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Enhanced Beam Quality for Medical Applications at 6.45 μm by Using a RISTRA ZGP OPO[1]

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Abstract—A high-average power ZGP OPO with a nonplanar ring RISTRA cavity, pumped by a Ho^{3+}:LLF MOPA is presented. A maximum pulse energy at 100 Hz repetition rate of 5.67 mJ at 6.45 μm with a M^2 = 1.8 was achieved. The slope efficiency was 16% and the emission spectrum is shown. With a repetition rate of 200 Hz an average output power of 0.95 W at 6.45 μm was reached.

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1. INTRODUCTION

Different laser sources are used in many medical fields like dermatology, ophthalmology and general surgery. In the neurosurgical field like brain and nerve surgery these lasers have not found any acceptance. The main reason can be found in their collateral damage which is acceptable for the first mentioned medical fields but at critical and sensitive surgery like brain and nerve treatment every collateral damage is unacceptable. Several laser experiments in the wavelength range of 6.0 to 6.45 μm with a Mark-III free-electron laser (FEL) [1–3] have demonstrated a not detectable collateral damage in the treated tissue. There, the FEL delivers bursts of complex picosecond superpulses to form a macropulse with tens of millijoules up to 30 Hz. The progress in collateral damage reduction could be achieved by a different ablation process where the treated tissue matrix was ablated only by heating the proteins and not by heating the water to evaporate. The high relative absorption in protein results from the incoupling into the 6.1 μm amide-I vibrational mode as well as the amide-II centered at 6.45 μm, both relatively broad spectral features [1]. With this huge progress but at low repetition rates which have no practical orientation a less expensive and more compact laser source at 6.1 to 6.45 μm is necessary for clinical usage worldwide because a FEL which needs an accelerator is limited to some installations in the world. A very straight possibility would be a cheap 1 μm pumped optical parametric oscillator (OPO) to create wavelengths above 6 μm. The amount of nonlinear crystals with a good transparency at 1 μm and in the mid-IR is very low but was already investigated, e.g., with $GaS_{0.4}Se_{0.6}$ with a very good perspective for nonlinear applications [4]. But due to its softness and even with high nonlinear coefficients a parametric process from 1 to 6 μm will show low conversion efficiency at 6 μm because of the energy conservation law. A very promising laser system with nanosecond pulses and at higher repetition rates than FELs can be a $ZnGeP_2$ (ZGP) OPO which is pumped by a 2 μm solid-state laser to reach intensities of >10^6 W/cm^2 which are necessary to ablate the tissue by protein absorption. The nonlinear crystal ZGP allows a broad tuning range from 2.4–12.4 μm. In 2000 a tunability 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 [5]. 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 [6]. However, the beam quality of the OPO output was not reported in both publications [5, 6]. With the first demonstration of a "Rotated Image Singly-Resonant Twisted RectAngle" (RISTRA) [7] 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 $M^2 = 1.8$ [8]. By using an additional amplifier the signal wavelength could be increased to >29 mJ at a repetition rate of 100 Hz with still a good beam intensity profile [9]. In general, in a single resonant OPO the resonant wavelength will have a better beam quality than the nonresonant outcoupled wavelength because of phase synchronization inside the nonlinear crystal. 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.

2. EXPERIMENTAL SETUP AND RESULTS

For our experiments we used a Ho^{3+}:LLF laser system [10] with an additional amplifier stage to pump a RISTRA ZGP OPO. The maximum pulse energy of the Ho^{3+}:LLF MOPA pump system was 68 mJ at a repetition rate of 100 Hz. To prevent damage on the

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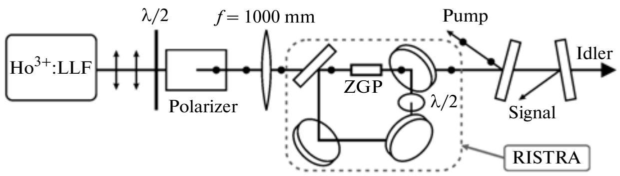

Fig. 1. Laser setup with RISTRA cavity and filter mirrors.

ZGP crystal during pumping the OPO, the pump system was limited to 48 mJ with a pulse width of 38 ns. The beam quality of the pump laser was measured to $M_x^2 = 1.01$ and $M_y^2 = 1.03$ at a wavelength of 2053 nm (x-axis was parallel to the polarization of the pump beam inside the ZGP crystal).

In Fig. 1 the schematic setup is displayed where the π-polarized Ho^{3+}:LLF laser beam can 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 is used to create a pump spot diameter of 3.85×3.65 mm^2 in the center of the ZGP crystal resulting in a maximum peak fluence of 0.86 J/cm^2. The RISTRA ring cavity has a physical length of 130 mm and consists of four plane mirrors and a half–wave plate for the resonant signal wavelength. The used 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 transmissive for the pump ($T > 98\%$) and the idler ($T > 94\%$) but highly reflective for the oscillating signal ($R > 99\%$). The ZGP crystal had a size of $7 \times 7 \times 16$ mm^3 and was cut at 56° with respect to the optical axis, which allows type-I phase-matching. It was wrapped with indium foil and fixed in a copper mounting without water cooling. For the analysis of the signal and idler energy the losses of the dichroic mirrors after the OPO were corrected. The incident pump energy is the corrected value after the input coupler of the RISTRA. Additional losses at the exit of the ZGP crystal were not taken into account. 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%.

Figure 2 shows the measured signal and idler output energies for two repetition rates of the Ho^{3+}: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. The signal at the same incident pump energy had an output energy of 10.25 mJ at 3.012 μm. The calculated slope efficiency for the idler wavelength at 100 Hz was 16.3% and for the signal 29.7%. At a higher repetition rate of 200 Hz a change in OPO output

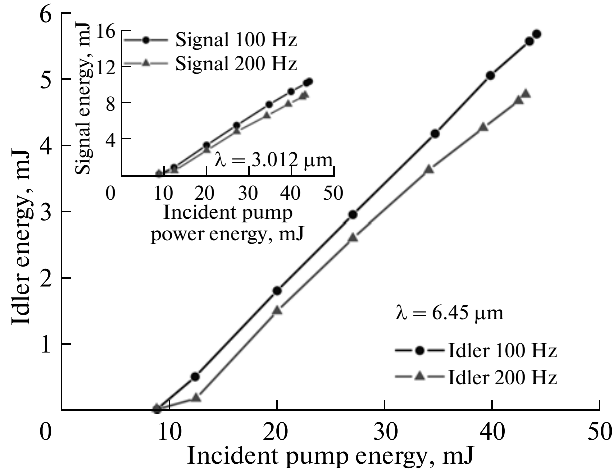

Fig. 2. Idler and signal pulse energy versus pump energy incident on crystal at two different repetition rates.

energy occurred. The threshold of the OPO remained but more pump energy was necessary to extract the same pulse energy. At 200 Hz an incident pump energy of 43 mJ created 4.76 mJ of idler and 8.74 mJ of signal energy resulting in an average output power of 0.95 W at 6.45 μm. The slightly observed roll-off at the end of the red curve could be the effect of a stronger thermal lens effect in the ZGP crystal due to the higher average pump power. The absorption coefficient of the ZGP crystal at 2.053 μm was measured to $\alpha = 0.053$ cm^{-1}. With our cavity setup and the measured data a temperature increase of $\Delta T = 0.14$ K ($\Delta T = 0.27$ K) was calculated creating a thermal lens of $f = 6.5$ m ($f = 3.3$ m) at 100 Hz (200 Hz). With these focal lengths the fundamental signal beam mode diameter at 100 Hz (200 Hz) inside the ZGP crystal is ~1.84 mm (~1.56 mm) which will increase the M^2 value with increasing heat load. These calculations were performed with the commercial software LasCAD [11] and the thermo-physical data from reference [12]. For the M^2 measurement we used CaF_2 wedges directly after the dichroic mirrors to avoid possibly thermal blooming effects which can decrease the beam quality of the mid-IR radiation.

Figure 3 shows the beam diameter by focusing the signal and the idler wavelength at a repetition rate of 100 Hz at maximum output energy. The M^2 of the signal at 3.012 m is calculated to $M_x^2 = 1.43$ and $M_y^2 = 1.38$, the idler at 6.45 μm was $M_x^2 = 1.81$ and $M_y^2 = 1.74$. In a first experiment, where we used a short linear plano-plano cavity an idler output energy of 4 mJ was obtained with a beam quality of $M_x^2 = 2.75$ and $M_y^2 = 6.6$. A direct comparison of the beam quality between linear and RISTRA cavity would need a comparable cavity length resulting in an increased thresh-

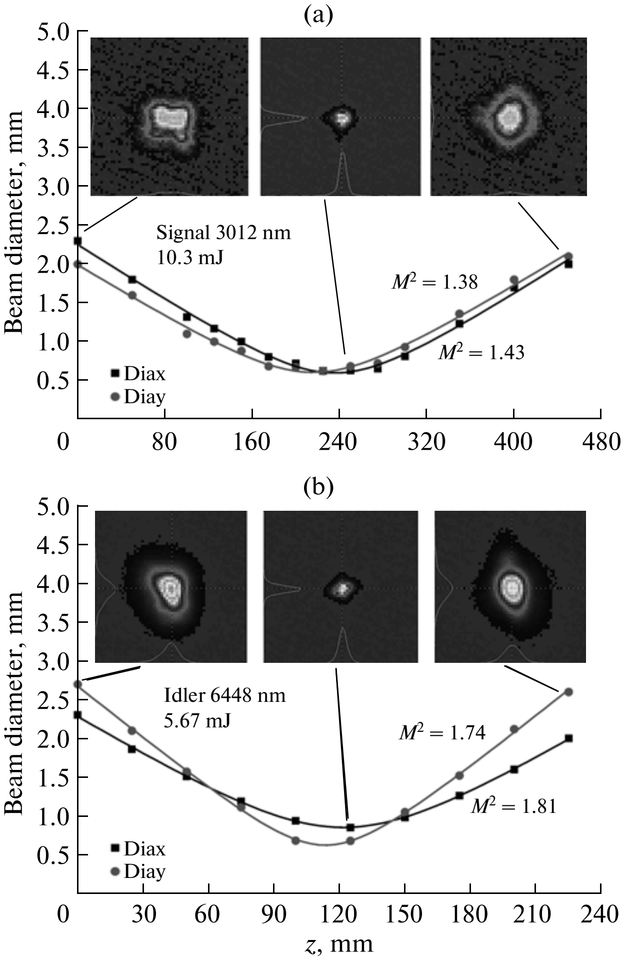

Fig. 3. Diameter of (a) signal and (b) idler beam as a function of the distance after focusing. Solid lines represent fits to the data.

old. This shows the advantage of the RISTRA, i.e., keeping a low threshold while enhancing the beam quality by lateral phase synchronization due to image rotation. At a repetition rate of 200 Hz the M^2 of the idler was measured to $M_x^2 = 2.66$ and $M_y^2 = 2.43$. For clinical surgery or ambulatory treatment precise handling of the 6.45 μm on the tissue is necessary. A beam propagation from the OPO to the tissue through a lens system needs mounting space and is not flexible enough for example in minimally invasive surgery. The solution of flexible handling are fibers which can transport the pulse energy directly and without any additional optics to the tissue. Commercial fibers, e.g. chalcogenide glass fibers, AgBrCl crystal fibers and hollow fibers are already available and have an attenuation of 0.6 to 1.0 dB/m at 6.10–6.45 μm. They can be used in minimally invasive surgery which decreases the complexity of the intervention and accelerate the healing process. Due to the good beam quality of the idler fibers with small core diameters can be used to get the high intensity on the tissue necessary for the ablation process. However, the limitation will be the damage threshold of the entrance facet of the fiber.

At maximum pump energy we measured the output spectrum which is shown in Fig. 5.

The red curve on top shows the standard atmospheric transmission for 20 cm path length calculated with the data of the HITRAN database at rH = 40% and $T = 300$ 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. Using dry air with rH < 10% in the box within the RISTRA cavity the spectrum did not change. In Fig. 4 we recorded the

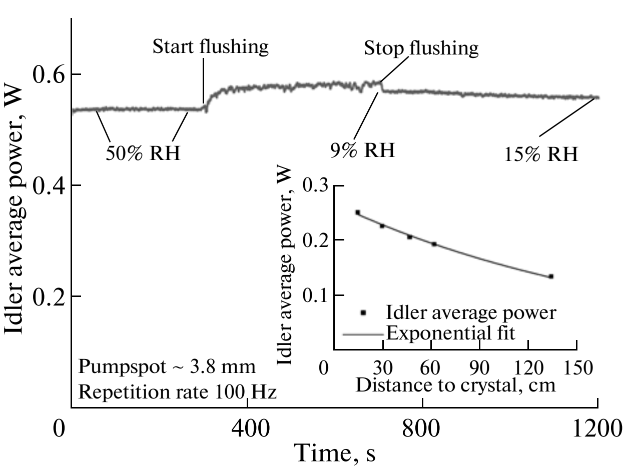

Fig. 4. Idler average power versus time during flushing the encapsulated OPO. Inset, attenuation behavior of idler average power with increasing distance to the ZGP crystal.

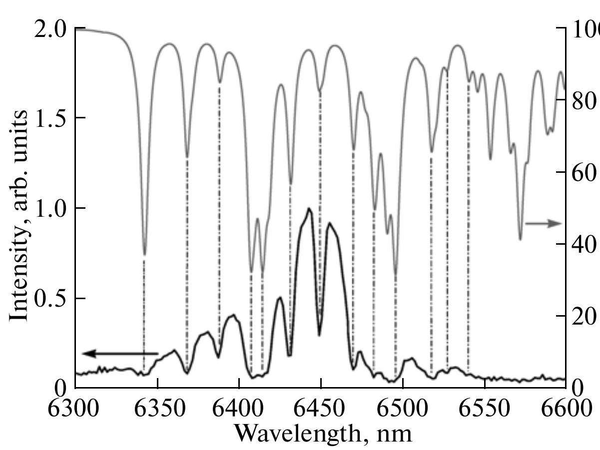

Fig. 5. Measured idler output spectrum at 5.67 mJ and theoretical transmission of 20 cm lab atmosphere.

idler average power at rH = 50% for some minutes without flushing with dry air where the OPO has shown a stable output power (rms < 0.25%). While flushing the box with dry air we observed a slightly increase of idler power but the stability of the output power was reduced (rms < 0.69%) due to the flowing air inside the box which influenced the OPO cavity. After stopping flushing at a value of rH = 9% inside the box the stability of the idler output was restored at a slightly lower average power. The inset in Fig. 4 shows the measured output power of the idler as a function of the distance from the OPO exit part at $T = 25°C$ and rH = 51%. Fitting an exponential decay to the data we calculated an average absorption coefficient of $\alpha = 0.0053\ cm^{-1}$ for the used air conditions.

3. CONCLUSIONS

In conclusion, we demonstrated a collinear RISTRA ZGP OPO with a pulse energy of 5.67 mJ at 100 Hz and a beam quality of $M_x^2 = 1.81$ and $M_y^2 = 1.74$ for the idler wavelength of 6.45 μm which is very suitable for fiber coupling. The pulse energy can be increased by using dry air during operation. Increasing the repetition rate to 200 Hz allow an average power up to 0.95 W without dry air, resulting in over 1 W of average power under dry air condition.

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