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Continuous-wave 532-nm-pumped singly resonant optical parametric oscillator with periodically poled KTiOPO4

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Abstract

We report on a continuous-wave singly resonant optical parametric oscillator (SRO) based on periodically poled $KTiOPO_4$. This is pumped by a frequency-doubled single-frequency Nd:YAG master oscillator power amplifier system. Pump wave enhancement allowed for external oscillation thresholds around 200 mW. Up to 72 mW of idler and 28 mW of signal radiation were generated at 1.2 W pump power. Output wavelengths between 865 and 1384 nm were obtained with a single 9 μm period grating by varying the crystal temperature from 37.5°C to 225°C. Mode-hop-free operation of the SRO was demonstrated for up to 69 min. © 2000 Elsevier Science B.V. All rights reserved.

Continuous-wave (cw) nonlinear frequency conversion using quasi-phasematched, domain-engineered ferroelectric crystals has become a relatively mature technique for efficiently generating radiation over a broad range of wavelengths. Periodically poled $LiNbO_3$ (PPLN) and $LiTaO_3$ (PPLT) have been the main focus of research in recent years [1–6]. However, when pumped by a visible light source, cw optical parametric oscillators (OPOs) using these materials are significantly affected by thermal effects originating from the relatively high absorption of the pump and, to a lesser degree, of the signal [7]. Furthermore, PPLN and PPLT show strong photorefractive effects that prevent the stable operation of cw-OPOs near room temperature. To reduce these effects, the nonlinear crystals have to be operated at temperatures above 140°C, which is inconvenient and significantly reduces the tuning range obtainable with a single grating period.

Therefore, the development and characterization of new periodically poled materials with low visible absorption and negligible photorefractive effects is of great relevance. Progress in the electric field poling of flux-grown $KTiOPO_4$ (KTP) has now made periodically poled KTP (PPKTP) a very promising candidate [8,9]. With its high nonlinearity of $|d_{\mathrm{eff}}| \approx 9.5$ pm/V, PPKTP is an interesting alternative to PPLN and PPLT. It has already been used in cw resonant second harmonic generation [10,11] and OPOs [12–15]. Cw difference frequency generation [16] and

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pulsed OPOs [17] with PPKTP have also been demonstrated.

In this work, we underline the potential of PPKTP by presenting a cw, singly resonant optical parametric oscillator (SRO) based on this material. We show that PPKTP can be used for cw frequency conversion at high power levels and over a large temperature range. The flux-grown crystal used in this device was obtained from North Crystal Materials Corporation (Beijing, People's Republic of China) and structured at Tel Aviv University by low-temperature electric field poling [8]. It has a length of 10 mm and a poling period of 9 μm, which gives phase-matching for second harmonic generation of 1064 nm light near room temperature [10].

Fig. 1 shows a schematic of the experimental setup. The SRO is pumped by a frequency-doubled Nd:YAG master oscillator power amplifier (MOPA) system producing 2.5 W of diffraction-limited light at 532 nm through single-pass second harmonic generation in PPLN. Since the narrow linewidth (<5 kHz) of the master oscillator is maintained in the nonlinear conversion process, this pump source features an extremely high spectral purity. Its output frequency can be tuned by 80 GHz. A Faraday isolator integrated in the MOPA system prevents back-reflections from the SRO into the laser.

The OPO resonator consists of two concave mirrors with a radius of curvature of $R = -25$ mm. They form a 5 cm long standing-wave cavity with a TEM_{00} waist of $w_0 = 35.2$ μm for the 532 nm pump. One of the cavity mirrors is mounted on a piezoelectric transducer that allows fine adjustment of the cavity length. The PPKTP crystal with an aperture of 0.5×2 mm^2 is located in the center of the resonator. Its two flat end faces carry double AR coatings for 1064 and 532 nm. The cavity mirrors are transmitting for the idler ($R < 20\%$) and highly reflecting for the signal ($R > 99.7\%$).

To keep the external threshold low, the pump wave is also resonated. The reflectivity of the input coupler was measured to be 94.8% at 532 nm, while the other cavity mirror has a reflectivity of 97.1% at this wavelength. Together with the observed finesse of $\mathscr{F} = 36$, these values indicate a relatively high absorption loss of 4% per cm at 532 nm in the PPKTP crystal.

At the output of the SRO, signal and idler waves were separated from the pump by a dichroic mirror. Another dichroic mirror was used to remove any residual signal radiation from the idler wave.

Tuning of the signal and idler wavelengths was possible by varying the temperature of the PPKTP crystal in an oven that featured an absolute temperature stability of ±0.01 K. For temperatures between 37.5°C and 225°C, the idler wavelength was measured with an optical spectrum analyzer (Anritsu MS9701B) while scanning the cavity length using the piezo. As shown in Fig. 2, idler emission from 1100 to 1384 nm was achieved. This corresponds to signal wavelengths between 865 and 1032 nm. On the high temperature side, the

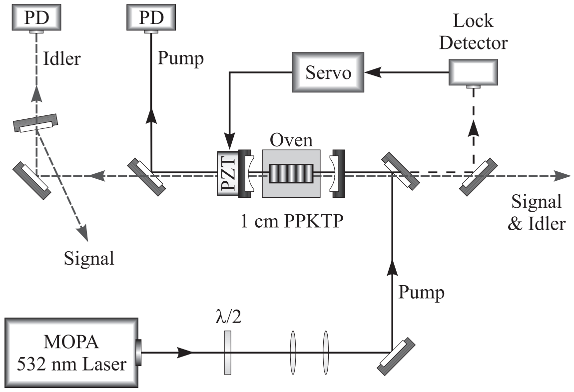

Fig. 1. Experimental setup – PD: photodiode.

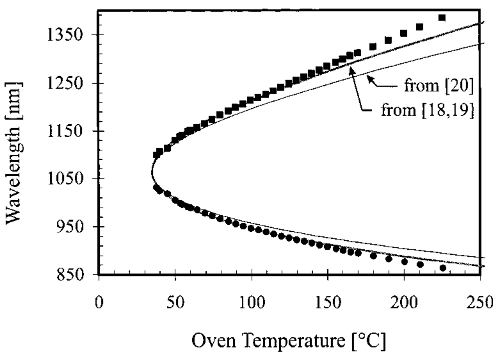

Fig. 2. Measured emission wavelengths (dots) obtained with a 9 μm grating period compared to theory (solid lines).

tuning range was only limited by the heating power of the oven. Oscillation near degeneracy was prevented by the decreasing reflectivity of the cavity mirrors for the signal.

The emission range obtained here exceeds the emission range of all single-grating $LiNbO_3$-SROs demonstrated so far [2]. This is mainly due to the absence of photorefractive effects in PPKTP so that in contrast to PPLN and PPLT the crystal can be operated near room temperature. The total temperature interval accessible for wavelength tuning is thus much larger.

Fig. 2 also shows theoretical tuning curves calculated from published Sellmeier equations [18–20]. Since Arie et al. [10] observed phase-matching for second harmonic generation of 1064 nm at 35°C in a PPKTP crystal with the same grating period, the degeneracy point of each curve was shifted to this temperature. While the prediction according to Fan et al. [18] and Wiechmann et al. [19] is better than the one by Kato [20], the deviations at crystal temperatures above 120°C indicate that the Sellmeier equations for KTP are still not accurately known.

Typical output powers of the SRO are shown in Fig. 3 for an idler wavelength of 1215.2 nm. All values were measured in scanned operation with a calibrated InGaAs photodiode and refer to the total power from both sides of the cavity. 67 mW of idler power was obtained from 1.18 W of pump power at 532 nm mode-matched into the cavity. The relatively low quantum efficiency of 13% can be explained by the high absorption loss of the pump wave in the PPKTP crystal and nonoptimized reflectivities of the cavity mirrors. For example, if the pump input coupler and backreflector had reflectivities of 91% and 100%, respectively, a maximum idler quantum efficiency of 55% would be expected at a pump power of 675 mW.

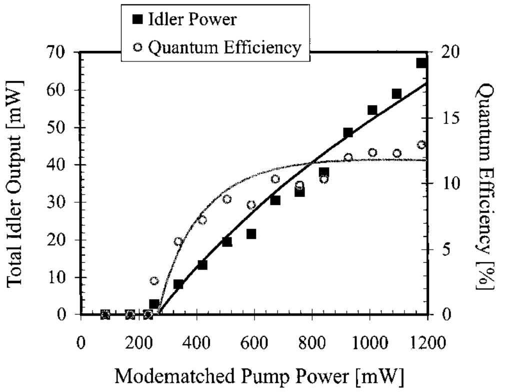

Fig. 3. Idler output power and quantum efficiency as a function of 532 nm pump power.

Solid curves represent a theoretical fit [21] with an oscillation threshold of 263 mW, corresponding to an internal pump power of 960 mW. The values imply a round trip loss of 2.2% for the signal wave at 947 nm. Approximately 1.2% can be attributed to reflections at the crystal faces so that a crystal absorption loss of 0.5% per cm at 947 nm can be deduced. This value is consistent with the result of Garashi et al. [12], who did not see any indication of induced infrared absorption in PPKTP with 80 mW at 532 nm present in the crystal. Since no increased absorption was observed in the present experiment, green induced infrared absorption in PPKTP should be negligible for 532 nm powers up to 2 W, corresponding to intensities of 51 kW/cm^2.

Oscillation threshold and output powers varied significantly when translating the PPKTP crystal without changing its temperature, indicating that absorption loss or poling quality were rather inhomogeneous throughout the material. This can be attributed to the fact that periodic poling of KTP is still a delicate task and strongly depends on the quality of the starting material. By carefully selecting the crystal position, a minimum oscillation threshold of 165 mW at a crystal temperature of 100°C was obtained. Given the measured value of the absorption loss at the pump wavelength, this value indicates a nonlinearity close to the optimum of 9.5 pm/V. At the corresponding idler wavelength of 1215 nm, output powers of 28 mW for the signal and 72 mW for the idler were observed.

Frequency-stable operation of the SRO was achieved by actively locking the cavity length to the pump frequency using a Pound–Drever–Hall technique [22]. For that purpose, the pump light reflected from the cavity was detected as leakage through a 45° mirror. The idler wavelength at 1172 nm was measured using a wavemeter (Burleigh WA-1500). As shown in Fig. 4, up to 69 min of mode-hop-free oscillation were achieved at a pump

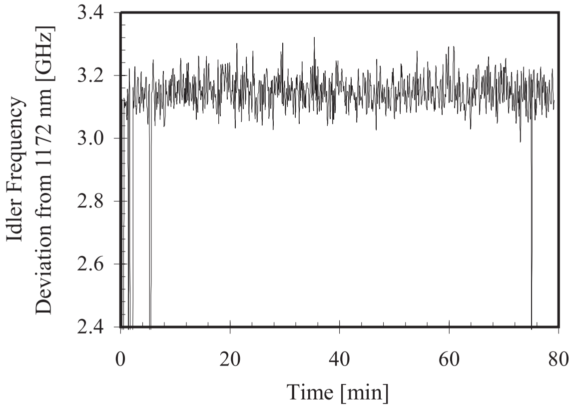

Fig. 4. Mode-hop-free operation over a period of 69 min. During that time, deviations of the idler frequency remain within the resolution of the wavemeter (220 MHz).

power of approximately 1.2 W. Hops between different longitudinal signal modes, which would also change the idler frequency by at least one free spectral range (2.54 GHz), did not occur during that time. While the intensity noise is only 0.8% rms over 50 ms, the idler power was unstable over longer time scales during the measurement due to unavoidable temperature fluctuations and other external influences affecting alignment. Improved long-term power and frequency stability should be feasible with an optimized servo loop and passive damping of the SRO setup.

Local heating of the PPKTP crystal through the strong absorption of the pump wave led to substantial thermal effects. In comparison to PPLN or PPLT, however, these effects seem to have less influence on the frequency stabilization of the SRO. They should thus become much less important if the loss in PPKTP can be lowered to a level below 1.5% per cm as observed in some unpoled KTP crystals.

In summary, we have demonstrated a cw SRO with PPKTP as a nonlinear medium. Wavelengths between 865 and 1384 nm were generated using a single grating period. Maximum output powers of 72 mW for the idler and 28 mW for the signal were obtained. Observed oscillation thresholds were as low as 165 mW. Mode-hop-free operation of the SRO was demonstrated for 69 min. The absence of photorefractive effects made it possible to operate the SRO over a very wide temperature range starting near room temperature. This is an advantage of this device over OPOs using PPLN or PPLT. The development of cw OPOs based on multigrating PPKTP with much lower loss at 532 nm will be an important next step.

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