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AN EFFICIENT, 2 µm OPTICAL PARAMETRIC AMPLIFIER BASED ON LARGE-APERTURE PERIODICALLY POLED RB:KTP

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INTRODUCTION

High-energy mid-infrared nanosecond sources are required in a number of applications including biomedicine, remote sensing, and standoff countermeasures, to name just a few. Sources which serve these applications include mid-infrared fiber and solid-state lasers, quantum cascade lasers, as well as optical parametric oscillators (OPO). Frequency schemes based on OPOs and optical parametric amplifiers (OPA) have several advantages which make them ideal candidates to serve high-energy applications.

In order to obtain radiation deep within the mid-infrared range, down conversion schemes are often utilized. This entails pumping a nonlinear crystal with 1 µm to down convert to 2 µm radiation. This 2 µm radiation then pumps another nonlinear crystal (such as ZGP) to reach longer wavelengths [1-2]. The final output energy and beam are highly dependent on the properties of the 2 µm radiation used and therefore this requires that the 2 µm source is efficient, narrowband, robust and possesses an excellent beam quality. The final output energy is often scaled further in a master oscillator power amplifier (MOPA) configuration [3].

2 µm OPOs and MOPAs based on $KTiOPO_4$ (KTP) and $Rb:KTiOPO_4$ (RKTP) have shown promise in reaching high-energies while still maintaining the favorable properties mentioned above [3]. KTP's broad transparency, high nonlinearity and high damage threshold make it an excellent material suited for high-energy frequency conversion. Additionally, MOPAs based on this material can utilize quasi-phase matching, since RKTP may be periodically poled (PPRKTP) leading to even greater optical to optical efficiencies. Combined with the large apertures presently available [4], PPRKTP allows further energy scaling of 2 µm MOPAs.

In this work we investigate the performance of large aperture PPRKTP crystals in the MOPA configuration described below. We demonstrate an efficient, near-degenerate, nanosecond 2 µm MOPA and highlight further pending improvements.

EXPERIMENTAL SETUP

The experimental setup of the MOPA is displayed in Fig. 1. A Nd:YAG, Q-switched laser operating at 1.064 µm was used as the pump source for the setup. The pump laser had a maximum energy of 200 mJ and delivered pulses with a duration of 10 ns (FWHM) at a repetition rate of 100 Hz. Additionally, the pump laser was injection-seeded and therefore operated on a single-frequency.

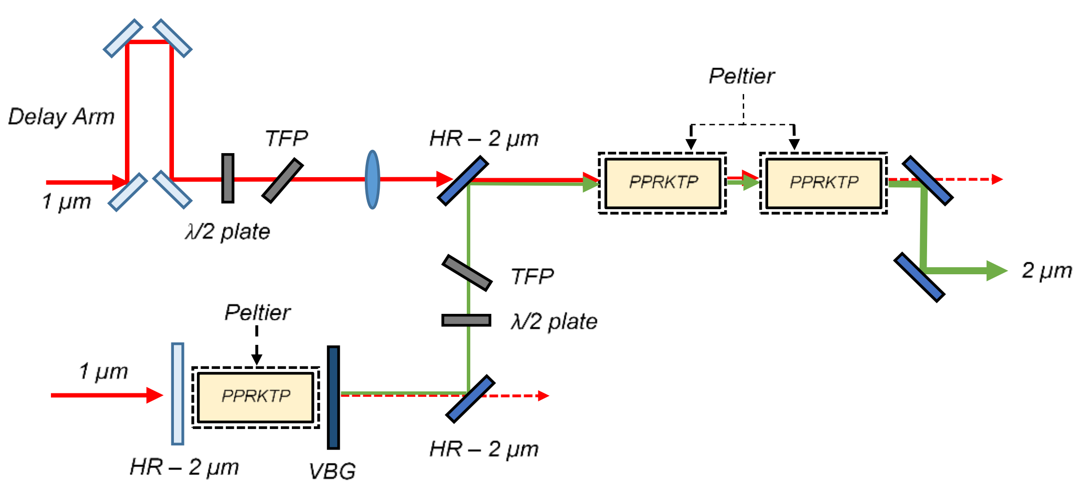

Fig. 1. Experimental setup of the 2 um MOPA.

The pump beam was further characterized with regard to its spatial profile. A Pyrocam III was used to study the spatial structure of the beam (Fig. 2. (left)). The pump beam had a Gaussian intensity distribution with M^2 values of 3.2 and 3.3 in the x and y directions respectively (measured with the 90-10 travelling knife edge technique). The beam was shaped with spherical and cylindrical optics to correct astigmatism and collimate the pump beam.

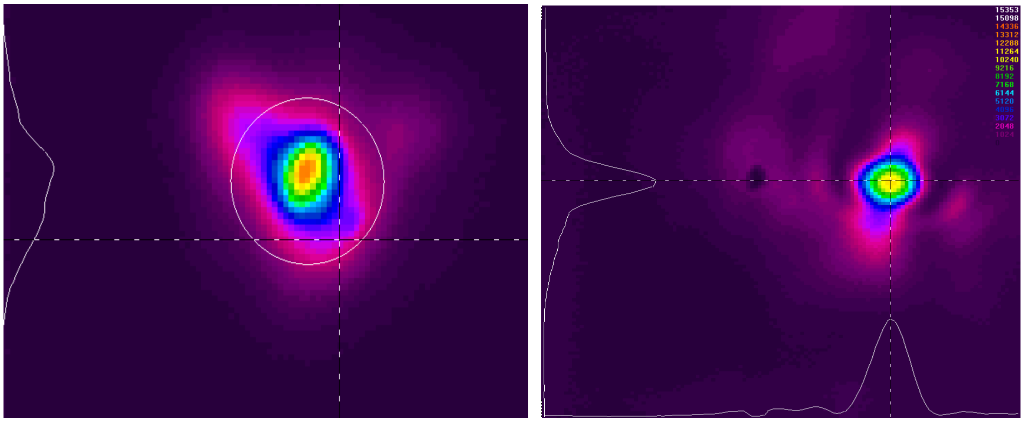

Fig. 2. Spatial profiles of the input pump beam (left) and seed beam (right).

The 1 µm source pumped a volume Bragg grating (VBG) OPO which acted as the seed for the MOPA. The VBG OPO consisted of a periodically poled Rb:KTP crystal with a period of Λ = 38.85 µm, giving a signal wavelength at degeneracy of 2.128 µm. The crystal was anti-reflection (AR) coated for the pump and signal wavelengths and had a length of L = 12 mm and an aperture thickness of 5 mm. A long crystal was used to provide a longer seed pulse, with a duration of ~ 8 ns. The VBG had an output coupling value of 50 % for the signal wavelength. All the crystals used in the experiment were temperature controlled via a peltier element, with the temperature set to 54 °C, to obtain operation slightly off degeneracy. The seed energy was varied with a $\lambda/2$ plate and thin-film polarizer (TFP) combination. The seed beam had M^2 values of approximately 4 and 6 for the x and y directions respectively with a Gaussian intensity distribution (Fig.2. (right)). The 1 µm pump and 2 µm seed were both linearly polarized along the c-axis of the crystal to utilize the d_{33} nonlinear coefficient of RKTP.

The 1 µm pump was separated into two arms, one to pump the VBG OPO and the other to amplify the seed present in the crystals. The total pump energy available for amplification was 150 mJ. A delay arm with a length of approximately 80 cm was included to ensure temporal overlap between the pump and seed pulses inside the amplifiers. The pump energy was also controlled via $\lambda/2$ plate and TFP combination. The pump beam was shaped and collimated with two spherical lenses. The pump and seed beams both had beam waist values of $w_0 \approx 2$ mm in x and y directions at the entrance of the amplifier and were optimized to ensure spatial overlap between the two beams. Both a single crystal and two crystal MOPA were realized. Both crystals were AR-coated for the pump and signal wavelengths and had the same dimensions as the crystal used in the VBG OPO. All beams within the OPO and OPA chain are collimated over the crystal lengths and therefore the interaction is collinear.

The crystals utilized in the experiments were periodically poled in house to yield a period of Λ = 38.85 µm, giving a signal/idler wavelength at degeneracy of 2.128 µm. The crystals were poled with a duty cycle of 50%, for first order quasi-phase matching (Fig. 3(a)). Rubidium doping of KTP has been shown to lower the ionic conductivity of the crystal and therefore improve its poling properties. All crystals were also AR-coated for the pump and signal wavelengths. Furthermore, laser-induced damage threshold (LIDT) measurements were performed on RKTP and KTP samples at both 1.064 µm and 2.128 µm [5].

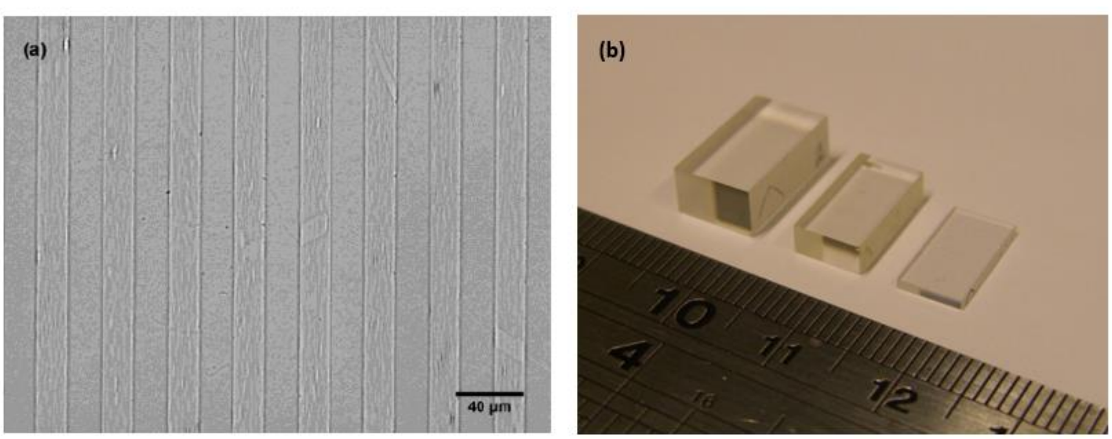

Fig. 3. Domain structures in RKTP (a); 5 mm RKTP crystal used in the experiment (b).

EXPERIMENTAL RESULTS

Prior to building the 2 µm MOPA, surface LIDT measurements were performed on KTP and RKTP crystals [5]. The procedure for the LIDT experiments follows that the procedure outlined by the ISO standard [6], and was an S-on-1 measurement with S = 200 (200 pulses per test site). The same pump source described above was used to perform the 1 µm LIDT measurement and similar VBG OPO operating at degeneracy was used to perform the 2 µm LIDT measurement. Both 1 µm and 2 µm LIDT measurements were necessary as these are the wavelengths of the fields present within the MOPA chain. Results show that KTP and RKTP exhibited similar damage threshold values between 10-12 J/cm^2 (Fig. 4). AR coated samples were shown to exhibit a much higher damage threshold of around 18 J/cm^2, allowing for much higher power and energy scaling.

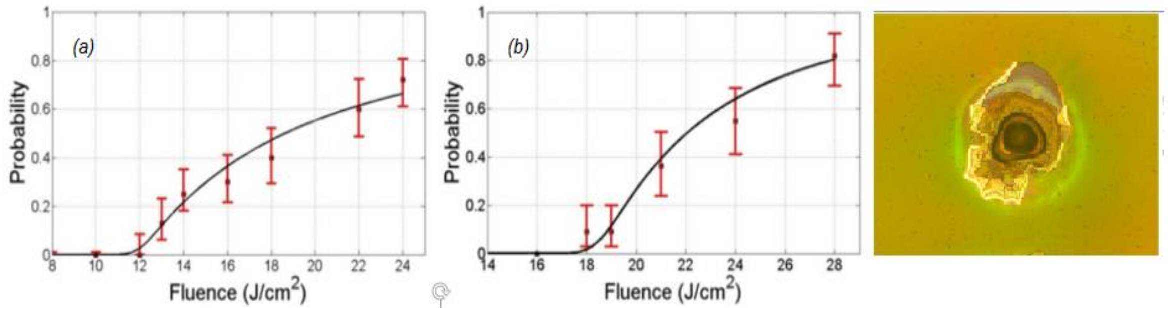

Fig. 4. Probability damage curve for uncoated KTP (a); Probability damage curve for AR-coated RKTP with associated damage site.

The performance of the seed VBG OPO was characterized with regard to its efficiency, spectral and temporal output. The VBG OPO was pumped roughly three times above its threshold (of ~6.5 mJ) and it was operated and characterized at this pump power. At a pump energy of 19 mJ the OPO yielded a signal energy of 7.21 mJ which corresponds to an overall conversion efficiency of 37.7 % (Fig. 5 (left)). The OPO was not pumped further owing to damage considerations. Also, this energy was more than sufficient for amplification in the OPO stage. A PEM detector was used to observe the temporal structure of the seed signal. A pulse duration of 8 ns was measured for this signal (Fig. 5 (right)).

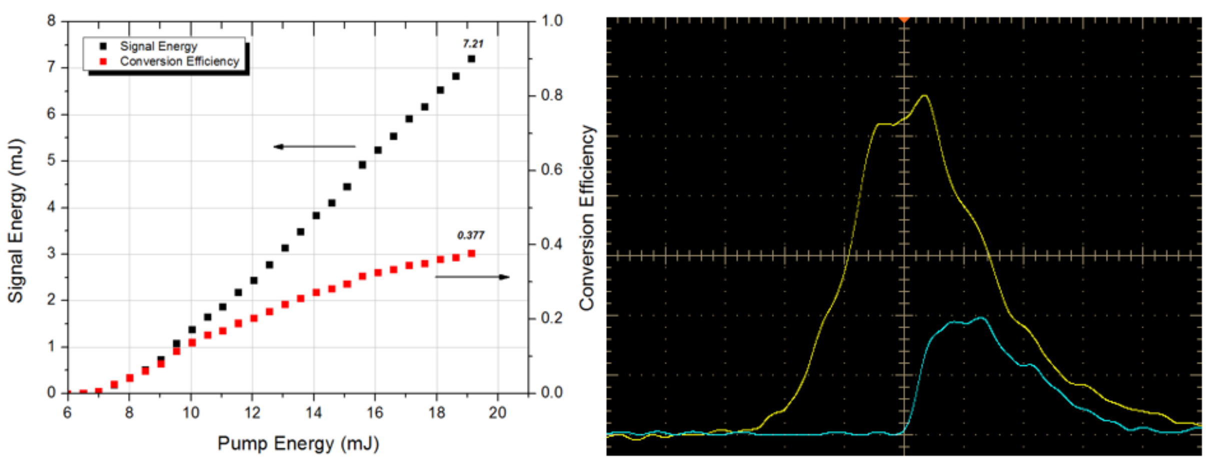

Fig. 5. Energy output for the VBG OPO (left); Oscilloscope trace of the depleted pump (yellow) and signal output (blue) (right).

The spectral output of the VBG OPO was measured using a diffraction grating monochromator, the grating have a groove density of 300/mm and also blazed for 2 µm. Slit widths were kept small to improve the overall resolution and slit size of 0.1 mm was chosen. A maximum resolution of 0.2 nm was possible with this monochromator at the signal wavelength. The spectral output was measured for different peltier/crystal temperatures and is shown below in Fig. 6.

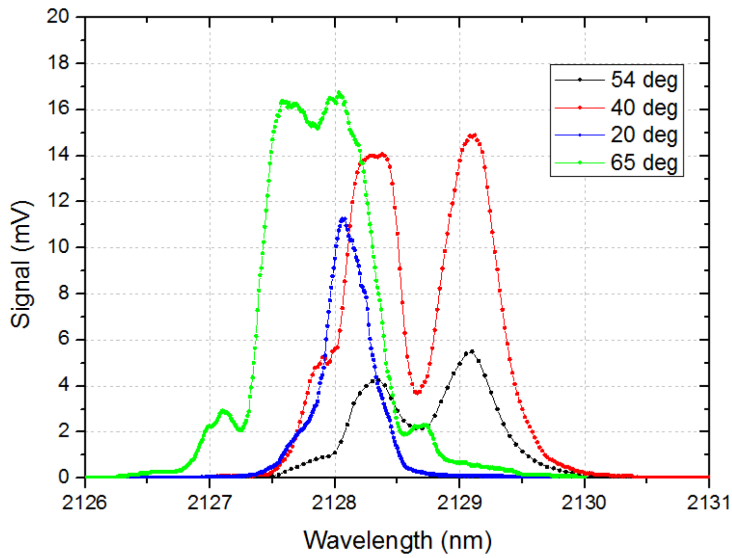

Fig. 6. Spectral output of the VBG OPO.

At low peltier temperatures around 20ºC, the signal output was narrow with a bandwidth of around 0.5 nm, and a center wavelength of ~ 2128.1 nm, indicating good performance of the VBG element. For increasing peltier temperatures, the spectral output broadens with signal and idler wavelengths no longer being degenerate. The crystal temperature for degenerate operation is closer to 55ºC, but since the VBG was not cooled, its refractive index is altered, leading to non-degenerate wavelengths for the signal and idler waves.

The results of the 2 µm MOPA are given below in Fig. 7 and Fig. 8. Different crystal lengths were employed for the amplifier. A single crystal and double crystal amplifier was investigated. For each case a seed energy of 6 mJ was utilized. A maximum signal energy of 58 mJ was obtained utilizing two L = 12 mm crystals. This was a small increase compared to the single crystal result of 54 mJ, due to the pump spatial profile being significantly depleted upon reaching the second crystal. The results indicate that a single crystal of L = 12 mm is sufficient to saturate the amplifier. The maximum signal energy of 58 mJ and 6 mJ seed, yields an amplification factor of 8.67. The maximum overall conversion efficiency achieved for the MOPA was 35%. With a pump beam radius of 2 mm, and a maximum pump energy of 150 mJ, the maximum input fluence on the crystal face was 2.39 J/cm^2.

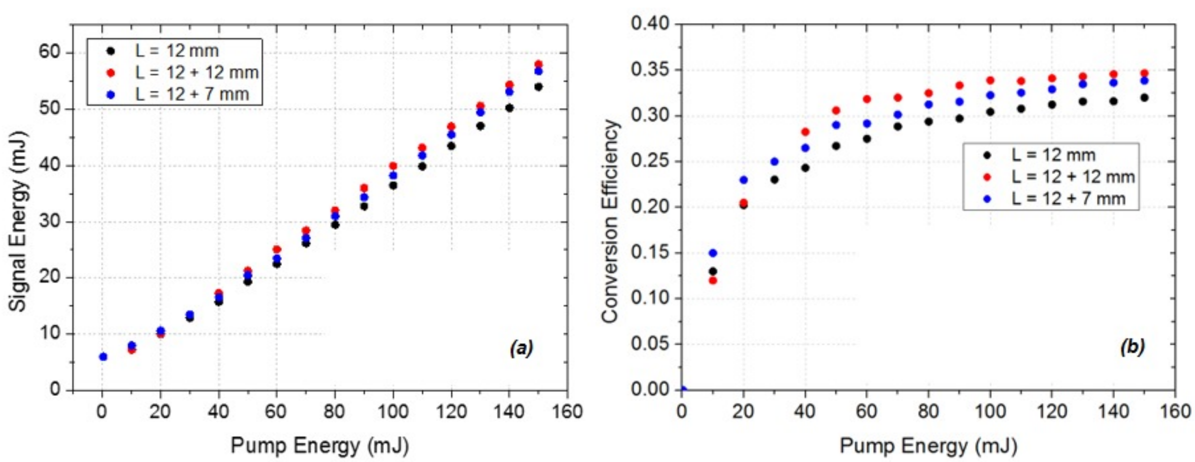

Fig. 7. Energy output for the 2 um MOPA (a); Conversion efficiencies for the MOPA (b).

M^2 values of 7.4 and 9 for the *x* and *y* directions respectively, were obtained for the single crystal MOPA beam. The beam in this case showed a reasonable Gaussian intensity profile. However, the spatial profile for the two crystal MOPA was significantly degraded, owning to back-conversion and the depleted pump profile. Also since the gain of the nonlinear crystal is not uniform over the aperture, we observed multiple intensity peaks in the spatial profile. There is also some slight astigmatism inherited from the pump profile which will be corrected in future work. The OPA architecture that we utilized is the simplest to implement, with removal of the depleted pump after each amplifier. However as seen from the spatial profile of the two crystal MOPA, this architecture does not ensure high beam qualities.

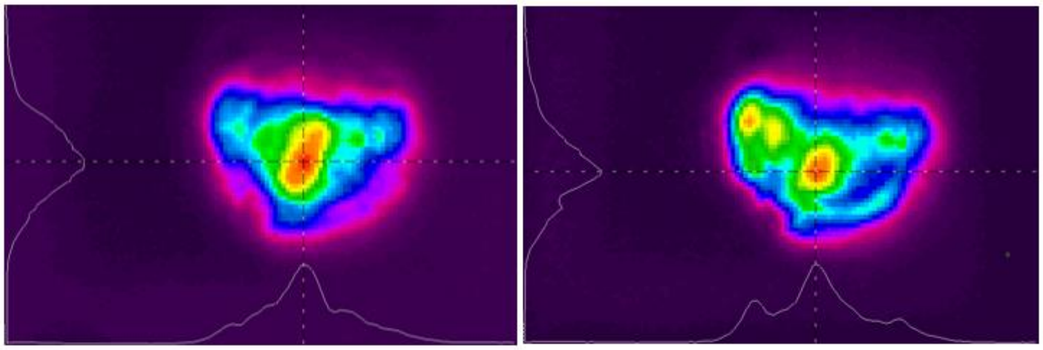

Fig. 8. Spatial profile of the amplified 2 µm output, with crystal length L = 12 mm (left) and L = 12+7 mm (right).

CONCLUSIONS

In this paper we demonstrate an efficient, near-degenerate 2 µm MOPA based on large-aperture PPRKTP. A maximum signal energy of 58 mJ was obtained using a pump energy of 150 mJ. This corresponds to an overall conversion efficiency of 35 %. The MOPA output may be further improved by utilizing two separate pump arms for each amplifier crystal. This would ensure higher output energies, conversion efficiencies and improved beam quality. Additionally, spatial filters may be employed to further clean the amplified beam. The VBG will also be temperature stabilized so as to ensure more robust and consistent performance in the MOPA. Since the maximum fluence incident on the amplifier stage was only 2.39 J/cm^2 and the LIDT of RKTP is far higher as has been shown, further optimization may be done by making the pump beam smaller and improving the conversion using less crystal length. Currently, the main limitation to further energy scaling is the available pump power.

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