Degenerate 1 GHz repetition rate femtosecond optical parametric oscillator

Markku Vainio,[1,2,*] Mikko Merimaa,[2] Lauri Halonen,[1] and Konstantin Vodopyanov[3]

[1]*Laboratory of Physical Chemistry, Department of Chemistry, University of Helsinki, P.O. Box 55, Helsinki FIN-00014, Finland*

[2]*Centre for Metrology and Accreditation, P.O. Box 9, Espoo FIN-02151, Finland*

[3]*E.L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA*

**Corresponding author: markku.vainio@helsinki.fi*

Received August 27, 2012; accepted September 24, 2012;
posted October 1, 2012 (Doc. ID 175084); published October 31, 2012

We report a degenerate femtosecond optical parametric oscillator (OPO) that is synchronously pumped by a mode-locked Ti:sapphire laser at 1 GHz repetition rate. The OPO produces an 85 nm (10 THz) wide frequency comb centered at 1.6 μm. Stable long-term operation with >100 mW of average output power has been achieved. © 2012 Optical Society of America

OCIS codes: 190.4410, 190.4970, 190.7110.

Optical frequency combs (OFCs) have become indispensable tools for time and frequency metrology, molecular spectroscopy, and many other applications. Most advances enabled by OFCs have taken place in the visible and near-infrared regions, where OFCs can readily be produced using mode-locked femtosecond lasers. Several techniques based on nonlinear optics have been studied in order to extend the spectral range of OFCs to wavelengths that are not directly accessible with mode-locked lasers [1]. One of these techniques uses a synchronously pumped femtosecond optical parametric oscillator (OPO) operating at degeneracy [2–6]. It has been shown that a degenerate femtosecond OPO can produce a wide frequency comb, which is inherently phase-locked to the frequency comb of the pump laser [2–4]. At degeneracy (for Type 1 or Type 0 phase matching), the signal and idler spectra become indistinguishable, and the generated OPO comb fulfills one of the two possible relations, deterministically selected by cavity length:

$$\nu_m = \frac{f_{\mathrm{ceo}}}{2} + m f_{\mathrm{rep}}, \tag{1a}$$

$$\nu_m = \frac{f_{\mathrm{ceo}}}{2} + \left(m + \frac{1}{2}\right) f_{\mathrm{rep}}, \tag{1b}$$

where ν_m is the frequency of mth mode of the OPO comb [2,4]. The repetition rate and the carrier-envelope offset frequency of the pump comb are denoted by f_{rep} and f_{ceo}, respectively. As Eq. (1) indicates, the degenerate OPO comb is automatically fully stabilized if a pump comb with stabilized f_{rep} and f_{ceo} is used [2,4].

The characteristics of degenerate femtosecond OPOs were first studied using a Ti:sapphire-laser pumped system [2]. The technology was then extended to generation of mid-infrared frequency combs [3–6]. As an example, an octave-spanning spectrum centered at 4.1 μm has been demonstrated using orientation-patterned GaAs as the nonlinear gain medium [6]. So far, this technique has only been used with pump lasers that have a relatively low (<200 MHz) repetition rate. In this Letter, we demonstrate that the same approach can be applied to high-repetition-rate OPOs as well.

In addition to the possibility of extending the OFC technology to entirely new spectral regions, the femtosecond OPOs can be used to transfer favorable characteristics of existing mode-locked lasers to regions where these characteristics are otherwise technically challenging to obtain. As an example, mode-locked Ti:sapphire lasers are known to be ideal for generating OFCs with good spectral purity and high repetition rates of up to several GHz [7]. These are both useful characteristics in applications, such as optical frequency metrology and calibration of astronomical spectrographs, but difficult to obtain, e.g., in the optical telecom region near 1.5 μm. The existing OFCs in this region are typically based on fundamentally mode-locked Er-doped fiber lasers, whose repetition rate is limited to a few hundred megahertz [8,9]. A possible solution is to transfer the high repetition rate of a Ti:sapphire-laser comb from 0.8 μm to a longer wavelength using a synchronously pumped OPO. This approach has previously been proposed and studied based on singly resonant OPOs [7,10–12]. The doubly resonant femtosecond OPO presented here is pumped with a mode-locked Ti:sapphire laser that has a repetition rate of 1 GHz. The center wavelength of the pump laser is 0.8 μm, and the OPO output spectrum is hence centered at 1.6 μm. As our scheme is based on a degenerate OPO, it offers some advantages over prior work: low oscillation threshold, broad instantaneous spectrum, as well as the possibility of achieving phase-locked operation with respect to the pump comb without complex electronic stabilization schemes.

The degenerate OPO is schematically shown in Fig. 1. The OPO is pumped with a Kerr-lens mode-locked Ti:sapphire laser (Gigaoptics Gigajet 20), which produces ~30 fs pulses at 1 GHz repetition rate, as specified by the manufacturer. The repetition rate and the carrier-envelope offset frequency of the pump laser comb were not stabilized during the experiments reported here. The center wavelength of the pump laser is 803 nm, and the average pump power incident on the OPO is up to 625 mW. The OPO is synchronously pumped, i.e., the round-trip length of the OPO cavity (30 cm) is matched with that of the pump laser. Mirror M4 is placed on a translation stage in order to roughly adjust the cavity length, and a piezoelectric actuator (PZT) glued to the

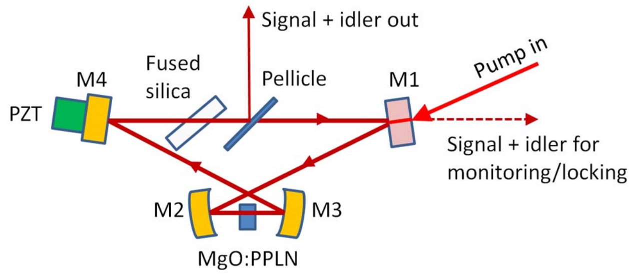

Fig. 1. (Color online) Schematic of the bow-tie ring cavity of the OPO. M1 and M4 are flat mirrors, and M2 and M3 are concave mirrors. The OPO output beam is extracted using a pellicle beamsplitter. A weak output beam through M1 can be used for monitoring and for active locking of the OPO cavity length.

mirror is used for fine tuning. The pump input coupler (mirror M1 in Fig. 1) is a dielectric mirror that transmits the pump beam but is highly reflective ($R > 99.9\%$) for the resonating signal and idler wavelengths between 1500 and 1750 nm. The other cavity reflectors are gold-coated mirrors. The half-folding angle of the cavity is as small as geometrically possible, ~6 deg, so as to minimize astigmatism.

The radius of curvature ($R = 25$ mm) of concave mirrors M2 and M3 was chosen such that a $1/e^2$ waist size of ~15 μm is obtained between the mirrors. The geometric spacing between the curved mirrors, $\sim R$, was optimized by maximizing the OPO output power. A 1 mm long MgO:PPLN crystal (Covesion Ltd. MSHG1550-1.0-1) is placed at the waist. The crystal is antireflection coated for the pump, signal, and idler wavelengths. The pump beam is reflected into the crystal by the curved mirror M2 such that the position of the waists and confocal parameters for the pump and resonating signal and idler beams match each other. A crystal poling period and temperature of 20.4 μm and 90°C, respectively, were used in the experiments. This gives Type 0 phase matching ($e \rightarrow e + e$) for the degenerate OPO process near 1.6 μm. The crystal's temperture is controlled with 0.05 K precision using a Peltier element, although the OPO operation was found to be insensitive to temperature changes of several degrees. A 5 mm thick uncoated plate of fused silica was placed at Brewster angle between the flat cavity mirrors in order to compensate (in the first-order approximation) group velocity dispersion of the MgO:PPLN.

A pellicle beam splitter (Thorlabs BP145B3) is used to couple out ~40% of the power resonating in the cavity. The total output power extracted by the beam splitter exceeds 100 mW with a maximum pump power 625 mW. The maximum pump depletion is more than 40%, and the threshold pump power was estimated to be below 300 mW.

Figure 2 shows the output power of the OPO as the cavity length is scanned with the PZT. The OPO oscillates only when the doubly resonant condition is met, which corresponds to several discrete values of cavity length detuning [3,4]. The smallest threshold and the largest output are obtained for the longest cavity, corresponding to the exact degeneracy. The output spectrum of the stable degenerate state (peaks A of Fig. 2) is shown in panel A of Fig. 3. The full width at half maximum of the spectrum is 85 nm (10 THz), which is capable of supporting sub

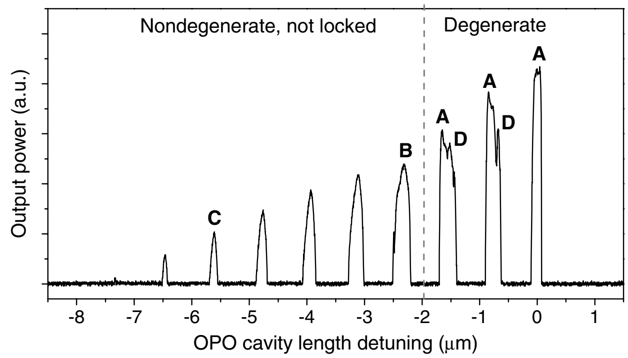

Fig. 2. Output power of the OPO recorded when scanning the cavity round-trip path length with a PZT. Labels A, B, C, and D denote different states of operation; see text for details. Zero detuning has been arbitrarily chosen to coincide with the first peak that corresponds to the degenerate state.

50 fs pulses (although no temporal characterization of the pulses was done). As the cavity length is shortened to coincide with resonance peak B (Fig. 2), the signal and idler spectra start to separate but remain partly overlapping. We refer to this state as a near-degenerate state, and the respective output spectrum of the OPO is presented in panel B of Fig. 3. A further decrease of the cavity length leads to gradual separation of the signal and idler spectra until distinct spectra are observed (peak C of Fig. 2 and panel C of Fig. 3).

The most favorable regime of operation, considering the use of the OPO as a source of a stable phase-locked frequency comb, is the degenerate state. In this state, the signal and idler combs become indistinguishable and a single comb with tooth spacing $f_{\mathrm{rep}} = 1$ GHz is obtained. This was confirmed by directing the OPO output beam to a fast photodiode in order to measure the radio-frequency (RF) spectrum of the beating comb peaks. Only a single peak at f_{rep} is observed, as is shown in Fig. 4. Another measurement with 3 kHz resolution bandwidth of the RF spectrum analyzer revealed that the beat signal peak has a –3 dB linewidth as small as 5 kHz. The OPO cavity length was not actively stabilized during these measurements.

Previous studies have shown that, in the degenerate regime, the OPO output comb has two possible

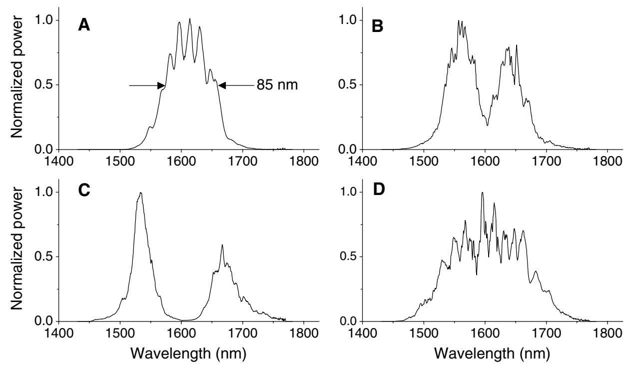

Fig. 3. OPO output spectrum for four different states of operation: A, degenerate state; B, near-degenerate state; C, nondegenerate state; D, intermediate state. The same symbols (A–D) indicate the respective resonance peaks in Fig. 2.

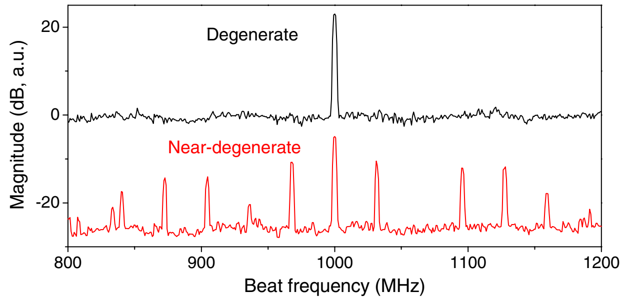

Fig. 4. (Color online) RF spectrum of the OPO output. Resolution bandwidth of the RF analyzer was 1 MHz.

eigenstates, which are unambiguously defined in terms of the pump comb; see Eq. (1) [2,4]. In the near-degenerate state, on the other hand, no stable injection locking is obtained despite the partially overlapping signal and idler spectra. This is evidenced by additional peaks in the RF spectrum (the red trace in Fig. 4), which are likely to be (i) due to frequency beats between the overlapping tails of the signal and idler waves, which have different f_{ceo}, or (ii) due to intrinsic instabilities.

The details of the RF spectrum vary depending on the OPO cavity length detuning, but it appears that the breakdown of injection locking can be reliably confirmed by measuring the RF spectrum.

Interesting intermediate states are observed immediately next to the resonance peaks of the stable degenerate state when scanning the OPO cavity length. Narrow peaks corresponding to this state are denoted with D in Fig. 2, and the respective optical spectrum is shown in panel D of Fig. 3. An exceptionally wide spectrum is observed, with the −10 dB bandwidth being more than 220 nm (25 THz, capable of supporting 20 fs pulses) around the 1606 nm center wavelength. This state is, however, unstable and the OPO typically stops oscillating or drifts to the more stable degenerate state within a few seconds of operation if no active stabilization of the OPO cavity length is applied. The RF spectrum of this state is similar to that of the near-degenerate state, indicating that no mutual injection locking of the signal and idler combs is obtained.

The OPO oscillates for extended periods of time on any of the resonance peaks shown in Fig. 2 (except for peaks D) even without active stabilization of the OPO cavity length, as long as no extreme perturbations, such as air flows, are present. Uninterrupted operation of more than 1 h has been observed. The output power is relatively stable in the degenerate state, typical peak-to-peak fluctuations being on the order of 30%. These fluctuations increase up to ~90% peak-to-peak (in a time scale of few tens of seconds) as the OPO is tuned far from degeneracy. We were able to reduce the fractional power fluctuations down to a few percent by actively locking the cavity length to the top of any of the resonance peaks shown in Fig. 2. A simple dither-and-lock approach [4] with a locking bandwidth of ~1 Hz was sufficient to do this. Active locking of the cavity length was observed to stabilize the spectral content of the OPO output as well.

In conclusion, we have reported a high-repetition-rate degenerate femtosecond OPO, which is pumped by a Kerr lens mode-locked Ti:sapphire laser. The OPO produces a stable, 10 THz wide frequency comb centered at 1.6 μm. The average output power is more than 100 mW. The width of the comb and the 1 GHz repetition rate significantly exceed those of a typical Er-doped fiber laser, which is the most widely used source for frequency comb generation in the optical telecom region [8,9]. Unlike the previously reported singly resonant high-repetition-rate OPOs [7,10–12], the degenerate OPO presented here enables simple self-phase-locked operation with respect to the pump comb. Future improvements include full stabilization of the OFC, which can be done by locking f_{rep} and f_{ceo} of the undepleted part of the pump comb to an atomic clock [7,13].

The University of Helsinki and the Academy of Finland are gratefully acknowledged for financial support. M. Vainio thanks the Emil Aaltonen Foundation for a travel grant that helped to accomplish this work.

References

1. A. Schliesser, N. Picqué, and T. W. Hänsch, Nat. Photonics **6**, 440 (2012).
2. S. T. Wong, K. L. Vodopyanov, and R. L. Byer, J. Opt. Soc. Am. B **27**, 876 (2010).
3. N. Leindecker, A. Marandi, R. L. Byer, and K. Vodopyanov, Opt. Express **19**, 6296 (2011).
4. A. Marandi, N. Leindecker, V. Pervak, R. L. Byer, and K. L. Vodopyanov, Opt. Express **20**, 7255 (2012).
5. K. L. Vodopyanov, E. Sorokin, I. T. Sorokina, and P. G. Schunemann, Opt. Lett. **36**, 2275 (2011).
6. N. Leindecker, A. Marandi, R. L. Byer, K. L. Vodopyanov, J. Jiang, I. Hartl, M. Fermann, and P. G. Schunemann, Opt. Express **20**, 7046 (2012).
7. R. Gebs, T. Dekorsy, S. A. Diddams, and A. Bartels, Opt. Express **16**, 5397 (2008).
8. T. Wilken, T. W. Hänsch, R. Holzwarth, P. Adel, and M. Mei, in *Conference on Lasers and Electro-Optics* (IEEE, 2007), paper CMR3.
9. H. Byun, D. Pudo, J. Chen, E. P. Ippen, and F. X. Kärtner, Opt. Lett. **33**, 2221 (2008).
10. X. P. Zhang, J. Hebling, A. Bartels, D. Nau, J. Kuhl, W. W. Rühle, and H. Giessen, Appl. Phys. Lett. **80**, 1873 (2002).
11. O. Kokabee, A. Esteban-Martin, and M. Ebrahim-Zadeh, Opt. Express **17**, 15635 (2009).
12. T. I. Ferreiro, J. Sun, and D. T. Reid, Opt. Express **19**, 24159 (2011).
13. M. Merimaa, K. Nyholm, M. Vainio, and A. Lassila, IEEE Trans. Instrum. Meas. **56**, 500 (2007).