Room-temperature, rapidly-tunable, green-pumped continuous-wave optical parametric oscillator

KAVITA DEVI[1,*] AND M. EBRAHIM-ZADEH[1,2]

[1]*ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain*
[2]*Institucio Catalana de Recerca i Estudis Avancats (ICREA), Passeig Lluis Companys 23, Barcelona 08010, Spain*
**Corresponding author: kavita.devi@icfo.eu*

Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

We report the first realization of a high-power, single-frequency, green-pumped continuous-wave optical parametric oscillator (OPO) capable of providing rapid and continuous tuning across wide spectral range in the near-infrared at room temperature. By exploiting the nonlinear crystal of MgO:sPPLT in a fan-out grating design, pumped at 532 nm in the green, the OPO can be tuned continuously across 1097–2100 nm in the idler, with corresponding signal tuning over 712–1033 nm using simple mechanical translation of the crystal at fixed temperature. The device can deliver hundreds of mW of idler power across the complete tuning range, with as much as 2.2 W at 1097 nm for 9 W of input pump power at 77% pump depletion. The passive power stability of the generated idler at 1110 nm, measured at 6.8 W of pump power, is better than 1% rms over 30 minutes. The signal frequency stability, measured at 837 nm, is 518 MHz over 2 minutes, with an instantaneous linewidth of 6.9 MHz, in high beam quality.

OCIS codes: *(190.4360) Nonlinear optics, devices; (190.4400) Nonlinear optics, materials; (190.4970) Parametric oscillators and amplifiers.*

http://dx.doi.org/10.1364/OL.99.099999

Continuous-wave (cw) single-frequency light sources capable of rapid and uninterrupted tuning are of great interest for diverse range of applications from spectroscopy and trace gas sensing to biomedicine [1]. Optical parametric oscillators (OPOs) are versatile sources of widely tunable radiation, capable of accessing spectral regions from the visible to infrared (IR), and operating in all time-scales from the cw to ultrafast femtosecond domain [2]. In the cw regime, owing to the small parametric gain available under low pump intensities, practical operation of OPOs relies almost exclusively on quasi-phase-matched (QPM) nonlinear materials [3], exploiting the highest nonlinear tensor coefficients combined with long interaction lengths under noncritical phase-matching (NCPM). For access to the near- and mid-IR spectrum, MgO-doped periodically-poled $LiNbO_3$ (MgO:PPLN) has been the QPM material of choice, enabling the development of cw OPOs with multi-Watts of output power across the ~1.4-4 µm range, using solid-state and Yb-fiber pump lasers near 1 µm [4]. For the generation of wavelengths below ~1.4 µm, however, where green pumping is required, MgO:sPPLT has proved the most viable QPM material due to its large resistance to photorefractive damage, relatively high optical nonlinearity (d_{eff}>10 pm/V), and large thermal conductivity (8.4 W/m-K), enabling the generation of multi-Watt optical powers across 848-1427 nm spectral range using temperature tuning [5,6]. For the attainment of rapid and continuous wavelength tuning, the use of QPM nonlinear crystals with fan-out grating design at a fixed temperature is a viable approach [7-9], as it is a fast process compared to temperature tuning and can be implemented at room temperature. Moreover, away from degeneracy, material dispersion in QPM crystals leads to reduced tuning rate under temperature phase-matching, thus requiring relatively large temperature changes for small variation in the output wavelengths [10]. The technique of grating period tuning at fixed temperature has already been successfully deployed in cw OPOs for direct near- and mid-IR generation using MgO:PPLN [8], and for internal frequency doubling into the visible using MgO:sPPLT [9]. However, for direct pumping in the green to

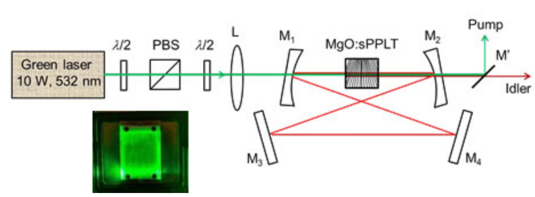

Fig. 1. Schematic of the rapidly tunable cw near-IR OPO. $\lambda/2$: half-wave plates; PBS, polarizing beam-splitter; L, lens; M_{1-4}, mirrors; M': dichroic mirror. Inset: Laboratory picture of the mounted MgO:sPPLT crystal.

generate wavelengths below ~1.4 µm, where short grating periods ($\Lambda \lesssim 10$) µm are necessary, there have been significant challenges in QPM fabrication technology to provide the required fan-out grating designs over sufficient interaction length, thickness, and lateral dimension of the crystal for wavelength tuning. In the case of MgO:sPPLT, the challenges in QPM technology are further compounded by the growth and fabrication of the stoichiometric material itself, which, unlike MgO:PPLN, is still in the earlier stages of development. These factors have thus presented a serious barrier to the advancement of green-pumped cw OPOs capable of rapid continuous tuning at a fixed temperature using fan-out grating QPM material designs. As such, in all green-pumped cw OPOs demonstrated to date, wavelength tuning has been achieved by variation of crystal temperature [4-6]. Moreover, due to the photorefractive effect, attainment of stable operation close to room temperature has remained challenging. Here we report what is to our knowledge the first cw OPO based on a fan-out grating QPM crystal pumped directly in the green. The device also represents the first cw OPO providing rapid broadband continuous tuning at room temperature in any wavelength range. The new cw OPO is realized by exploiting the latest advances in QPM technology, which have enabled the fabrication of large MgO:sPPLT crystals in fan-out grating design with short grating periods of $\Lambda \lesssim 10$ µm over long interaction lengths, with practical thickness and wide lateral dimension. We demonstrate stable and reliable operation of the cw OPO under green pumping for broadband near-IR generation at room temperature, without any photorefractive damage to the crystal. The OPO can provide continuous tuning across 712–1033 nm in the signal and 1097–2100 nm in the idler, with an idler power as much as 2.2 W at 1097 nm at a pump depletion of >77%, with a passive power stability of 1% rms over 30 minutes.

The schematic of the experimental setup is shown in Fig. 1. The pump source for the OPO is a cw single-frequency solid-state laser delivering up to 10 W of output power at 532 nm in a linearly polarized beam with M^2<1.1. To maintain stable output characteristics, the laser is operated at maximum power and a combination of a half-wave plate (HWP) and a polarizing beam-splitter is used for power attenuation. A second HWP is used to adjust the pump polarization for phase-matching in the nonlinear crystal, which is 29-mm-long, 31-mm-wide, and 0.8-mm-thick MgO:sPPLT in fan-out grating design with periods varying over Λ=7.8-9.5 µm across its lateral dimension. It is housed in an oven

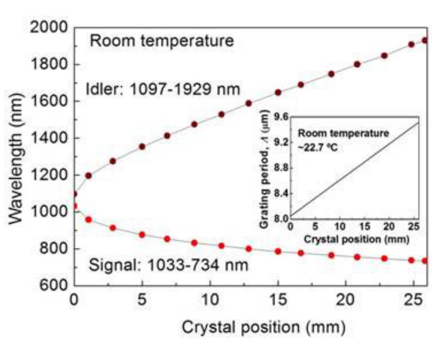

Fig. 2. Rapid wavelength tuning with crystal translation at room temperature. Inset: Theoretically calculated grating period corresponding to the crystal position used.

with a stability of ±0.1 °C, adjustable from room temperature to 200 °C, and mounted on a linear stage with resolution of 10 µm to enable fine and continuous translation of the crystal for smooth grating tuning across its width. The end-faces of the crystal are antireflection (AR)-coated at 532 nm (R<2%), 700-1050 nm (R<0.5%), and 1050-2200 nm (R<15%). A laboratory photograph of the MgO:sPPLT crystal is shown in the inset of Fig. 1. The OPO is configured in a compact ring cavity comprising two concave mirrors, $M_{1,2}$ (r=-100 mm), and two plane mirrors, $M_{3,4}$. All mirrors are highly reflecting (R>99.8%) for the signal (620–1030 nm) and highly transmitting (T>97%) for the idler (1078–3550 nm) and pump, ensuring singly-resonant signal oscillation. Using a lens, L, of focal length, f=150 mm, the pump beam is focused to waist radius of w_p~36 µm, while the design of the OPO resonator results in a signal waist radius of w_s~56 µm at the center of the MgO:sPPLT crystal. A dichroic mirror, M′, is used to separate the output idler from the transmitted pump.

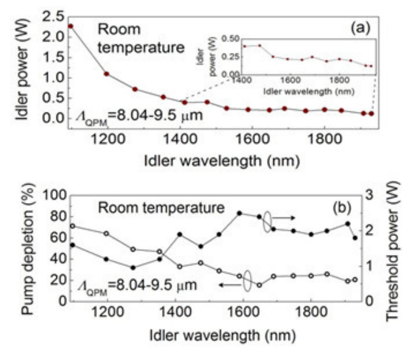

Fig. 3. Variation of (a) Idler power, and (b) Pump depletion and threshold power across the grating tuning range at room temperature.

Wavelength tuning in the present OPO can be achieved by linear mechanical translation of the crystal, which results in the variation of grating period, or by controlling its temperature, while keeping either parameter fixed. We initially maintained the crystal at room temperature and recorded the output signal wavelength using a spectrometer, while varying the grating period, and pumping for maximum output power generation. The idler wavelengths were calculated from energy conservation. The room temperature in the laboratory was measured to be 22.7 ºC. The measured signal (734-1033 nm) and corresponding idler (1097-1929 nm) wavelengths as function of crystal position across its width are shown in Fig. 2, while the inset shows the corresponding theoretically calculated grating periods using relevant Sellmeier equations [10]. Having determined the longest signal wavelength at which the OPO operation could be achieved at room temperature, tuning was initiated at this point (1033 nm, corresponding to Λ=8.04 µm) by translating the crystal over 26 mm out of its full width of 31 mm. This resulted in signal tuning across 1033-734 nm, corresponding to a calculated grating period variation of Λ=8.04-9.5 µm. Signal tuning in steps of ~0.2 nm, corresponding to crystal translation of ~100 µm, across the tuning range was deduced from the measurements. Given the smooth translation of the linear stage, the signal and the corresponding idler could be finely and uninterruptedly tuned. However, measurements in step of <0.2 nm were limited by the resolution of the spectrometer. Using a motorized translation stage, we further verified that the OPO can be tuned across the full wavelength range within 20 seconds.

Figure 3(a) shows the maximum generated power measured across the idler tuning range (1097-1929 nm) at room temperature. Also, a zoomed version for the idler power at longer wavelengths is shown in the inset of Fig. 3(a). As evident, the OPO can provide >120 mW of idler power over the entire tuning range, with up to 2.2 W at 1097 nm. The corresponding pump depletion and threshold pump power are shown in Fig. 3(b). The pump depletion is above ~20% and pump threshold power is below ~2.5 W over the entire tuning range. The drop in idler power and pump depletion at longer wavelengths is attributed to the reduction in parametric gain away from degeneracy, as well as the stronger saturation in idler power at longer wavelengths at higher pump power levels, as also observed in earlier reports on MgO:sPPLT [5]. It is to be noted that all recorded idler powers reported here do not account for the coating losses of mirror, M_2, and dichroic mirror, M'.

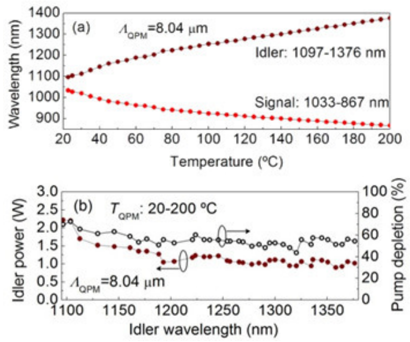

Fig. 4. (a) Temperature tuning, and (b) Variation of idler power and corresponding pump depletion across the tuning range for the shortest grating period of Λ=8.04 μm.

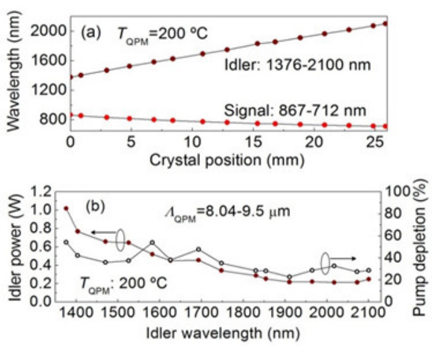

Fig. 5. (a) Grating tuning, and (b) Idler power and pump depletion across the tuning range at a fixed crystal temperature of 200 ºC.

We then varied the crystal temperature from room temperature to 200 ºC, while keeping the crystal grating period fixed at Λ=8.04 μm, and measured the generated output wavelength as a function of temperature, with the results shown in Fig. 4(a). The measured idler output power and the corresponding pump depletion across the obtained idler tuning range of 1097-1376 nm are shown in Fig. 4(b). The idler power varies from 2.2 W at 1097 nm (22.7 ºC) to 0.9 W at 1358 nm (185 ºC), while the pump depletion remains above 40% over the entire tuning range.

Given the decrease in signal wavelength with increase in crystal temperature, in order to generate the shortest signal wavelength we performed grating period tuning, while keeping the crystal temperature fixed at the maximum 200 ºC. Figure 5(a) shows the measured signal (712-867 nm) and the corresponding idler (1376-2100 nm) wavelengths as a function of the same crystal positions as in the inset of Fig. 2. It can be seen that operating the crystal at 200 ºC results in the shortest signal wavelength of 712 nm compared to 734 nm at room temperature. The maximum generated idler power and the corresponding pump depletion across the tuning range are shown in Fig. 5(b). As can be seen, the idler power varies from 1 W at 1376 nm to 213 mW at 2018 nm, with >20% pump depletion across the tuning range.

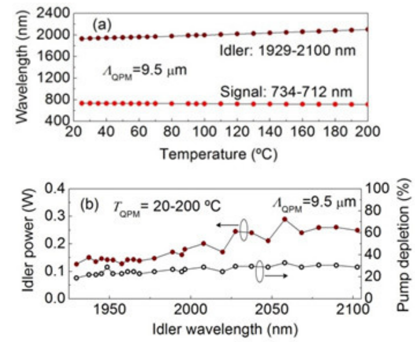

Fig. 6. (a) Temperature tuning, and (b) Variation of idler power and pump depletion across the tuning range for the longest grating period of Λ=9.5 μm.

We further performed temperature tuning at the longest grating period in the crystal, with the results shown in Fig. 6(a). We obtained a signal tuning range across 712-734 nm at the fixed grating period of Λ=9.5 μm by varying the crystal temperature from 22.7 ºC to 200 ºC, with the corresponding calculated idler range over 1929-2100 nm. As expected, at the longer grating periods, as we move further away from degeneracy, the variation in the signal and idler wavelength with temperature is small, only 22 nm and 171 nm, respectively, due to the dispersion properties of MgO:sPPLT, similar to other QPM crystals [3]. The measured idler output power and the corresponding pump depletion across the obtained tuning range are shown in Fig. 6(b). The idler power varies between 260 mW and 126 mW, while the pump depletion remains above ~20% across the full tuning range.

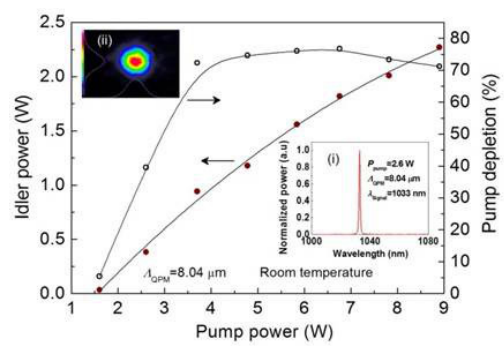

Fig. 7. Idler output power and pump depletion as function of pump power at room temperature. Inset: (i) Signal spectrum at 1033 nm, and (ii) Far-field energy distribution of the signal at 826 nm.

In order to investigate the power scaling capability of the OPO at room temperature, we measured the idler output power as a function of pump power. The result is shown in Fig. 7, where a maximum idler power of 2.2 W at 1097 nm is obtained, with a pump power threshold of 1.6 W. Also shown in Fig. 7 is the pump depletion, which is observed to rapidly increase to 77% before the onset of saturation. Using the leaked-out signal power from mirror, M_4, we recorded the typical spectrum of the corresponding signal centred at 1033 nm, as shown in inset (i) of Fig. 7. Also shown in inset (ii) is the far-field energy distribution of the output signal beam together with the orthogonal intensity profiles at a shorter wavelength of 826 nm at maximum power, confirming a high spatial quality in Gaussian profile with circularity >95%.

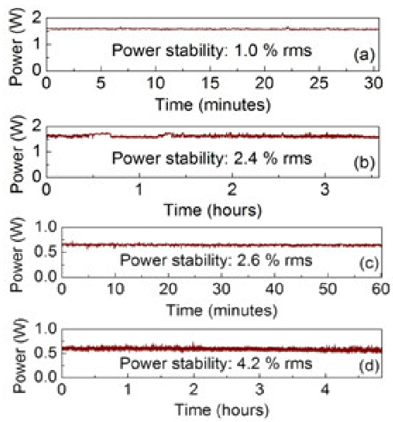

Fig. 8. Passive power stability of the idler at room temperature for (a) 30 min, and (b) >3 h, and at 200 ºC for (c) 60 min, and (d) >4 h.

We also recorded the power stability of the output idler at 1120 nm and 1460 nm, under free-running conditions, with the crystal at room temperature and 200 ºC, respectively. The results are shown in Fig. 8 (a-d). As evident, the idler power exhibits a passive stability better than 1.0% rms over 30 minutes and 2.4% rms over >3 hours at room temperature, while at 200 ºC the stability is 2.6% rms over 1 hour and 4.2% rms over >4 hours. The higher power stability at room temperature is attributed to the negligible temperature fluctuations, as compared to that when the crystal is at 200 ºC.

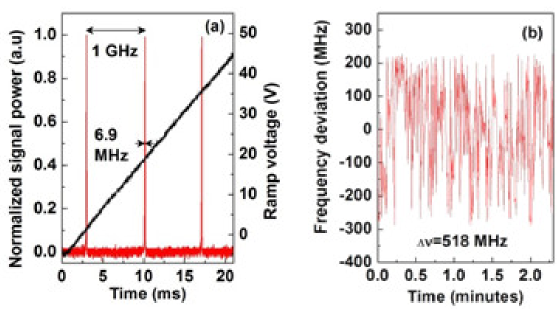

Fig. 9. (a) Single-frequency spectrum, and (b) Frequency stability of the signal at 837 nm.

We also studied the frequency characteristics of the OPO by introducing a 0.4 mm-thick uncoated UV fused silica etalon (FSR=255 GHz, Finesse <1) into the cavity between mirrors, M_3 and M_4, for frequency selection. With the intracavity etalon, no reduction in output power was observed, although the threshold increased by ~200 mW across the tuning range. Using a confocal Fabry–Perot interferometer (FSR=1 GHz, finesse~400), we recorded the transmission spectrum of the output signal at 837 nm, where an instantaneous linewidth of 6.9 MHz was measured, as shown in Fig. 9(a), confirming single-frequency operation. We also determined the passive frequency stability of the OPO by recording the signal wavelength as a function of time using a wavemeter (High finesse, WS/U-30). The result is shown in Fig. 9(b). Under free-running conditions, the signal output exhibited a peak-to-peak frequency deviation of Δν~518 MHz over ~2 minutes measured at a central wavelength of 837.09514 nm.

In conclusion, we have demonstrated what is to our knowledge the first cw OPO providing broad and continuous wavelength coverage in the near-IR at room temperature, by exploiting a fan-out grating design in MgO:sPPLT, pumped in the green. We have generated continuously tunable signal radiation across 1033-712 nm, with the corresponding idler tunable over 1097-2100 nm. The OPO provides hundreds of mW of output power across the full idler tuning range, with as much as 2.2 W at 1097 nm. The exploitation of the fan-out grating design at room temperature results not only in wide, rapid, and uninterrupted wavelength tuning, but also improved output power and frequency stability. In the absence of active control, the OPO exhibits an idler power stability better than 1% rms over 30 minutes and a signal frequency stability of ~518 MHz over ~2 minutes, which can both be improved by further mechanical and vibration isolation of the system. After long-term operation of the OPO at room temperature over several months, we have not observed any damage to the MgO:sPPLT crystal, or any degradation in the output beam quality and other performance characteristics of the system. The continuous tuning coverage can be further extended to shorter signal and longer idler wavelengths by exploiting longer grating periods in the fan-out design in MgO:sPPLT under the same green pumping scheme. Moreover, the practical low threshold pump power of the OPO at room temperature suggests the feasibility of deploying suitable output coupling to extract significant amounts of signal power from the device. These characteristics make the OPO a highly versatile and practical source of widely and rapidly tunable near-IR radiation for many applications.

Funding. Ministerio de Economía y Competitividad (MINECO), Spain (NuOPO, TEC2015-68234-R); European Commission (Mid-Tech, H2020-MSCA-ITN-2014); Generalitat de Catalunya (CERCA Programme); Severo Ochoa Programme for Centres of Excellence in R&D (SEV-2015-0522); Fundació Privada Cellex.

Acknowledgment. We thank Dr. S. Chaitanya Kumar for his assistance in the early stages of this work.

References

1. D. D. Arslanov, M. Spunei, J. Mandon, S. M. Cristescu, S. T. Persijn, and F. J. M. Harren, Laser Photon. Rev. **7**, 188 (2013).
2. M. Ebrahim-Zadeh, Mid-infrared ultrafast and continuouswave optical parametric oscillators, in: Solid-State Mid-Infrared Laser Sources, edited by I. T. Sorokina and K. L. Vodopyanov, Springer-Verlag Science Series, Top. Appl. Phys. 89, 184–224 (2003).
3. M. Ebrahim-Zadeh, "Continuous-wave optical parametric oscillators," in *Handbook of Optics* (OSA, McGraw-Hill, vol. **IV**, Chap. 17, pp. 1–33 (2010).
4. M. Ebrahim-Zadeh, S. Chaitanya Kumar, and K. Devi, IEEE J. Sel. Top. Quantum Electron. **20**, 0902823 (2014).
5. G. K. Samanta, G. R. Fayaz, and M. Ebrahim-Zadeh, Opt. Lett. **32**, 2623 (2007).
6. S. Chaitanya Kumar, K. Devi, G. K. Samanta, and M. Ebrahim-Zadeh, Laser Phys. **21**, 782 (2011).
7. P. E. Powers, T. J. Kulp, and S. E. Bisson, Opt. Lett. **23**, 159 (1998).
8. A. Henderson and R. Stafford, Opt. Express **14**, 767 (2006).
9. K. Devi, S. Chaitanya Kumar, and M. Ebrahim-Zadeh, Opt. Lett. **37**, 5049 (2012).
10. A. Bruner, D. Eger, M. B. Oron, P. Blau, M. Katz, and S. Ruschin, Opt. Lett. **28**, 194 (2003).

References (with title)

1. D. D. Arslanov, M. Spunei, J. Mandon, S. M. Cristescu, S. T. Persijn, and F. J. M. Harren, "Continuous-wave optical parametric oscillator based infrared spectroscopy for sensitive molecular gas sensing," Laser Photon. Rev. **7**, 188-206 (2013).
2. M. Ebrahim-Zadeh, Mid-infrared ultrafast and continuouswave optical parametric oscillators, in: Solid-State Mid-Infrared Laser Sources, edited by I. T. Sorokina and K. L. Vodopyanov, Springer-Verlag Science Series, Top. Appl. Phys. 89, 184–224 (2003).
3. M. Ebrahim-Zadeh, "Continuous-wave optical parametric oscillators," in *Handbook of Optics* (OSA, McGraw-Hill, vol. **IV**, Chap. 17, pp. 1–33 (2010).
4. M. Ebrahim-Zadeh, S. Chaitanya Kumar, and K. Devi, "Yb-fiber-laser-pumped continuous-wave frequency conversion sources from the mid-infrared to the ultraviolet," IEEE J. Sel. Top. Quantum Electron. **20**, 0902823 (2014).
5. G. K. Samanta, G. R. Fayaz, and M. Ebrahim-Zadeh, "1.59 W, single-frequency, continuous-wave optical parametric oscillator based on MgO:sPPLT," Opt. Lett. **32**, 2623-2625 (2007).
6. S. Chaitanya Kumar, K. Devi, G. K. Samanta, and M. Ebrahim-Zadeh, "Fiber-laser-based green-pumped continuous-wave singly-resonnat optical parametric oscillator," Laser Phys. **21**, 782-789 (2011).
7. P. E. Powers, T. J. Kulp, and S. E. Bisson, "Continuous tuning of a continuous-wave periodically poled lithium niobate optical parametric oscillator by use of a fan-out grating design," Opt. Lett. **23**, 159-161 (1998).
8. A. Henderson and R. Stafford, "Low threshold, singly-resonant CW OPO pumped by an all-fiber pump source," Opt. Express **14**, 767-772 (2006).
9. K. Devi, S. Chaitanya Kumar, and M. Ebrahim-Zadeh, "High-power, continuous-wave, single-frequency, all-periodically-poled, near-infrared source," Opt. Lett. **37**, 5049-5051 (2012).
10. A. Bruner, D. Eger, M. B. Oron, P. Blau, M. Katz, and S. Ruschin, "Temperature-dependent Sellmeier equation for the refractive index of stoichiometric lithium tantalite," Opt. Lett. **28**, 194-196 (2003).