ZGP RISTRA OPO operating at 6.45 µm and application in surgery

G. Stoeppler[1], M. Eichhorn[1], M. Schellhorn[1], S. L. Been[2], and R. M. Verdaasdonk[3]
1) French-German Research Institute, ISL, 5 rue du Général Cassagnou, 68301 Saint-Louis, France
2) University Medical Center, Heidelberglaan 100, 3584 CX Utrecht, The Netherlands
3) Vrije University Medical Center, De Boelelaan 1118, 1007 MB Amsterdam, The Netherlands

Author e-mail address: georg.stoeppler@isl.eu

Abstract: We report a Ho:LLF MOPA pumped ZGP OPO based on Rotated Image Singly-Resonant Twisted RectAngle (RISTRA) cavity producing a pulse energy of 5 mJ at 100 Hz at 6.45 µm. Application in surgery is discussed.
OCIS codes: (140.3580) Lasers, solid state; (190.4970) Parametric oscillators and amplifiers, (170.1020) Ablation of tissue

1. Introduction

Since lasers found their way into medical applications, the main interaction phenomenon for laser surgery has been blood and water absorption. Therefore, the direct or indirect heating and consequent boiling of cellular water dominate the cutting effect associated with a zone of collateral damage. To reduce the thermal side effects, several laser experiments [1] with human tissue have shown an enhanced absorption by the amid-II vibration mode of proteins around a wavelength of 6.45 µm. As a result, a pulsed laser at this wavelength could induce a 'non-thermal' ablation process by bond breaking which would enable high precision surgery with minimal adverse thermal effects. However, these experiments were performed using a free-electron laser which has been the only available source for high-energy 6.45 µm radiation which is not accessible and practical for medical treatments. A promising alternative could be a $ZnGeP_2$ (ZGP) OPO which is pumped by a 2 µm solid-state laser producing nanosecond pulses at high repetition rates and intensities of > 10^6 W/cm² which are necessary to ablate the tissue by protein absorption. Broad tuning range from 3.8 – 12.4 µm with a maximum idler pulse energy of 1.2 mJ at 6.6 µm and a repetition rate of 10 Hz was demonstrated with a pump source at 2.93 µm and a linear ZGP cavity [2]. Pumping a ZGP planar ring oscillator with a 2.05 µm laser ~ 5 mJ of idler energy around 6.5 µm at 10 Hz was achieved with a tuning range of 4.3 – 10.1 µm [3]. However, the beam quality of the OPO output was not reported in both publications [2, 3]. With the first demonstration of a "Rotated Image Singly-Resonant Twisted RectAngle" (RISTRA) [4] ring OPO, an improvement of the beam quality was reported. A pulse energy of 10 mJ at a signal wavelength of 3.4 µm was demonstrated with a ZGP OPO based on RISTRA cavity at 500 Hz with a beam quality of M² = 1.8 [5]. In this paper, we present a 2 µm-pumped ZGP RISTRA OPO providing high pulse energy and Watt-level average output power at 6.45 µm with simultaneous high beam quality which enables focusing on tissue or efficient coupling in fibers. This settings were tested in initial tissue ablation experiments.

2. Experimental setup

A Ho:LLF laser system [6, 7] with an additional amplifier stage was used to pump a RISTRA ZGP OPO. The maximum pulse energy of the Ho:LLF MOPA pump system was 82 mJ at a repetition rate of 100 Hz. To prevent damage on the ZGP crystal during pumping the OPO, the pump system was limited to 48 mJ at a pulse width of 38 ns. The pump beam quality was measured to M^2_x = 1.01 and M^2_y = 1.03 at a wavelength of 2053 nm (x -axis is parallel to the polarization of the pump beam inside the ZGP crystal). In Fig. 1 the schematic setup is shown.

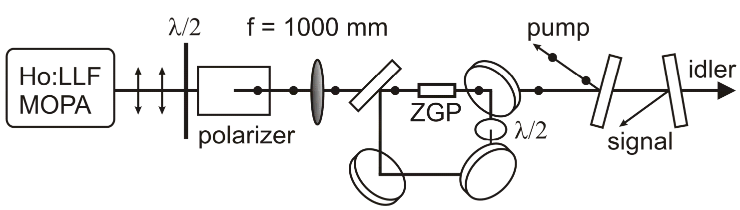

Fig. 1. Setup of the Ho:LLF MOPA pumped ZGP OPO RISTRA system.

The π - polarized pump beam could be attenuated by a half - wave plate and a polarizer to operate the OPO at constant pump pulse width. A focusing lens with f = 1000 mm was used to create a pump spot diameter of

3.85 mm x 3.65 mm in the center of the ZGP crystal resulting in a maximum peak fluence of 0.86 J/cm². The RISTRA ring cavity had a physical length of 130 mm and consisted of four plane mirrors and a half - wave plate for the resonant signal wavelength. The output coupler had a reflectivity of 65 % for the signal and high transmission for the pump (T > 95 %) and idler (T > 98 %) wavelength. The other three mirrors were highly transparent for pump (T > 98 %) and idler (T > 94 %) but highly reflective for the oscillating signal (R > 99 %). The ZGP crystal had a size of 7 x 7 x 16 mm³ and was cut at 56° with respect to the optical axis, which allows type 1 phase-matching. It was wrapped with indium foil and fixed in a copper mounting without water cooling. The RISTRA was aligned for collinear phase-matching conditions and was placed in a box which can be closed for flushing with dry air. All experiments were done in lab atmosphere at T = 28°C and a relative humidity (rH) of 40 %.

3. ZGP RISTRA OPO results

Fig. 2 shows the measured idler output energy as a function of the incident pump energy at a repetition rate of 100 and 200 Hz of the Ho:LLF system. At a repetition rate of 100 Hz and an incident pump energy of 44 mJ a maximum output energy of 5.67 mJ at 6.45 µm with a pulse width of 30 ns was observed. At 200 Hz repetition rate a maximum idler pulse energy of 4.76 mJ was obtained at an incident pump energy of 43 mJ. The calculated slope efficiency for the idler at 100 Hz was 16.3 %. The slightly observed roll-off at 200 Hz could be the result of a stronger thermal lens effect in the ZGP crystal due to the higher average pump power. We measured the absorption coefficient of the ZGP crystal at 2.053 µm to be $\alpha = 0.053\ cm^{-1}$. The corresponding signal energy at 3.012 µm was 10.25 mJ and 8.74 mJ at a repetition rate of 100 and 200 Hz, respectively. The inset in Fig. 2 shows the measured output spectrum at maximum idler pulse energy. The red curve on top shows the standard atmospheric transmission for 20 cm path length calculated with the data of the HITRAN database at a relative humidity of 40 % and a temperature of 300 K. The calculated positions of the water absorption lines agree very precisely with the measured dips in the emission spectrum of the idler output of the OPO. The spectral emission bandwidth at maximum pump energy was 250 nm. Flushing the box within the RISTRA cavity with dry air it was possible to reach rH < 10 % but without any change in the spectrum.

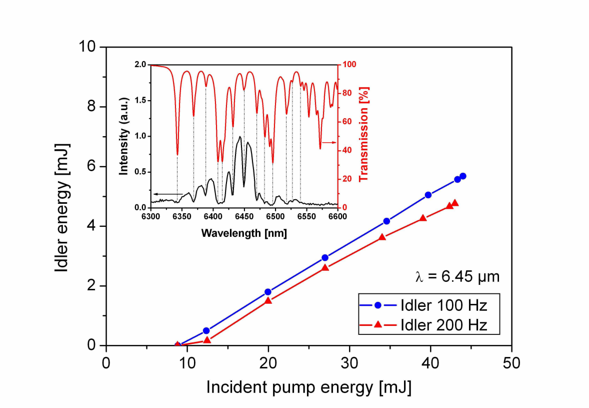

Fig. 2. Idler pulse energy versus pump energy incident on crystal at two different repetition rates. The inset shows the idler spectrum at a pulse energy of 5.67 mJ and a calculated transmission curve through 20 cm of lab atmosphere.

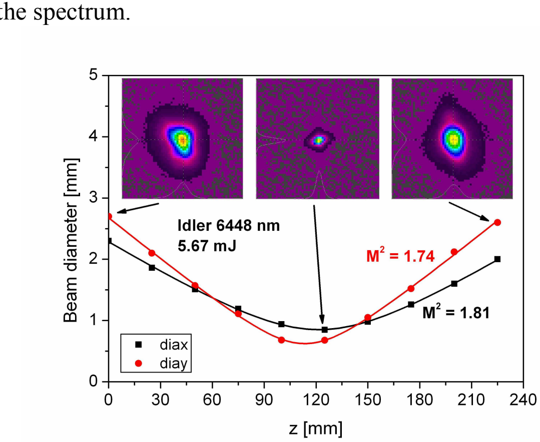

Fig. 3. Diameter of idler beam as a function of the distance after focusing. Solid lines represent fits to the data.

Brightness determination has been done using a CaF_2 wedge directly behind the RISTRA cavity and focusing the idler beam with a f = 150 mm CaF_2 lens. Fig. 3 shows the beam diameter as a function of distance at maximum output energy of 5.67 mJ. The M² of the idler at 6.45 µm was $M^2_x = 1.81$ and $M^2_y = 1.74$. The M^2 values of the corresponding signal beam at 3.012 µm was $M^2_x = 1.43$ and $M^2_y = 1.38$.

4. Application in surgery

To verify ablation and coagulation characteristics of the OPO system, initial experiments were performed in pork and bovine tissue (liver and steak) in cooperation with the University Medical Centres of Utrecht and Amsterdam, The Netherlands. To verify the ablation efficiency of this system, discrete pulse trains have been used to ablate the tissue at one spot. Both the pump beam (2.05 µm) and the idler beam (6.45 µm) were focused using a f = 100 mm CaF_2 lens to a spot diameter of 530 µm. After irradiation, the ablation crater characteristics were analyzed from images taken with a microscope camera, as shown in Fig. 4. Consequently, tissue cuts were obtained by moving the tissue with a linear actuator through the focused idler beam. The characteristics of the cuts were analyzed from images (Fig. 5). The edge of the cut seems unaffected with minimal thermal damage at the tissue surface. Histological processing of the tissue samples will provide quantitative data on the thermal damage at cellular level in the tissue. The results will be compared to tissue effects of other Mid-IR laser systems (Erbium 2.9 µm and CO_2 10.6 µm).

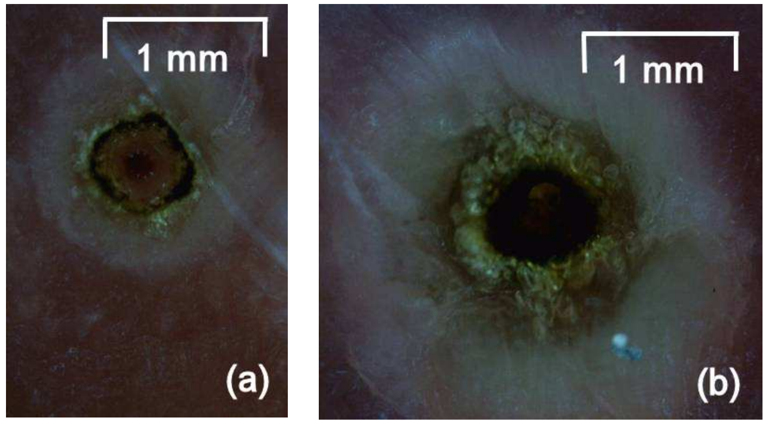

Fig. 4. Crater in bovine steak after (a) 4.7 mJ pulse train at 6.45 µm and (b) 8 mJ pulse train at 2.05 µm of the Ho:LLF pump laser at a repetition rate of 100 Hz.

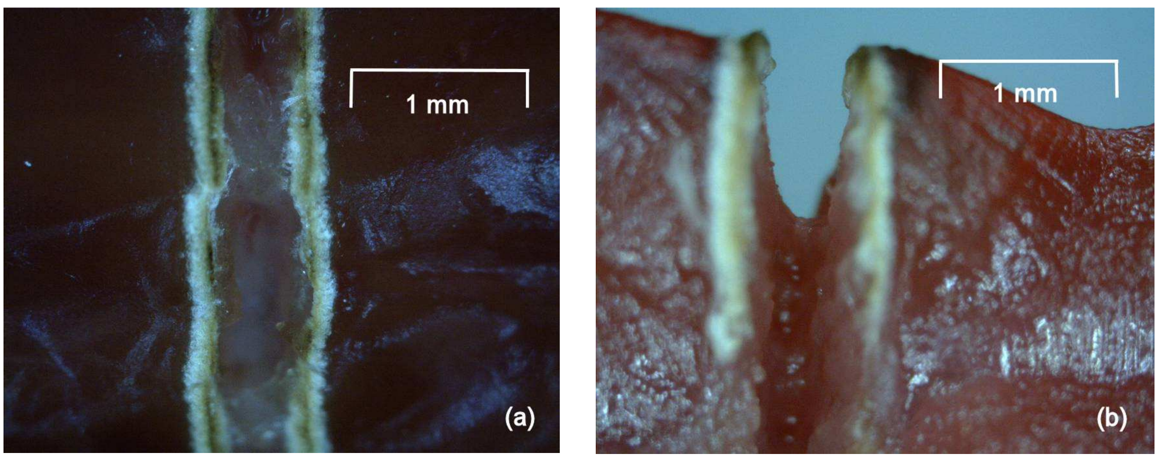

Fig. 5. Cutting of (a) pork liver and (b) bovine steak with 4.7 mJ pulse train (6.45 µm) at a repetition rate of 100 Hz.

5. Summary

A Ho:LLF MOPA pumped ZGP RISTRA OPO has been developed producing a pulse energy of 5 mJ at 100 Hz at 6.45 µm. First experiments in biological tissues showed promising results in regard of precise tissue ablation with minimal thermal side effects.

6. References

1. G.S. Edwards, R.H. Austin, F.E. Carroll, M.L. Copeland, M.E. Couprie, W.E. Gabella, R.F. Haglund, B.A. Hooper, M.S. Hutson, E.D. Jansen, K.M. Joos, D.P. Kiehart, I. Lindau, J. Miao, H.S. Pratisto and J.H. Shen, Y. Tokutake, A.F.G. van der Meer, and A. Xie, „Free-electron-laser-based biophysical and biome-dical instrumentation“, Review of Scientific Instruments **74**, 3207 (2003).
2. K. L. Vodopyanov and F. Ganikhanov and J. P. Maffetone and I. Zwieback and W. Ruderman, „ZnGeP2 optical parametric oscillator with 3.8-12.4µm tunability“, Opt. Lett. **25**, 841 (2000).
3. H.R. Lee, J. Yu, N.P. Barnes, and Y. Bai, „High pulse energy ZnGeP2 singly resonant OPO“, in Advanced Solid-State Photonics, OSA Technical Digest (Optical Society of America, 2004), paper TuC3.
4. A.V. Smith, and D.J. Armstrong, „Nanosecond optical parametric oscillator with 90 degrees image rotation: design and performance“, Journal of the Optical Society America B **19**, 1801 (2002).
5. A. Dergachev, D. Armstrong, A. Smith, T. Drake, and M. Dubois, „3.4-µm ZGP RISTRA nanosecond optical parametric oscillator pumped by a 2.05-µm Ho:YLF MOPA system“, Opt. Express **15**, 14404 (2007).
6. M. Schellhorn, „High-energy, in-band pumped Q-switched Ho^{3+}:$LuLiF_4$ 2 µm laser“, Opt. Lett. **35**, 2609 (2010).
7. M. Schellhorn, „ A comparison of resonantly pumped Ho:YLF and Ho:LLF lasers in CW and Q-switched operation under identical pump conditions “, Appl. Phys. B **103**, 777 (2011).