electronic feedback loops.

The mechanism for self-phase-locking in the degenerate OPO is mutual injection between the signal and the idler. In an OPO, the signal and the idler share the same cavity and act as complementary injected fields. Because both injected waves are derived from the same source, we identify this coupling interaction as self-injection.

Although the phases of the signal and the idler can be free-running, oscillation requirements for frequency and phase are $\omega_p = \omega_s + \omega_i$ and $\phi_p = \phi_s + \phi_i - \pi/2$, respectively. When phase locked, the phase difference between the signal and the idler is a multiple of 2π. This implies that

$$2\phi_{s,i} - \phi_p = m2\pi + \pi/2, \tag{1}$$

where m is an integer. When the signal and idler phases are simultaneously changed by π, Eq. (1) still holds. A cw OPO is automatically phase locked at de-

generacy, because the signal and idler are indistinguishable [10].

The locking analysis for an SPOPO, however, is more complicated, owing to the multi-axial-mode structure of frequency combs, represented as $f_n = nf_{rep} + \delta$, where n is the mode number, f_{rep} is the mode spacing, and δ is the carrier-envelope offset (CEO) frequency. The synchronous-pumping condition stipulates that f_{rep} is equivalent for the pump, signal, and idler combs. Hence, both $n_p = n_s + n_i$ and $\delta_p = \delta_s + \delta_i$ need to be satisfied. The difference of the CEO frequencies of coresonant signal pulses in an SPOPO has been observed to linearly follow the internal pump–idler beat [11]. The SPOPO is considered phase locked when the difference between the signal and the idler CEO frequencies is a multiple of the mode spacing, because the corresponding temporal carrier-envelope phase slips are identical, provided that the carrier frequencies remain equal. Analogous to the phases in Eq. (1), the locking condition for the CEO frequencies is

$$2\delta_{s,i} - \delta_p = mf_{rep} \rightarrow 2\delta_{s,i} - \delta_p = 0. \tag{2}$$

When the SPOPO is degenerate, the signal/idler CEO frequency is half that of the pump. If the degenerate signal and idler combs are shifted by half a mode spacing in opposite directions, the SPOPO remains in the phase-locked (degenerate) regime; hence, there are two distinct phase eigenstates separated by $0.5f_{rep}$. According to Eq. (2), however, this distinction disappears after doubling the SPOPO comb to compare with the pump comb for confirming phase coherence.

The nonlinear gain element used for the SPOPO was a 1-mm-long 5% MgO-doped periodically poled lithium niobate (PPMgO:LN) crystal (HC Photonics, Inc.) that had a uniform grating period of 18.92 μm and was noncritically phase matched at 140 °C for 1550 nm with a gain bandwidth of 300 nm at degeneracy. The nonlinear crystal was placed inside a near-

symmetrically folded confocal cavity, as shown in Fig. 1. The radius of curvature of the mirrors in the confocal section was selected to create a waist inside the PPLN crystal with a FWHM of 30 μm for the signal and idler at 1550 nm. A Ti:sapphire mode-locked laser (180 fs pulses at 80 MHz) was employed with the pump at 775 nm and focused to a FWHM waist of 20 μm to mode match to the SPOPO cavity. A 50% output coupler was used to extract a large fraction of the intracavity power and to reduce the cavity Q for better tolerance against cavity length perturbations. A 6-mm-long antireflection-coated plate of fused silica was inserted inside the SPOPO cavity to provide anomalous group-velocity dispersion (GVD) at 1550 nm and to compensate for the normal GVD accumulated in the nonlinear crystal. The SPOPO cavity length was controlled by a motorized translation stage for coarse adjustments and by a piezoelectric transducer for fine adjustments.

The degenerate SPOPO pump threshold was measured to be 140 mW. A maximum output power of 250 mW when pumped at 900 mW was observed. The spatially averaged pump depletion reached 60%. The slope efficiency with respect to incident pump power was 32%. The FWHM spectral bandwidth at degeneracy was 200 cm^{-1} or 50 nm centered around 1550 nm. The duration of the degenerate output pulses, measured with background-free autocorrelation via second-harmonic generation (SHG), was 70 fs, which is transform limited for Gaussian profiles.

While the pump wavelength and crystal temperature were kept fixed, a change in the SPOPO cavity length was applied to alter the operating state. Within the degenerate regime, adjusting the round-trip cavity length by $\lambda_c/2$ (where λ_c is the 1550 nm oscillating wavelength) switched between the phase-locked eigenstates. A substantial cavity length change caused the SPOPO to become nondegenerate such that distinct signal and idler peaks appeared in the spectrum. As shown in Fig. 2, the optical spectrum is the primary metric for distinguishing between degenerate and nondegenerate operation.

Three measurement techniques were applied to test for phase locking between the pump and signal/idler pulses in the degenerate and nondegenerate regimes. In the first method, the SPOPO signal and idler output was frequency doubled and interfered with the pump at a low angle between the beams. To
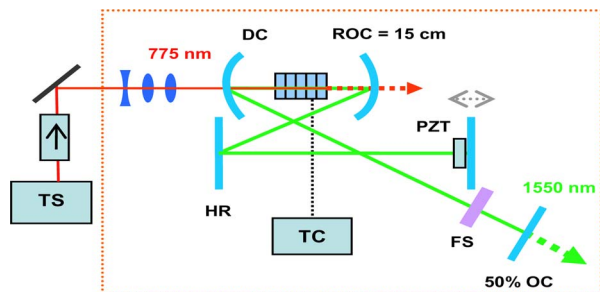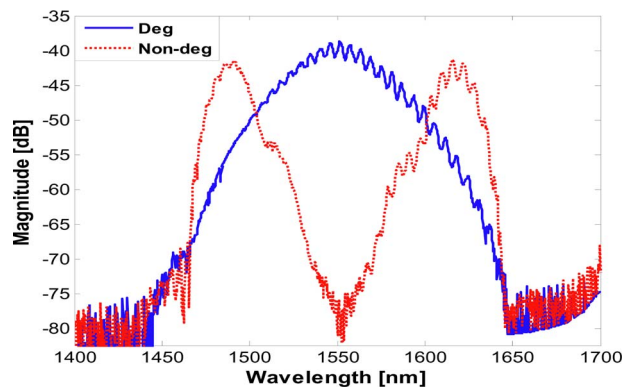

Fig. 2. (Color online) Signal and idler SPOPO spectra for degenerate and nondegenerate operation. The degenerate SPOPO forms a broad spectrum centered at 1550 nm. In the nondegenerate SPOPO, the signal and idler pulses oscillate at different carrier frequencies. The shown spectra have a cavity length detuning of 5 μm between them.

minimize sum-frequency generation (SFG) between the signal and the idler, which always reconstructs the pump, we used spectral filters. These were centered away from degeneracy to 1500 or 1600 nm to block most of the SFG and transmit only the SHG of the signal and the idler from 10 nm slices of the broad SPOPO output comb. The pump comb was broadened with a microstructure fiber and filtered at 750 or 800 nm to overlap with the corresponding SHG spectrum of the SPOPO output. Observation of stationary fringes from the interference established phase coherence, whereas lack of a stable interference pattern indicated a random signal or idler phase with respect to the pump. The fringe results between the locked and unlocked cases were equivalent for all sets of filters used.

The second measurement technique used the collinear interference between the frequency-doubled SPOPO output and the pump to characterize the rf beat-note spectrum. Observation of beat notes corresponding to only integer multiples of the pump-laser repetition rate confirmed that the output was phase locked, whereas the appearance of satellite beat notes indicated unlocked signal and idler outputs due to mismatched CEO frequencies.

Figure 3 shows the observed fringe patterns and corresponding rf beat-note spectra for degenerate and nondegenerate operation. We consistently observed the dramatic onset of fringes, which correlated well with the disappearance of satellite beat notes when the SPOPO entered the degenerate phase-locking regime. When the SPOPO became nondegenerate, the stable fringe pattern vanished while satellite beat notes emerged in the rf spectrum, thus indicating unlocked operation.

The third technique used a cw laser source emitting 1550 nm as an external phase reference relative to the pump mode-locked laser and the SPOPO output separately. Beating a comb of frequencies with a single cw line required substantially narrower spectral filtering of the pump laser and SPOPO to a bandwidth on the order of 0.1 nm so that the cw mode could beat with fewer axial modes to resolve its beat notes. We acquired the rf beat frequencies between

Fig. 1. (Color online) SPOPO standing-wave cavity whose length is 185 cm (80 MHz). The PPMgO:LN crystal is phase matched for 1550 nm and pumped at 775 nm.
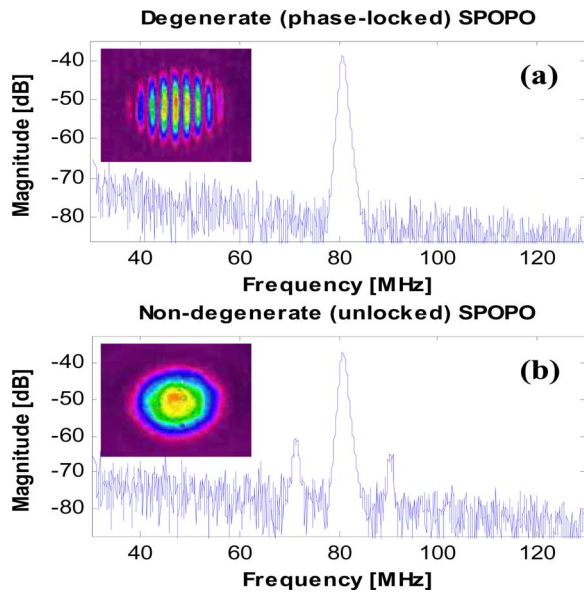
Fig. 3.   (Color online) Measurements obtained from frequency doubling the SPOPO output and interfering with the pump: (a) observed fringes and lack of satellite beat notes when phase locked; (b) observed satellite beat notes (0.5 MHz linewidth at 200 kHz resolution bandwidth) and lack of fringes when unlocked.
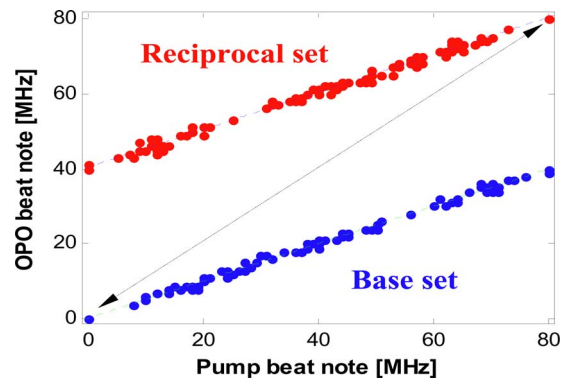

Fig. 4.   (Color online) Scatter plot of beat notes between the phase-locked SPOPO output and the cw laser (referenced at 1550 nm) versus beat notes between the pump and the cw laser SHG (at 775 nm). The slopes for the base and reciprocal sets of beat notes are both one-half.

the filtered pump and the frequency-doubled cw laser and the rf beat notes between the filtered degenerate SPOPO and the same cw laser. The pump laser comb was allowed to drift with respect to the reference cw laser to observe how the CEO frequency of the SPOPO follows the pump CEO. As expected from Eq. (2), the subharmonic SPOPO output beat frequency was always half of the pump beat note when the SPOPO operated in the phase-locked regime. Figure 4 shows a scatter plot of the degenerate SPOPO output beat note versus the pump beat-note drift and indicates that the slope is one-half. Over a frequency span of the 80 MHz repetition rate, the nominal pair of beat frequencies is referred as the base set. The other pair, symmetrical around 40 MHz, is the reciprocal set. The slopes for both sets are the same at one-half.

No feedback servo was needed for the SPOPO to maintain self-injection-locked oscillation. Despite the lack of active stabilization, the phase-locked SPOPO would routinely regain self-phase locking after application of deliberate, small perturbations. When the cavity length detuning falls within the locking range, which is dependent on gain and cavity Q, self-injection forces the signal and idler comb modes to oscillate at their respective degenerate frequencies. The degenerate SPOPO operated stably for up to 1 h when there was minimal external noise.

To our knowledge, this is the first demonstration of a self-stabilizing phase-locked divide-by-2 type I SPOPO operating in the degenerate regime. In the past, implementations of type I degenerate mode-locked OPOs were avoided, owing to the common belief that such systems are intrinsically unstable with doubly resonant effects [12]. We show that these OPOs, while not eminently tunable, are well behaved. The SPOPO also displayed significant comb broadening that was limited by the bandwidth of intracavity components. Upgrading the cavity optics could achieve a full octave of output spectrum for the generation of few-cycle mid-IR pulses. Cascading these broadband degenerate SPOPOs and implementing phase-preserving optical parametric amplification stages could synthesize stable high-peak-power frequency combs at far-IR wavelengths that are not readily accessible to solid-state lasers.

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