Phase-stabilized, 1.5 W frequency comb at 2.8–4.8 μm

Florian Adler,[1,*] Kevin C. Cossel,[1] Michael J. Thorpe,[1] Ingmar Hartl,[2] Martin E. Fermann,[2] and Jun Ye[1]

[1] *JILA, National Institute of Standards and Technology and University of Colorado, and Department of Physics, University of Colorado, Boulder, Colorado 80309-0440, USA*

[2] *IMRA America Inc., 1044 Woodridge Avenue, Ann Arbor, Michigan 48105, USA*

**Corresponding author: fadler@jila.colorado.edu*

Received February 11, 2009; accepted March 16, 2009;
posted March 31, 2009 (Doc. ID 107383); published April 20, 2009

We present a high-power optical-parametric-oscillator (OPO) based frequency comb in the mid-IR wavelength region. The system employs periodically poled lithium niobate and is singly resonant for the signal. It is synchronously pumped by a 10 W femtosecond Yb:fiber laser centered at 1.07 μm. The idler (signal) wavelength can be continuously tuned from 2.8 to 4.8 μm (1.76 to 1.37 μm) with a simultaneous bandwidth as high as 0.3 μm and a maximum average idler output power of 1.50 W. We also demonstrate the performance of the stabilized comb by recording the heterodyne beat with a narrow-linewidth diode laser. This OPO is an ideal source for frequency comb spectroscopy in the mid-IR.

OCIS codes: 190.4970, 320.7160, 140.7090.

In recent years, frequency combs have become attractive laser sources for a variety of applications—the latest of which is the direct use of comb sources for precision spectroscopy. Frequency combs provide a unique combination of large wavelength coverage and high spectral resolution, and therefore they allow for simultaneous, precise, and rapid scanning of wide regions of interest [1–6]. Furthermore, the spectroscopic sensitivity may be massively increased by efficiently coupling the comb to a high-finesse optical enhancement cavity. Consequently, cavity-enhanced direct frequency comb spectroscopy (CE-DFCS) [7] proved very successful for the detection of small quantities of trace gases [4,8].

Despite its success, CE-DFCS has so far not been able to exploit its full potential. Practical comb sources are mostly limited to Ti:sapphire and Er:fiber lasers and therefore to the near-IR spectral region of less than 2 μm; however, fundamental rovibrational absorption bands of nearly all molecules lie in the mid-IR of 3 to 12 μm and beyond. Therefore, currently used frequency combs have to rely on weaker overtone vibrations, compromising the detection sensitivity by about 2-3 orders of magnitude. There are two common strategies to generate a mid-IR frequency comb. The first one is difference-frequency generation, which offers flexible and simple IR comb generation [9–11]. The second approach is the use of optical parametric oscillators (OPOs). In particular, femtosecond OPOs based on periodically poled lithium niobate (PPLN) are able to provide high output power and easy alignment owing to quasi phase matching [12,13]; however, stable mid-IR combs [14,15] have not been demonstrated for wavelengths higher than 2.5 μm at a power level, repetition rate, and spectral coverage sufficient for frequency comb spectroscopy (>1 μW per comb mode).

In this Letter we present a fiber-laser pumped OPO based on a fan-out MgO-doped PPLN crystal that provides a high-power frequency comb in the mid-IR spectral region. We generate up to 0.3-μm-wide idler spectra, which are continuously tunable from 2.8 to 4.8 μm with an average power of up to 1.5 W. We also present a scheme for full electronic stabilization of the mid-IR frequency comb with a demonstration of the optical beat note between the doubled idler signal and a narrow-linewidth diode laser at 1.545 μm.

A schematic of our setup is depicted in Fig. 1(a). The OPO is designed with a five-mirror linear cavity and is singly resonant for the signal. Its length is matched to the repetition rate of the pump laser

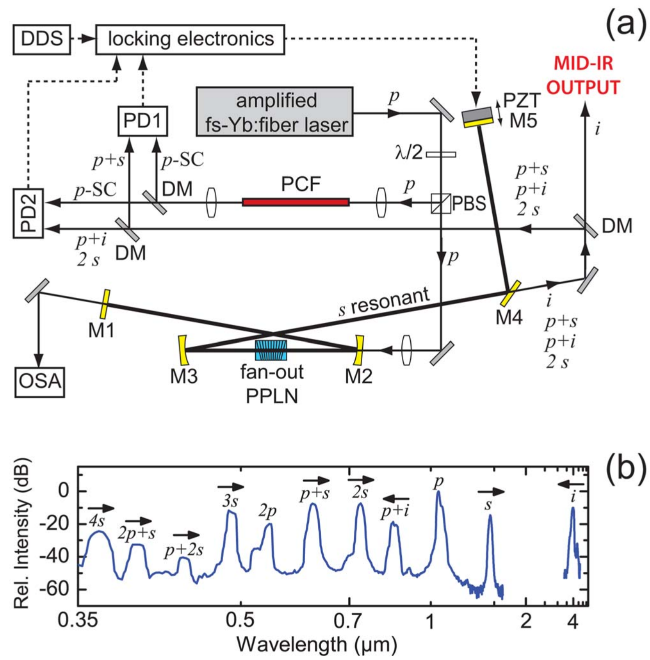

Fig. 1. (Color online) Schematic of the OPO setup: M1–M5, OPO cavity mirrors; DM, dichroic mirrors; PBS, polarizing beam splitter; PD1 and PD2, Si photodiodes; PCF, photonic crystal fiber; DDS, rf synthesizer; PZT, piezo. (b) Snapshot of all emitted wavelengths (intensity not to scale); the arrows indicate the spectral shift for increasing crystal poling period.

(f_{rep}=136 MHz), resulting in a 110 cm OPO cavity. The amplified Yb:fiber pump laser delivers 100 fs pulses with a maximum average power of 10 W at a center wavelength of 1.07 μm [16] and is coupled into the cavity through mirror M2 ($T>97\%$). The OPO crystal is a 7-mm-long MgO-doped PPLN with a fan-out grating structure; the poling period varies linearly over the width of the crystal from 25.5 to 32.5 μm. Therefore, the OPO's wavelength is tuned by simply translating the PPLN. As a precaution to prevent damage from the intense pump beam, the crystal is heated to a temperature of 71 °C. As we currently do not require the signal output, all cavity mirrors (M1–M5) in the present setup are highly reflective for 1.35–1.80 μm. M4 couples out both pump and idler with an average transmission of 95%. A variety of generally non-phase-matched mixing signals is emitted along with signal (s) and idler (i). Figure 1(b) shows a spectrum of the light leaking through end mirror M1 recorded with an optical spectrum analyzer (OSA) along with the corresponding idler spectrum. The most prominent mixing signals are the sum frequencies of pump and signal ($p+s$), pump and idler ($p+i$), and frequency-doubled pump ($2p$) and signal ($2s$). Although these wavelengths are only by-products from the OPO process, they exhibit powers of several milliwatts and are used to stabilize the mid-IR comb.

The powerful pump laser and the large nonlinearity of the PPLN lead to a high conversion efficiency into the IR over a wide tuning range. Figure 2 shows the idler output power (triangles, left axis) and photon conversion efficiency (circles, right axis) measured at the M4 output port for different center wavelengths. The pump laser is operated at 8.47 W at all crystal positions. The maximum idler power (1.42 W) is obtained at 3.19 μm, whereas the highest photon conversion efficiency of 51% is observed at a wavelength of 3.59 μm (1.29 W of average power). Most notably, a power of at least 1 W is maintained over a tuning range of more than 1 μm. The drops at short and long idler wavelengths agree well with the expected trend due to the mirror reflectivities (gray dashed curve). To extract the OPO threshold and slope efficiency, we plot the mid-IR output power against pump power at one specific crystal position (λ_{idler}=3.01 μm), as shown in the inset of Fig. 2. The threshold pump power is 1.7 W, which is reasonable considering the fact that the OPO cavity and the pump laser are not dispersion managed and that the strong pump light is not tightly focused into the crystal. The slope efficiency starts off at 0.29 and reduces to 0.16 at about 4 W of pump power due to the onset of a competing conversion process. Most notably, we do not observe any indication of nonlinear losses with up to 9.17 W of pump power, where we measure 1.50 W of idler power. In addition, spectral data are recorded with a scanning monochromator and a liquid-nitrogen-cooled InSb detector (see Fig. 3). The center wavelength is tuned solely by translating the crystal and ranges from 2.8 to 4.8 μm. The largest simultaneous bandwidth (FWHM) is 0.3 μm, obtained at 3.26 μm.

Finally, we stabilize and characterize the mid-IR idler frequency comb. Its nth comb tooth may be described by the usual equation $\nu_n^i = f_0^i + n f_{rep}$, where f_0^i stands for the idler comb offset and n is an integer number on the order of $10^5 - 10^6$. The superscript i may be replaced by s or p when referring to the signal or pump comb, respectively. The three comb offset frequencies are connected by the relation $f_0^p = f_0^s + f_0^i$. The stabilization scheme is implemented by exploiting the generated parasitic mixing signals (see Fig. 1). In general we utilize $p+s$ and $p+i$, which are separated by a dichroic mirror (DM) and focused onto separate Si detectors (PD1 and PD2, respectively). To obtain a useful beat note, we pick off a small portion of the pump light before the OPO cavity and broaden the spectrum in a photonic crystal fiber (PCF). The generated pump supercontinuum (p-SC) provides spectral coverage down to 600 nm and is superimposed with $p+s$ and $p+i$ on the respective detectors. Hence, the observed heterodyne beats correspond to f_0^s and f_0^i, respectively. Typically, f_0^s is locked to a stable rf reference (DDS) via a piezo (PZT)-actuated M5, thus stabilizing the OPO cavity length. Then f_0^i may be stabilized via $f_0^s + f_0^i = f_0^p$ by feeding back to the fiber laser's pump diode power (which acts on f_0^p).

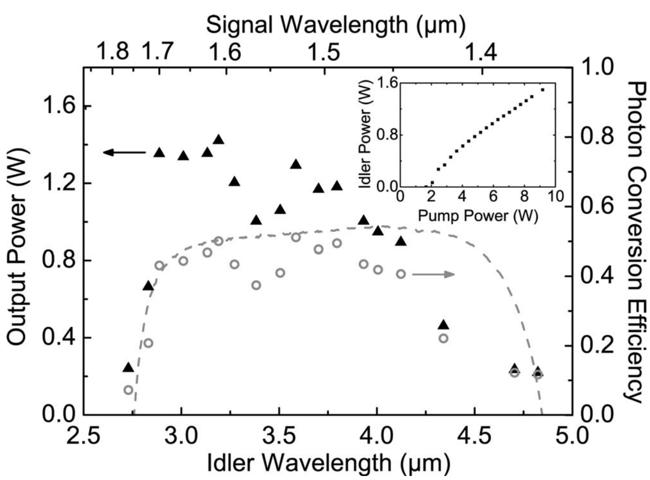

Fig. 2. Idler output power (triangles) and photon conversion efficiency (circles) of the OPO for different idler wavelengths. The gray dashed curve represents the trend for the conversion efficiency expected from the mirror reflectivities. The inset shows the idler power versus pump power characteristics at λ_{idler}=3.01 μm.

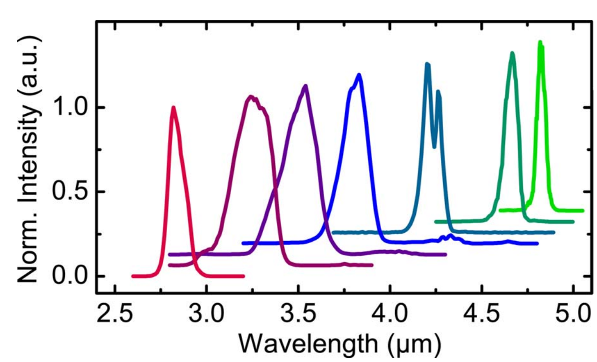

Fig. 3. (Color online) Collection of typical idler spectra (normalized and vertically offset for clarity).

The resulting stability and comb-tooth linewidth is demonstrated with an optical beat between $2i$ and a 10 kHz linewidth external cavity diode laser (ECDL) operating at 1.545 μm, as shown in Fig. 4. The idler spectrum is tuned to a center wavelength of 3.09 μm, frequency doubled in a GaSe crystal, and combined with the ECDL light in a single-mode fiber. We lock f_{rep} of the pump laser by generating an optical beat note between the Yb:fiber comb and a 1 kHz linewidth, 1.064 μm nonplanar ring oscillator (NPRO) [see Fig. 4(a)], thus obtaining high short-term stability. With the idler tuned to 3.09 μm (and signal to 1.64 μm) the stabilization of f_0^i is particularly simple, because the mixing signals $p+i$ and $2s$ happen to be spectrally overlapped. Therefore the beam focused onto PD2 contains an intrinsic heterodyne beat, and light from the PCF is no longer required. The resulting rf frequency represents $2f_0^i - f_0^s$ and is therefore an appropriate feedback for stabilizing the OPO length [see Fig. 4(b)], since the free-running f_0^p shows sufficient stability (and so is $f_0^s + f_0^i = f_0^p$). Once $2f_0^i - f_0^s$ is locked, a constant beat note between $2i$ and the ECDL is detected [see Fig. 4(c)]. The wide pedestal is consistent with the one observed in the f_{rep} lock. The coherent peak of the beat signal exhibits a 3 dB linewidth of 80 kHz, which corresponds to 40 kHz in the fundamental idler comb. This linewidth is currently limited by the feedback bandwidth of the PZT.

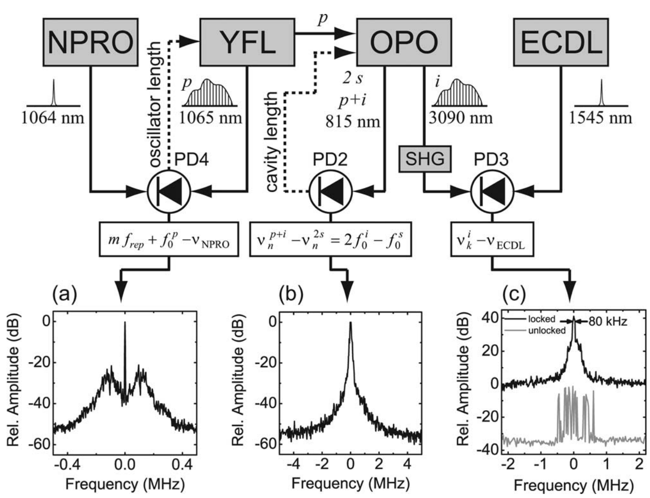

Fig. 4. Experimental setup and rf signals for stabilization of the OPO and measurement of the idler-comb linewidth. NPRO, nonplanar ring oscillator; YFL, Yb:fiber pump laser; ECDL, external-cavity diode laser; PD2-PD4, photodiodes; SHG, second-harmonic-generation crystal (GaSe). (a) In-loop signal for stabilization of f_{rep}, 1 kHz resolution bandwidth (RBW). (b) In-loop signal for stabilization of $2f_0^i - f_0^s$, 3 kHz RBW. (c) Out-of-loop beat note between $2i$ and ECDL, with locked OPO (black; 2 s sweep time, 3 kHz RBW) and unlocked OPO (gray; 0.5 s sweep time, 10 kHz RBW); the traces are vertically offset for clarity

In summary, we have presented a high-power OPO frequency comb that will serve as an excellent source for coherent spectroscopy techniques such as CE-DFCS in the wavelength range of 2.8 to 4.8 μm. The maximum idler power of 1.50 W is the highest power reported to date for a synchronously pumped OPO in the mid-IR wavelength region, which promises exceptional signal-to-noise ratio for spectroscopy experiments. Additionally, the covered spectral region contains strong fundamental vibrational bands of many important trace gases. Thus detection sensitivities will be drastically enhanced compared to experiments operating in the near-IR [4,8]. Owing to the robust fiber-based pump source and the electronic lock, the OPO provides a stable comb with more than 30 μW per mode over hours of operation, which is essential for real-world spectroscopy experiments.

We thank D. C. Yost, M. J. Martin, and T. R. Schibli for valuable assistance. F. Adler acknowledges support by the Alexander von Humboldt foundation. This work is funded by U.S. Air Force Office of Scientific Research (AFOSR), the Defense Advanced Research Projects Agency (DARPA), the National Institute of Standards and Technology (NIST), and Agilent.

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