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Tunable no-tracking OPO-OPA tandem in the near-infrared pumped by a Ti:Sapphire laser

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Abstract. We report the performance of a type-II KTP optical parametric oscillator-amplifier tandem pumped in a non-critical phase-matching configuration by a flashlamp-pumped Ti:Sapphire laser, scanned from 730 to 900 nm. Tunable signal and idler wavelengths are generated from 1.065 to 1.290 μm and from 2.320 to 2.970 μm, respectively, without crystal tracking. Slope efficiency is as high as 32% for the signal conversion only. A $KNbO_3$ crystal has also been tested as a parametric amplifier in a no-tracking configuration and yields comparable gain.

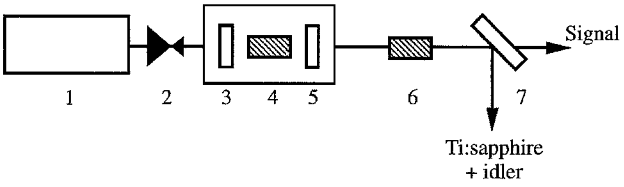

Fig. 1. No-tracking OPO-OPA experimental setup: *1* pump laser; *2* twofold telescope; *3* input OPO cavity mirror; *4* non-linear OPO crystal; *5* output OPO mirror; *6* OPA crystal; *7* dichroic mirror

Non-linear interaction in crystals offers a well-recognized technique to obtain solid-state tunable lasers over a broad spectral range with high power output. In particular, optical parametric oscillation has emerged as the standard technique for this purpose. By tilting crystal angle or adjusting crystal temperature, a wide frequency range, from the ultraviolet to the near-infrared region, can be covered. A very attractive alternative to these tuning methods is a new no-tracking phase matching configuration. With the advent of new tunable all-solid-state laser systems, such as vibronic lasers, optical parametric oscillation can indeed be achieved just by changing the pump-source wavelength without tilting the crystal. This provides easier operation and tuning of the optical parametric oscillator (OPO) and gives a simple and frequency-variable laser source.

KTP can be pumped by a Ti:Sapphire laser in a no-tracking configuration, and more precisely in a type-II non-critical phase matching configuration (NCPM). Besides its geometrical advantages, NCPM configuration allows several spectral improvements in comparison with usual optical parametric oscillators. It maximizes the acceptance angle, reduces the output bandwidth and essentially eliminates walk-off problems.

Recently, Kato and Masutani [1] and Zenzie and Moulton [2] have shown the advantages of an NCPM-KTP system with both a Nd:YAG pumped dye laser and a Nd:YAG pumped Ti:Sapphire laser. In this paper we present the first OPO followed by an optical parametric amplifier (OPA) with two KTP crystals pumped by a flashlamp-pumped Ti:Sapphire laser. Moreover, because of its potentially wider tuning range, $KNbO_3$ is of great interest. Therefore, a $KNbO_3$ crystal was also used as amplifier of the KTP OPO [3, 4]. A scheme of this OPO-OPA tandem is presented in Fig. 1.

KTP has large non-linear coefficients, large temperature acceptance and a high damage threshold. It is transparent up to 3 μm for crystal lengths used in OPOs [5, 6]. Futhermore, one of its most attractive applications is its 90° phase matchability ($\Theta = 90°$, $\Phi = 0°$). The possibility of generating energy between 1 and 3 μm without any crystal tracking offers a very simple tunable laser source.

The pump laser was a Q-switched flashlamp-pumped Ti:sapphire laser (Twin Spark model, Elight Lasers Systems) scanned from 720 to 950 nm [7]. It has a linewidth of 1 Å, a 0.5-mrad divergence, a 30-ns pulsewidth and a repetition rate adjustable from 1 to 20 Hz. The output energy delivered at 800 nm reaches 120 mJ at the output of the oscillator, and can be amplified to 250 mJ in the amplifier. The spot size was reduced to 2 mm after focusing in a twofold telescope. In all the presented experiments, the main limitation was the damage threshold of the mirrors, which can not exceed a pump power of 60 MW cm^{-2}.

The two KTP crystals cut for type-II NCPM are identical: 15 mm long, x-cut, without any coating (5 × 5-mm aperture). The Fresnel losses per face were around 5% for the pump wavelength. The NCPM OPO cavity was a single resonant configuration: two flat mirrors 4 cm apart from each other. The input mirror has a 90% transmission for the pump beam and a 99% reflectivity for the signal. The output mirror transmitted 10% of the signal, 75% of the idler and 95% of the pump. At the OPO output, the three superposed beams were sent into the second crystal for amplification and finally a dichroic mirror separated the signal from the pump and idler.

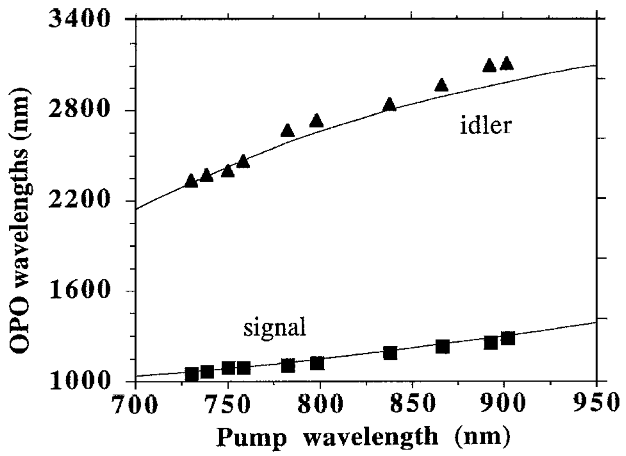

Fig. 2. NCPM phase-matching curve for KTP parametric oscillation as a function of pump wavelength. The lines are calculated with the index formula given in [6]. The *dots* correspond to experimental values

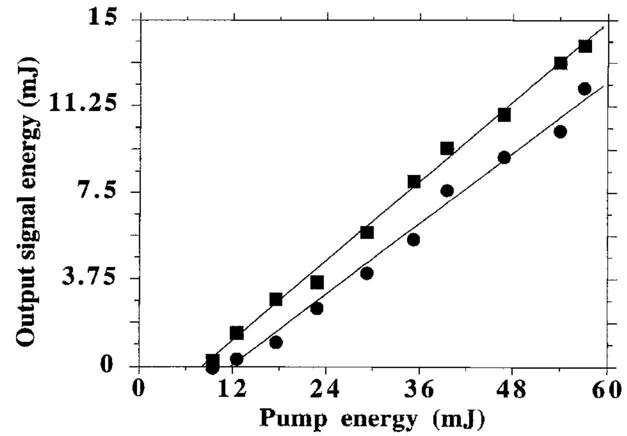

Fig. 3. Output signal energy as a function of pump energy at 800 nm. The *straight lines* are linear fits of the measured values. *1 circles:* output of the KTP OPO; *2 squares:* output of the KTP OPO-OPA

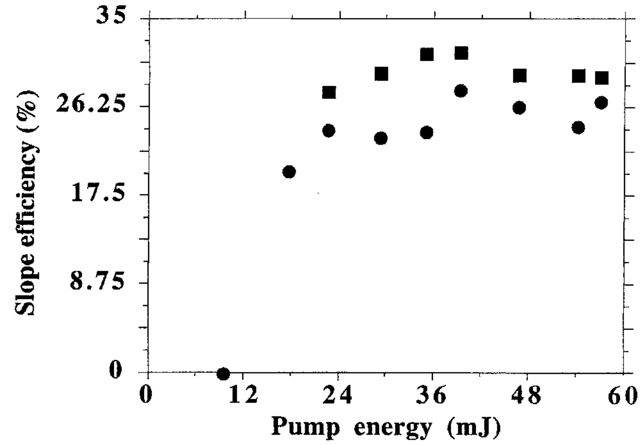

Fig. 4. Efficiency curves of the KTP OPO (*circles*), the KTP OPO-OPA (*squares*), with respect to the pump energy at 800 nm

The idler wavelength was completely absorbed in the mirror substrate. The wavelengths were measured with a H20 Jobin Yvon spectrometer, and the signal detected with an infrared germanium photodiode (88XL Photodine). By scanning the pump wavelength from 730 to 900 nm, a signal between 1.065 and 1.290 μm and corresponding idler from 2.320 to 2.970 μm were generated. The measured data correctly agreed with the calculated curves based upon Sellmeier equations of [6]. They are compared in Fig. 2.

In Fig. 3 the energy of the signal output at a pump wavelength of 800 nm is plotted as a function of pump energy. The first curve (*dots*) corresponds to the simple OPO configuration. We obtained an oscillation threshold of 12 mJ, i.e. 12 MW cm^2, and an output of 12 mJ at a pump energy of 60 mJ, leading to a slope conversion efficiency [$=E_{\mathrm{out}}/(E_{\mathrm{in}} - E_{\mathrm{threshold}})$ of 24% (for the signal only). In comparison, Zenzie and Moulton [2] measured, with their Nd:YAG pumped Ti:Sapphire, a total energy of 22 mJ (signal + idler), corresponding to a total conversion efficiency of 37% at the same pump energy. Assuming roughly a branching ratio, implied by the wavelength dependency, our idler output should be about 6 mJ, so that the total OPO energy at 60-mJ pump energy reaches 18 mJ. The slight difference with the results of [2] is easily explained by their use of an AR-coated crystal, while ours was uncoated.

The second curve (*squares*) represents the OPO-OPA results. The threshold is slightly lowered. This is simply due to the amplification of the noise created in the stage just before oscillation in the OPO cavity. By increasing the pump power near to 60 mJ, we obtained a signal of up to 14 mJ. This leads to a slope conversion efficiency of 32%; this also applies for signals with 40-mJ pump energy (Fig. 4).

The second crystal we used in our experiment was a KNbO$_3$ [8, 9] provided by FEE (Forschungsinstitut für Edelsteine/Edelmetalle GmbH, Postfach 12 24 70, D-55716 Idar-Oberstein, Germany) (dimensions: 10 × 6 × 6 mm). This material has large non-linear coefficients and a broader transparency range than KTP (up to 5 μm). A major disadvantage is its small temperature acceptance. Stabilization to 0.1° C is recommended. The 10-mm-long crystal was cut at $\Theta = 49°$, $\Phi = 0°$ to the c-axis and AR-coated for the signal beam from 1 to 2 μm. A type-I phase-matching pumping by the Ti:Sapphire laser from 730 to 875 nm leads to an extremely attractive tuning range in the near IR from 1 to 4 μm (Fig. 5). First, the KNbO$_3$ crystal was used in exactly the same OPO configuration as KTP. We obtained an oscillation threshold of 140 MW cm^{-2} at 800 nm, which is considerably higher than for the KTP. This result is consistent with the threshold measured by W.R. Bosenberg and Jarman [10], i.e. 145 MW cm^{-2} at 1.064 μm. However, recent measurements from Zenzie and Moulton [2] reported a much lower threshold of 20 mJ at 760 nm ($\approx$30 MW cm^{-2}) with a coated crystal for the signal region. In our case, Fresnel losses are 11.3% per face for the pump wavelength, and we measured an absorption of the crystal at 800 nm of approximatively 6%. These values could explain the higher threshold, and further experimentation with new crystals is in progress. The KNbO$_3$ crystal was then used as amplifier of the KTP OPO. By slightly adjusting the crystal orientation around 49°, it could be pumped at 800 nm for amplification of the KTP signal wavelength. KTP and KNbO$_3$ data are compared after corrections by losses of the crystal entry face. Better single-pass amplification ($E_{\mathrm{out}}/E_{\mathrm{in}}$) is observable for the KTP OPA (1.92) than for the KNbO$_3$ OPA (1.86) at 31-mJ pump energy. However, the crystal lengths

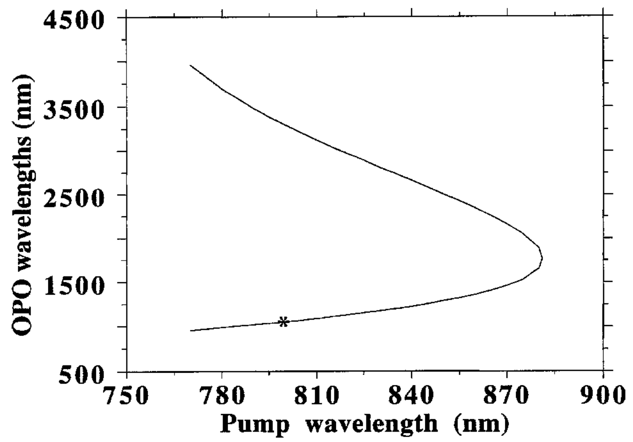

Fig. 5. Phase-matching curve for $KNbO_3$ parametric oscillation as a function of pump wavelength for $\Theta = 49^\circ$ and $\Phi = 0^\circ$

Table 1. Comparison of the parametric amplification in KTP and $KNbO_3$ at 800 nm. The first and second data lines correspond to the output energies (mJ) before and after loss correction, respectively. All OPO and OPO-OPA results are only for the signal wavelength. The second and third lines are the signal single-pass gain ($E_{\mathrm{out}}/E_{\mathrm{in}}$) and the single pass amplification per cm ($E_{\mathrm{out}}/lE_{\mathrm{in}}$), respectively, where l is the crystal length; pump energy was 31 mJ in both cases

	OPO	OPA	
	KTP	KTP	$KNbO_3$
Raw output energy (mJ)	2.9	5.1	5.1
Output energy after loss corrections on crystal faces (mJ)	2.8	5.4	5.2
OPA single pass gain	xxx	1.92	1.86
OPA single pass amplification per cm	xxx	1.3	1.8

were different. If we calculate the amplification gain for one pass and per cm ($E_{\mathrm{out}}/lE_{\mathrm{in}}$, where l is the length of the crystal), we find that $KNbO_3$ has a better efficiency. These results are promising for future $KNbO_3$ OPOs if the optical quality of this material is improved.

$KNbO_3$ has been demonstrated as a good candidate for OPO applications. However, improvements such as crystal quality, as well as spectral laser quality, have to be made. Experiments of pump laser injection with a diode are in progress; lead to an evident bandwidth narrowing down to 300 MHz of the pump [11, 12] and, by conservation, of the signal and idler beams too. Also, the OPO threshold conditions are lowered. Furthermore, other crystals are tested, such as KTA, which also exhibits a transparency range up to 4.5 μm.

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