Coherent frequency division with a degenerate synchronously pumped optical parametric oscillator

CHENCHEN WAN,^{1, 2, †} PENG LI,^{1, ‡} AXEL RUEHL,^{1, §} AND INGMAR HARTL^{1, *}

¹Deutsches Elektronen-Synchrotron (DESY), Notkestraße 85, 22607 Hamburg, Germany

²Electro-optics Program, University of Dayton, 300 College Park, Dayton, OH, 45469-0245, USA

[†]Current affiliation: Thorlabs Inc., 56 Sparta Ave., Newton, NJ, USA

[‡]Current affiliation: IMRA America Inc., 1044 Woodridge Ave., Ann Arbor, MI 48105, USA

[§]Current affiliation: Leibniz University Hannover, QUEST-Leibniz-Research School, Institut für Quantum Optics, Welfengarten 1, 30167 Hannover, Germany

*Corresponding author: ingmar.hartl@desy.de

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Synchronously-pumped optical parametric oscillators (OPOs) are important tools for frequency comb (FC) generation in the mid-IR spectral range, where few suitable laser gain materials exist. For degenerate OPOs self-phase-locking to the pump FC has been demonstrated. Here, we present a phase noise study of the its carrier envelope offset frequency, revealing a -6 dB reduction compared to the pump frequency comb over a wide Fourier frequency range. These results demonstrate that a degenerate optical parametric oscillator can be an ideal coherent frequency divider without any excess noise.

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Optical frequency combs (FC) consisting of equally spaced frequency modes have enabled advances in numerous applications in the field of optical metrology [1] and spectroscopy [2]. There is a growing demand of extending the spectral range of FCs to the mid-IR (2-20 μm) and molecular fingerprint region, respectively where mid-IR FC spectroscopy can be used to understand molecular structures or to perform gas analysis for biological and environmental applications [3]. Direct generation of mid-IR FCs has been reported using mode-locked lasers based on novel gain media, quantum cascade laser technology [4] and micro-resonator based Kerr comb [5], nonlinear frequency conversion process such as difference frequency generation [6,7] and optical parametric oscillation [8] still have the advantages of a mature technology platform enabling a wide wavelength coverage.

Optical parametric oscillators (OPOs) synchronously pumped by a femtosecond FC have been used to generate FCs in both single [9] and doubly resonant [10] operation regimes. In doubly resonant OPOs, the oscillation occurs at discrete cavity lengths ("resonances"), separated by $\lambda/2$, where λ is the center wavelength of the OPO. When operated at non-degeneracy [11], the OPO output spectrum is tunable. Here, the output spectrum consists of two combs for the signal- and idler- field respectively. Their respective carrier envelope offset frequency f_0 is not fixed to the driving FC, requiring an additional active feedback loop for stabilization. On the other hand, degenerate OPOs (DOPO) have shown to produce a sub-harmonic of the driving FC. Here the sub-harmonic OPO field is self-phase-locked to the pump [12-16]. Although a dither-lock of the OPO cavity length is usually applied to keep the DOPO long-term stable at a cavity resonance, the self-phase-locking of DOPOs combs to the pump combs has been observed even without active stabilization [12]. The frequency comb lines of DOPOs can only take two sets of modes shifted by $f_{\text{rep},p}/2$, where $f_{\text{rep},p}$ is the pump repetition frequency [15]. The DOPO comb alternates between those two sets when tuning from one cavity resonance to the next. While the DOPO comb's repetition frequency is always equal to the pump FC's $f_{\text{rep},p}$, its offset frequency alternates between $f_{0,p}/2$ and $f_{0,p}/2 + f_{\text{rep},p}/2$, where $f_{0,p}$ is the pump offset frequency. In both cases the DOPO comb is self-locked to the pump FC.

Understanding the phase noise transfer of DOPOs has been a focus of various studies. Initially the self-locking of f_0 has been verified by a stable beat note of DOPO with a reference cw laser [12]. A recent phase noise study directly measured the f_0 of a DOPO by beating the outputs parasitic sum frequency with the pump. A phase noise comparison of the pump and the DOPO f_0 indicates self-locking [16]. Here, the DOPOs f_0 phase noise power spectral density exceeds the pump lasers', with the exception of a small Fourier frequency range around 10 kHz.

However, an early study by Nabors et al. on single-frequency DOPOs, could show a 6 dB reduction in modulation sidebands with respect to the modulated pump field [19]. As expected from an ideal times- n frequency multiplier, where phase noise scales with n^2 . This 6dB reduction did hold for low modulation frequencies, until the lifetime of the DOPO cavity was further damped. For typical cavity lifetimes the on-set of this effect is observed at modulation frequencies in the MHz range.

In this letter, we study the f_0 coherence of a free-running DOPO by measuring the phase noise transfer function from the driving FC to the DOPO field. Our results prove for the first time, to the best of our knowledge, that the DOPO has a f_0 phase noise 6dB lower than the driving FC in the Fourier frequency range from 1 kHz to ~200 kHz, showing strong phase-noise suppression up to several MHz Fourier frequencies. The noise reduction indicates that DOPO pumped by fs-FCs can serve as a coherent frequency divider just as their single-frequency counterparts.

The experimental setup sketched in Fig. 1 consists of a doubly resonant OPO based on a 1 mm long MgO:PPLN crystal with a poling period of 31.245 μm placed in a bowtie cavity. The OPO is pumped through a dichroic mirror exhibiting a reflection greater than 99.8% of the OPO field. One of the cavity mirrors is mounted on a piezo stage for cavity length control. The driving FC is a Yb: fiber based system consisting of a 150 MHz Yb: fiber oscillator and chirped-pulse amplifier delivering 100 fs pulses with up to 13 nJ pulse energy [20]. The FC repetition rate is stabilized by phase-locking a single comb line to a single-frequency nonplanar ring oscillator at 1064 nm with feedback to the oscillator cavity length. The f_0 is detected with an inline f-2f interferometer and phase-locked to an RF reference by feedback to the current of the oscillator pump diode. The phase-stabilized pulse train passes an additional acousto-optic modulator (AOM) allowing to phase-modulate f_0 of the pump FC for the transfer function measurements.

Fig. 1. Experimental setup. PLL: phase lock loop; PZT: piezo stage; AOM: acousto-optic modulator; HNLf: highly nonlinear fiber; DM: dichroic mirror, NPRO: single frequency laser. PLL to pump power and AOM are the two frequency modulation methods for OPO pump comb.

The f_0 of the OPO output is obtained by beating the parasitic sum-frequency signal of pump and OPO field at a wavelength of 700 nm with an additional supercontinuum (SC) branch of the pump FC generated in a suspended-core highly nonlinear fiber (HNLf) [21]. It can easily be shown that this scheme directly reveals the f_0 signal of the OPO which was further analyzed in the phase-noise and transfer function measurements described below.

When the OPO cavity length is tuned, several discrete resonances are observable which are separated by half of the OPO wavelength. When pumping the OPO 10 times above threshold, a maximum of 11 resonances could be observed. Within the central resonances,

the OPO is initially oscillating at degeneracy but would jump to non-degeneracy with increasing the cavity length. This behavior is illustrated in Fig. 2 showing the optical spectrum, the OPO f_0 and the OPO output power vs. cavity length. At degeneracy, the OPO spectrum exhibits a single peak at the sub-harmonic of the pump and the OPO f_0 is self-locked and stays unchanged when tuning the cavity length [12]. The setup is sufficiently passively stable to remain in a degenerate operation for tens of minutes without cavity length stabilization. When scanning the OPO cavity length from short to long in one resonance, the system undergoes a region of unstable oscillations before non-degenerate operation can be observed. Here, the optical spectrum as well as the f_0 of the OPO are split into two branches representing signal and idler field. Since only the sum of these quantities is fixed, both fields hence exhibit a strong dependence on the cavity length. Depending on the slope of signal and idler f_0 with respect to the cavity length, self-phase locked behavior could indeed be observed [22] but a detailed phase-noise study would require the absolute stabilization of the cavity length which is currently not possible with our setup. The study and discussion presented here is hence restricted to degenerate operation commonly used for FC generation with OPOs.

Fig. 2. Transition from degenerate to non-degenerate operation when tuning the cavity length. (a) OPO optical spectrum, (b) OPO f_0 and (c) OPO output power. Note: the output power was measured using an extended InGaAs diode, whose sensitivity is strongly wavelength dependent.

First, the phase noise of in-loop pump f-2f beating and the OPO f_0 beating were recorded simultaneously at OPO degeneracy. As shown in Fig. 3 at lower frequency (<1 kHz) the OPO has higher f_0 phase noise due to technical excess noise such as vibrations picked up by the unlocked OPO cavity. Over the entire ~1 kHz to 5 MHz span, the OPO's f_0 phase noise power spectral density is lower than the pump's. A maximum reduction of 10 dB was observed at 10 kHz.

Fig. 3 Phase noise of pump and DOPO f_0 . Solid lines are the RF power spectral density (PSD); dashed lines are the integrated phase noise.

Since the OPO cavity is not actively locked, any technical noise that changes the cavity length would be coupled to the phase noise. To eliminate this effect, we measure the pump to DOPO f_0 phase noise transfer function. For this measurement we phase modulate the pump's f_0 and detect the DOPO f_0 response. In our experiments we applied two different pump f_0 modulation methods.

In our first method, we add a small modulation signal to the control signal used for pump f_0 stabilization, the Yb: fiber oscillator pump diode current. The modulation frequency is scanned from 1 kHz to 8 MHz. As shown in Fig. 4 the modulation will generate sidebands on the pump f_0 beat note as well on the DOPO f_0 beat note. For small phase modulation, the modulation index can be determined by the relative peak powers of the first sidebands to the carrier. We calculate the transfer function's value for a particular modulation frequency by taking the ratio of the modulation indices for DOPO and pump f_0 .

Fig. 4. The modulation sidebands on the pump and the OPO f_0 where the modulation index is determined by the sideband strength. In this plot, the modulation frequency is at 30 kHz.

Fig. 5 is a typical transfer function measurement. The modulation index of the pump f_0 increases monotonically from 1 kHz to ~ 50 kHz then it has a dip in the range of ~ 50 kHz to ~ 500 kHz and within this range the modulation index shows large fluctuations. When the modulation frequency is above 500 kHz, the modulation index does not oscillate and monotonically decreases. The corresponding transfer function is shown in Fig. 5. It shows a 6 dB modulation suppression in the range from 1 kHz to ~ 50 kHz. Above 500 kHz, the transfer function is negative again with a minimum of -10 dB. In the range of ~ 50 kHz to ~ 500 kHz the DOPO f_0 has stronger sidebands than the pump which could be interpreted as a larger DOPO f_0 phase noise than the pump. However, it turns out that the strong feature in the modulation frequency range from 50 kHz to ~ 500 kHz is the result of our modulation method. Since the modulation is added to the current of the pump diode, it modulates both amplitude and f_0 of the pump FC [23]. At low Fourier frequencies, the phase modulation is dominant and amplitude modulation can be neglected. However

the pump current modulation causes large amplitude modulation in the ~ 50 kHz to ~ 500 kHz as it drives the relaxation oscillation of the laser gain material. In our measurement, only pump f_0 phase modulation is considered, thus the transfer function measurement becomes invalid around the relaxation oscillation frequency.

Fig. 5. Transfer function (TF) measured with pump diode modulation method. Top: modulation index of the modulation of pump and DOPO f_0 beats. The ratio of DOPO and pump modulation indices gives the f_0 noise transfer function.

To overcome this limitation and to confirm the problems with the pump power modulation discussed above, we applied a second pump f_0 phase modulation method by implementing a resonant acousto-optic modulator (AOM) after our Yb-FC and using the diffracted beam to pump the OPO. We add a small frequency modulation to the driving RF of the AOM. The AOM will frequency shift all comb lines so it is effectively a shift of the f_0 of the driving FC. We experimentally confirmed that this method does not produce any amplitude modulation.

Fig. 6. Measured f_0 phase noise transfer functions measured via pump power modulation (red traces) and AOM modulation (blue traces). The gray line is the phase noise difference calculated from Fig. 3 and the dashed black line shows the ideal transfer function of a monolithic DOPO according to Ref. [24].

All individual transfer function measurements together with the average for both modulation methods are presented in Fig. 6 together with the analytical phase noise transfer function of a monolithic DOPO according to Ref. [24]. The calculated transfer function exhibits a 6 dB phase noise reduction until the cavity linewidth limit of 5 MHz for our OPO cavity. The transfer functions for both modulation methods agree well in the Fourier frequency range 1 kHz to ~ 50 kHz and show a -6 dB noise reduction, as expected for a coherent frequency divider. In the range of ~ 50 kHz to ~ 500 kHz where the pump power modulation method suffers

from the lasers relaxation oscillation, the AOM modulation method confirms the -6 dB noise reduction. Above ~200 kHz, the transfer function measured with AOM modulation also shows some fluctuations which are most likely caused by driving our RF source beyond its specified modulation frequency limit of 100 kHz. In fact, we observed a carrier frequency shift of the modulated RF source when the modulation frequency was above 200 kHz. Above ~500 kHz, the transfer function measured via pump power modulation is negative again and even below the analytical -6 dB line. This, however, might be a measurement artifact arising from phase to amplitude coupling. As a comparison, the phase noise difference calculated from Fig. 3 is also plotted in the background in Fig. 6. It also shows constantly the phase noise reduction of the OPO until 1 MHz. Above 1 MHz, in this measurement the phase noise ratio increases, because we are reaching the detector noise floor for the OPO phase noise measurement (compare Fig 3.).

In summary, we presented a measurement of the f_o phase noise transfer function from the driving frequency comb to the output of a DOPO. We find that the DOPO has a 6 dB phase noise reduction with respect to the pump comb in the Fourier frequency range from 1 kHz to 200 kHz and a substantial phase-noise reduction from 500 kHz to 8 MHz which constitutes the full frequency range accessible with our experimental setup. These measurements prove that a synchronously pumped OPO operated at degeneracy can serve as an ideal coherent frequency divider and constitutes a well-suited scheme for the generation of low-noise FCs in the important mid-IR spectral region.

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