Ho:YLF & Ho:LuLF slab amplifier system delivering 200 mJ, 2 µm single-frequency pulses

H. J. Strauss,[*] W. Koen, C. Bollig, M. J. D. Esser, C. Jacobs, O. J. P. Collett, and D. R. Preussler

National Laser Centre, Council for Scientific and Industrial Research, PO Box 395, Pretoria, 0001, South Africa
[*]hstrauss@csir.co.za

Abstract: A single-frequency single-pass amplifier based on Ho:YLF and Ho:LuLF in a scalable slab architecture delivering up to 210 mJ at 2064 nm is demonstrated. The amplifier was end-pumped by a 1890 nm Tm:YLF slab laser and was seeded with a 69 mJ single-frequency Ho:YLF ring laser operating at 50 Hz.

OCIS codes: (140.0140) Lasers and laser optics; (140.3070) Infrared and far-infrared lasers; (140.3280) Laser amplifiers; (140.3570) Lasers, single-mode; (140.3580) Lasers, solid-state; (140.5680) Rare earth and transition metal solid-state lasers.

References and links

1. M. Petros, J. Yu, B. Trieu, B. Yingxin, P. Petzar, and U. N. Singh, "300mJ, injection seeded, compact 2 µm coherent Lidar transmitter," Proc. SPIE **6409**, 64091A (2006).
2. L. R. Botha, C. Bollig, M. J. D. Esser, R. N. Campbell, C. Jacobs, and D. R. Preussler, "Ho:YLF pumped HBr laser," Opt. Express **17**(22), 20615–20622 (2009).
3. B. M. Walsh, N. Barnes, M. Petros, J. Yu, and U. N. Singh, "Spectroscopy and modeling of solid state lanthanide lasers: application to trivalent Tm^{3+} and Ho^{3+} in $YLiF_4$ and $LuLiF_4$," J. Appl. Phys. **95**(7), 3255–3271 (2004).
4. B. M. Walsh, N. P. Barnes, and B. Di Bartolo, "Branching ratios, cross sections, and radiative lifetimes of rare earth ions in solids: application to Tm^{3+} and Ho^{3+} ions in $LiYF_4$," J. Appl. Phys. **83**(5), 2772–2787 (1998).
5. B. M. Walsh, N. P. Barnes, and B. Di Bartolo, "On the distribution of energy between the Tm $^3F_4$ and Ho $^5I_7$ manifolds in Tm-sensitized Ho luminescence," J. Lumin. **75**(2), 89–98 (1997).
6. J. Yu, B. C. Trieu, E. A. Modlin, U. N. Singh, M. J. Kavaya, S. Chen, Y. Bai, P. J. Petzar, and M. Petros, "1 J/pulseQ-switched 2 µm solid-state laser," Opt. Lett. **31**(4), 462–464 (2006).
7. A. A. Nikitchev, "Upconversion coefficient measurements in Tm-Ho:YLF and YAG crystals," in *Advanced Solid State Lasers*, B. H. T. Chai, ed., OSA Proceedings Series (Optical Society of America, 1995), Vol. 24, p. SC9.
8. S. So, J. I. Mackenzie, D. P. Shepherd, W. A. Clarkson, J. G. Betterton, and E. K. Gorton, "A power-scaling strategy for longitudinally diode-pumped Tm:YLF lasers," Appl. Phys. B **84**(3), 389–393 (2006).
9. W. A. Clarkson, N. P. Barnes, P. W. Turner, J. Nilsson, and D. C. Hanna, "High-power cladding-pumped Tm-doped silica fiber laser with wavelength tuning from 1860 to 2090 nm," Opt. Lett. **27**(22), 1989–1991 (2002).
10. M. Schellhorn, S. Ngcobo, and C. Bollig, "High-power diode-pumped Tm:YLF slab laser," Appl. Phys. B **94**(2), 195–198 (2009).
11. A. Dergachev, D. Armstrong, A. Smith, T. Drake, and M. Dubois, "High-power, high-energy ZGP OPA pumped by a 2.05-µm Ho:YLF MOPA system," Proc. SPIE **6875**, 687507 (2008).
12. J. W. Kim, J. I. Mackenzie, D. Parisi, S. Veronesi, M. Tonelli, and W. A. Clarkson, "Efficient in-band pumped $Ho:LuLiF_4$ 2µm laser," Opt. Lett. **35**(3), 420–422 (2010).
13. M. Schellhorn, "High-energy, in-band pumped Q-switched $Ho^{3+}:LuLiF_4$ 2 µm laser," Opt. Lett. **35**(15), 2609–2611 (2010).
14. C. Bollig, M. J. D. Esser, C. Jacobs, W. Koen, D. Preussler, K. Nyangaza, and M. Schellhorn, "70 mJ single-frequency Q-Switched Ho:YLF ring laser-amplifier system pumped by a single 82 W Tm fibre laser," presented at the Middle-Infrared Coherent Sources, Trouville, France, 8–12 June 2009.
15. J. W. Kim, J. I. Mackenzie, D. Parisi, S. Veronesi, M. Tonelli, and W. A. Clarkson, "Efficient fiber-laser pumped $Ho:LuLiF_4$ laser," Proc. SPIE **7721**, 77210V (2010).
16. 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 (2011), doi:10.1007/s00340-011-4467-6.

1. Introduction

High energy, single-frequency sources at 2 µm are sought after for remote sensing of CO_2 [1] as well as for pumping of molecular lasers [2]. Excellent sources of 2 µm radiation are lasers built with Thulium (Tm^{3+} or just Tm) and Holmium (Ho^{3+} or just Ho) doped materials which oscillate in the region of 1.9 µm and 2 µm respectively.

#146145 - $15.00 USD Received 18 Apr 2011; revised 27 May 2011; accepted 27 May 2011; published 7 Jul 2011

Ho and Tm have relatively long upper-state lifetimes in $YLiF_4$ (YLF) of 16 ms and 16.2 ms respectively [3]. Ho's emission cross section is several times higher than that of Tm, making it an ideal material for high energy 2 µm lasers [3,4]. However, it is not possible to pump Ho efficiently with readily available near infrared diodes as is the case with Tm. One solution to this problem is to co-dope Tm and Ho in the same crystal [5]. This is the main approach that has been followed to scale diode-pumped 2 µm lasers to very high energies. Single-frequency pulses of up to 300 mJ at 10 Hz [1] and multimode pulses of up to 1.1 J [6] have been reported from diode-pumped co-doped systems. However, co-doped systems have reduced upper-state lifetimes and therefore reduced energy storage efficiencies due to a strong upconversion process [7] in which energy is transferred between the excited $^3F_4$ and $^5I_7$ states of Tm and Ho respectively. The upconversion process also leads to increased thermal heat loads in the co-doped crystals. In order to avoid this, high energy co-doped systems have to be pumped and Q-switched for a time period of the order of 1 ms before a significant amount of energy is transferred in the upconversion process. This requires very high peak pump powers and therefore a large number of pump diodes [6].

Another approach is to resonantly pump Ho doped materials with a Tm doped laser because Ho absorbs strongly at 1.9 µm. This overcomes most of the difficulties of co-doped systems and still produces relatively high energy pulses. The development of new high average power Tm pump sources led to a further increase in energy levels of 2 µm, Ho doped systems. This was largely due to the improvements made in thermal management by Tm doped rod [8], fibre [9] as well as slab lasers [10]. Dergachev [11] reported multi longitudinal mode ~150 mJ pulses at repetition rates from single shot to 500 Hz from a 3x120 W Tm:fibre laser pumped, Ho^{3+}:$YLiF_4$ (Ho:YLF) MOPA system. The system also delivered over 100 mJ at 1 kHz. Efficient resonantly pumped Ho^{3+}:$LuLiF_4$ (Ho:LuLF) systems have also recently been demonstrated [12,13]. We have previously reported 70 mJ of single-frequency 2.064 µm pulses from a Ho:YLF ring laser-amplifier system pumped by a single 82 W Tm:fibre laser [14]. In this paper, we present a slab amplifier system in order to amplify these single-frequency pulses even further.

A modified version of the Tm:YLF laser described in [10] was used to pump two Ho doped slab crystals. An all-slab geometry was chosen because the heat load is distributed in the horizontal direction so that the crystals could be pumped harder. This also reduced the risk of thermal damage, specifically in the Tm doped crystals. The elongated pump beam from the high average power Tm:YLF slab laser was also naturally suited to pump the Ho doped slab amplifier crystals. In addition, using a slab-geometry in an amplifier does not lead to a significant disparity between the beam quality in the two orthogonal directions as was found for slab oscillators [10] because there are no mode oscillations. Output energies of up to 210 mJ were obtained from this system which is, to our knowledge, the highest published 2 µm single-frequency pulse energies obtained from a non co-doped system.

2. Experimental setup

A 2.064 µm single-frequency Q-switched Ho:YLF ring laser and pre-amplifier system [14] was power amplified by the slab amplifier. The ring laser and pre-amplifier system was pumped by a single commercial 80 W, 1940 nm, Tm:fibre laser from IPG and injection seeded with a single-frequency diode from TOPTICA. However, for the sake of conciseness, the ring laser and pre-amplifier system is termed the seed laser in the rest of this document ("Seed Laser" in Fig. 1). The seed laser system delivered up to 73 mJ per pulse at 50 Hz, with a pulse duration of ~365 ns in a diffraction limited beam. The energy from the seed laser was constantly monitored behind a 95% partial reflector (M_1 in Fig. 1).

#146145 - $15.00 USD Received 18 Apr 2011; revised 27 May 2011; accepted 27 May 2011; published 7 Jul 2011

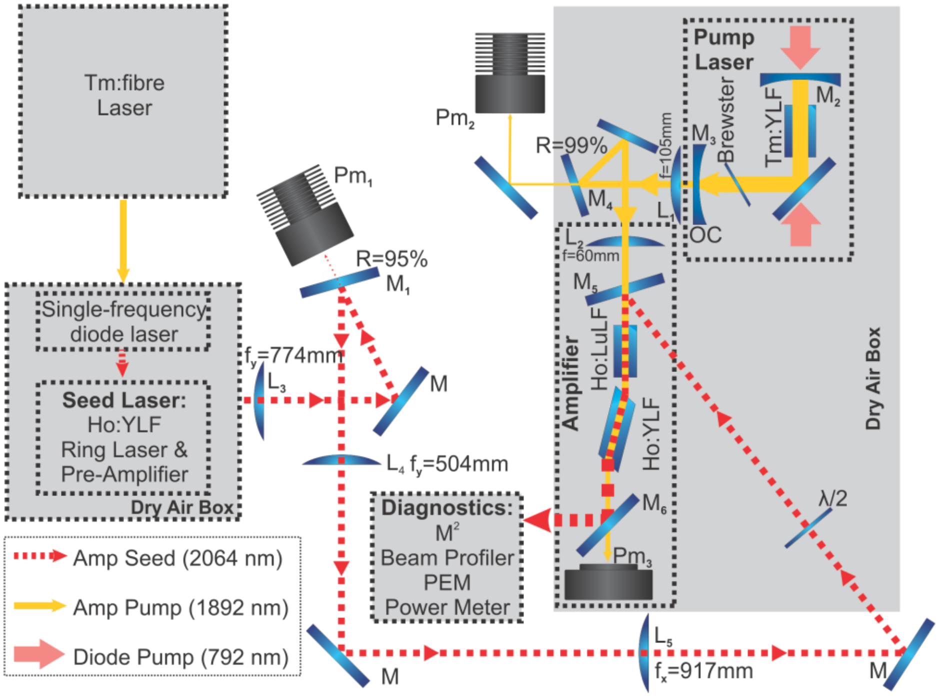

Fig. 1. Experimental layout of the 2 μm slab amplifier system.

The amplifier crystals were end-pumped with a Tm:YLF slab laser ("Pump Laser" in Fig. 1). This was a modified version of the slab laser reported in [10] (which naturally oscillated at 1910 nm on the σ-polarisation). However, since Ho:YLF and Ho:LuLF absorb more strongly at either 1890 nm or 1940 nm (Fig. 2(a) [4] and Fig. 2(b) [15] respectively), the Tm:YLF laser was forced to operate on the π-polarisation which oscillated at 1890 nm. This polarization change was achieved by inserting a Brewster plate and redesigning the resonator so that it was stable for the strong negative thermal lens associated with the π-polarisation. The modified Tm:YLF resonator consisted of a 200 mm concave high reflector (M_2), a 11 × 1.5 × 19 mm^3 ($c \times a \times a$) 2.5% doped *a*-cut Tm:YLF crystal, a 45° folding mirror and a R90% 300 mm concave output coupler (M_3 in Fig. 1). The physical resonator length was 182 mm. The 1890 nm (1.9 μm) output beam of the pump laser was constantly monitored with a Coherent power meter (Pm_2 in Fig. 1) placed behind a 99% partial reflector (M_4 in Fig. 1). The maximum pump power incident on the amplifier crystals was measured to be 181 W.

A numerical simulation of the amplifier system indicated that for the available pump power, the optimum length of a 0.5% doped Ho:YLF crystal in a single-pass configuration is between 80 and 120 mm. However, only a 10 × 2 × 43 mm^3, ($c \times a \times a$) *a*-cut Brewster faced Ho:YLF crystal (50 mm from tip to tip) was available for the amplifier experiments. To increase the total length and efficiency an AR-coated 10 × 2 × 20 mm^3, ($c \times a \times a$) *a*-cut Ho:LuLF crystal was added 12 mm from it in series. Both crystals were 0.5% doped and orientated with their *c*-axes horizontal, so that the π-polarisation had a low loss on the Brewster faces of the Ho:YLF crystal. From Fig. 2 it can be observed that both materials have almost the same absorption cross sections at 1890 nm. However Ho:LuLF has a slightly lower emission cross section for the π-polarisation at 2064 nm [15].

#146145 - $15.00 USD Received 18 Apr 2011; revised 27 May 2011; accepted 27 May 2011; published 7 Jul 2011

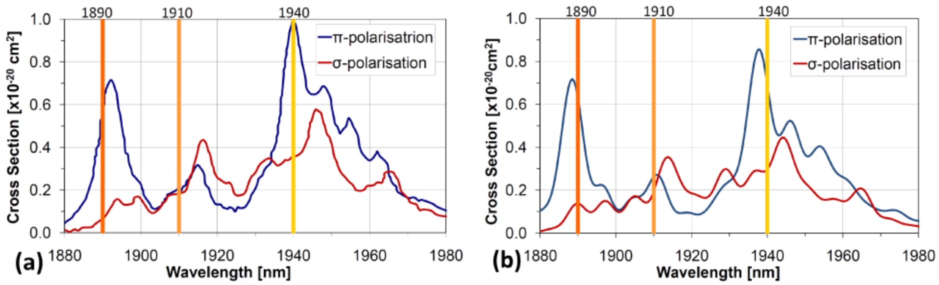

Fig. 2. Absorption spectra of Ho:YLF (a) [4] and Ho:LuLF (b) [15].

The elongated pump beam from the Tm:YLF slab laser was first collimated with an f = 105 mm spherical lens (L_1 in Fig. 1) placed directly behind the output coupler. The beam was then focussed into the two Ho doped slab crystals by using a spherical lens with an f = 60 mm focal length (L_2 in Fig. 1). The horizontal x-axis of the Tm:YLF slab laser pump beam was elongated ($M_x^2 \approx 440$ and $M_y^2 \approx 3.8$) and had a large horizontal divergence (95 mrad, half-angle divergence). The pump beam was also horizontally polarised parallel to the c-axes of the two Ho doped crystals. The pump beam measured in air had horizontal and vertical beam waist radii of $w_{0,x}$ = 2.8 mm (which expanded to 4.17 mm in the Brewster cut Ho:YLF crystal) and $w_{0,y}$ = 0.49 mm respectively. The resulting horizontal and vertical Raleigh lengths were 29.5 mm and 105 mm in air. The horizontal waist position was located on the pump enter-face of the Ho:YLF crystal while the vertical waist position was located on the pump exit-face of the Ho:LuLF crystal.

The pump beam was designed such that both crystals would fit within the horizontal and vertical Rayleigh ranges. However, measurements of the pump beam propagation in air indicated that the horizontal divergence was slightly larger than expected. Consequently the pump enter-face of the Ho:LuLF crystal fell just outside the horizontal Rayleigh range, which was deemed acceptable since the beam was not clipping on the crystal.

The seed ring laser was optimised at 50 Hz to yield maximum output energy of 73 mJ of which of 69 mJ was available for seeding. The diffraction limited seed beam was shaped with three cylindrical lenses (L_3, L_4 and L_5 in Fig. 1) to be collimated in the horizontal direction and focussed in the vertical direction. By adjusting the position of L_5 the seed beam's horizontal radius could be adjusted between 2.9 mm and 3.4 mm in the amplifier crystals. By adjusting L_4 the vertical seed beam waist radius could be varied between 0.34 and 0.52, while the crystals remained inside the Rayleigh range of the focus. Final positions for L_4 and L_5 were determined by adjusting for maximum output energy. The final seed beam radii were 2.9 mm and 0.49 mm in the horizontal and vertical directions respectively. This matched the pump sizes in the crystals fairly well so that good extraction efficiency was obtained. The polarisation of the seed beam was rotated by 90° with a $\lambda/2$ plate in order to take advantage of the higher emission cross-section of the π-components of Ho:YLF and Ho:LuLF. The seed beam was coupled collinear to the 1.9 µm pump beam with a normal incidence HT 1.9 µm HR 2 µm mirror (M_5 in Fig. 1). Both the Tm:YLF pump laser and the Ho doped amplifier crystals were placed inside a box and flushed with dry air to reduce spiking of the Tm:YLF laser due to atmospheric water absorption at 1.9 µm. The amplifier output was separated from the 1.9 µm pump light by means of a 45° mirror which had a high reflectivity at 2 µm and a high transmission at 1.9 µm.

3. Results

The amplified beam was attenuated and its average power was measured with a power meter from which the output energy per pulse could be calculated. The amplifier output energy and gain are plotted in Fig. 3(a) as functions of the pulse repetition frequency (PRF) of the ring seed laser. The gain increased with the PRF up to ~3.15 at which it remained constant for PRF values higher than 150 Hz. The output energy increased with decreasing PRF down to 50 Hz and flattened out at ~200 mJ at lower PRFs. The same behaviour was also observed for the seed energy from the Ho:YLF ring laser which flattened out at ~73 mJ at PRFs below 50 Hz. This was expected because the time between pulses became longer than the upper level lifetimes of Ho:YLF and Ho:LuLF of 16 ms [3] and 16.9 ms [15] respectively.

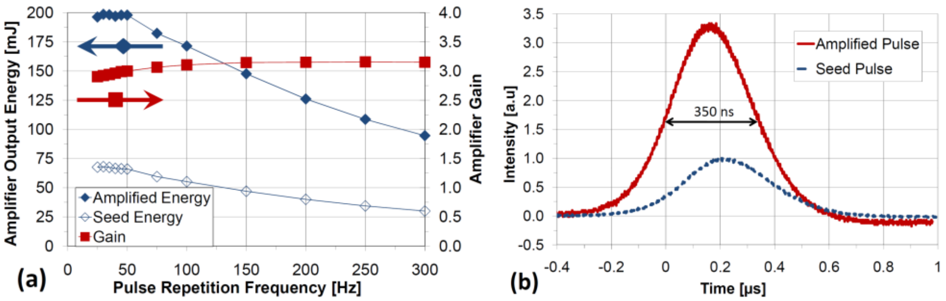

Fig. 3. The amplifier output energy, seed energy and gain as a function of the PRF of the seed laser (a). The seed and amplified pulse shapes at full output power (b).

The pulse shapes of the amplified and seed pulses were measured with a photo electromagnetic (PEM) detector at 50 Hz and at full pump power and are shown in Fig. 3(b). The FWHM of the amplifier pulse was measured to be ~350 ns which was slightly shorter than that of the seed pulse at ~365 ns. The absence of mode beating on both the seed and amplified pulses was due to the single-frequency operation of the system. The pumped power that was transmitted through the two amplifier crystals was also monitored during amplification. Some pump bleaching was observed at full pump power with only ~40% absorbed, compared to ~60% at low pump powers. The output of the amplifier can therefore be improved by using longer crystals to counter bleaching, as was expected from the numerical calculations. The absorption at lower pump powers was also lower than expected. This can be attributed to an uncertainty of ± 3 nm in the wavelength measurement setup, so that the bandwidth of the Tm:YLF laser could not be resolved.

At the full incident 1.9 µm pump power of 181 W, the amplifier was optimised to deliver pulse energies of up to 210 mJ from 69 mJ seed pulses at a pulse repetition rate of 50 Hz, resulting in a gain of 3.2 with 70 W of the pump light absorbed. Figure 4(a) illustrates the amplified energy and amplifier gain as functions of absorbed pump power and shows that the increases in output energy and gain were almost linear.

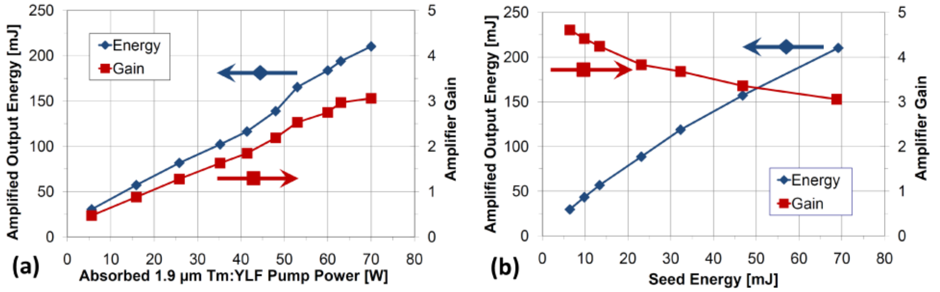

Fig. 4. The amplifier output energy and gain versus absorbed 1.9 µm Tm:YLF pump power (a) and seed energy (b).

The amplifier output energy (at 50 Hz and full pump power) as a function of incident seed energy from the single-frequency ring laser system is plotted in Fig. 4(b). A range of seed energies were obtained by inserting different partial reflectors with reflectivities ranging from 33% to 99% into the path of the seed laser beam before it entered the amplifier. The amplified energy varied from 29.6 mJ for a seed energy of 6.4 mJ (gain of 4.6) to 210 mJ for a seed energy of 68.8 mJ (gain of 3.05). The increasing output energy indicates that the amplifier was not yet saturated. This was to be expected since the saturation fluences of Ho:YLF and Ho:LuLF are 6 J/cm^2 and 6.3 J/cm^2 [16] respectively. The performance of the amplifier could therefore be improved further by double passing the seed through the amplifier crystals.

The amplified beam profile was measured with a Pyrocam I camera from Spiricon. The horizontal and vertical M^2 beam quality factors of the amplified beam were determined by measuring the beam widths at various positions after an f = 500 mm lens. The obvious astigmatism of the beam was due to the different cylindrical lens focussing geometries in the two planes which could easily be corrected by adding additional cylindrical lenses. The two dimensional intensity profile of the amplified beam (inset in Fig. 5) indicated that the initial diffraction limited seed beam deteriorated slightly after amplification. This was confirmed by the measured M^2 values of $M_x^2 = 1.4$ and $M_y^2 = 1.3$ which were slightly higher than that of the initial seed beam (M^2 = 1.05). The slight deterioration was most probably due to structures in the beam profile of the 1.9 µm pump beam in the amplifier crystals.

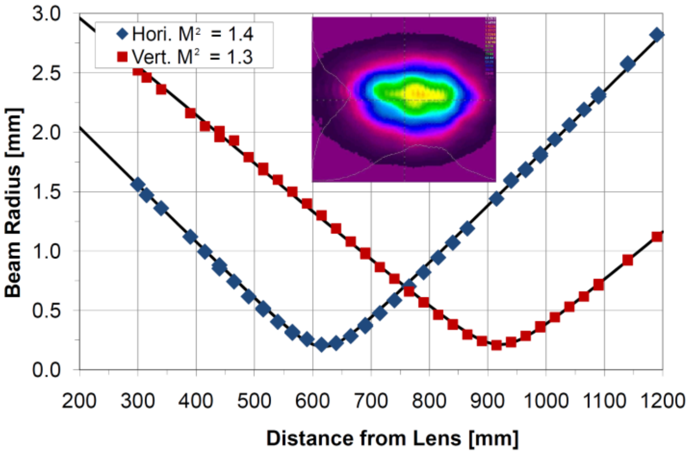

Fig. 5. The horizontal and vertical beam radii of the amplified beam after an f = 500 mm lens. The beam profile without the lens (at the 800 mm position) is shown in the inset.

4. Conclusion

We presented a 2 µm slab amplifier using both a Ho:YLF and a Ho:LuLF crystal. The system amplified pulses from a single-frequency Ho:YLF ring laser that was pumped by a 181 W Tm:YLF slab laser. It delivered pulse energies of up to 210 mJ at 2064 nm while maintaining fairly good beam quality in both planes. Increased performance with even higher output energies may be possible by using longer crystals and by double passing the seed beam through the crystals.

Acknowledgments

The authors thank K. Nyangaza for his assistance in performing the experiments.