Quasi-two-level Yb:KYW laser with a volume Bragg grating

Jonas E. Hellström,* Björn Jacobsson, Valdas Pasiskevicius, and Fredrik Laurell

Laser Physics, KTH – Royal Institute of Technology, 106 91 Stockholm, Sweden
**Corresponding author: jh@laserphysics.kth.se*

Abstract: Using a volume Bragg grating as input coupler, we demonstrate an Yb:KYW laser with a very small quantum defect (1.6%) and an output power of 3.6 W. The laser was longitudinally diode-pumped at 982 nm and the laser wavelength was determined by the grating to 998 nm, with a laser bandwidth of 10 GHz (33 pm). Due to the low quantum defect, the laser should be readily scalable to 20 W or more without critical thermal effects.

OCIS codes: (050.7330) Volume gratings; (140.3480) Lasers, diode-pumped; (140.6810) Thermal effects; (140.3615) Lasers, ytterbium.

References and links

1. Y. Jeong, J. K. Sahu, D. N. Payne and J. Nilsson, "Ytterbium-doped large-core fibre laser with 1 kW of continuous-wave output power," Electron. Lett. **40**, 470-472 (2004).
2. R. Peters, C. Kränkel, K. Petermann and G. Huber, "Broadly tunable high-power Yb:Lu_2O_3 thin disk laser with 80% slope efficiency," Opt. Express **15**, 7075-7082 (2007).
3. N. V. Kuleshov, A. A. Lagatsky, A. V. Podlipensky, V. P. Mikhailov and G. Huber, "Pulsed laser operation of Yb-doped $KY(WO_4)_2$ and $KGd(WO_4)_2$," Opt. Lett. **22**, 1317-1319 (1997).
4. S. Biswal, S. P. O'Connor, and S. R. Bowman, "Thermo-optical parameters measured in ytterbium-doped potassium gadolinium tungstate," Appl. Opt. **44**, 3093-3097 (2005).
5. S. A. Payne, L. L. Chase, L. K. Smith, W. L. Kway and W. F. Krupke, "Infrared cross-section measurements for crystals doped with Er^{3+}, Tm^{3+}, and Ho^{3+}," IEEE J. Quantum Electron. **28**, 2619-2630 (1992).
6. S. Chénais, F. Balembois, F. Druon, G. Lucas-Leclin, P. Georges, "Thermal lensing in diode-pumped ytterbium Lasers-Part II: evaluation of quantum efficiencies and thermo-optic coefficients," IEEE J. Quantum Eletron. **40**, 1235-1243 (2004).
7. S. Biswal, S. P. O'Connor and S. R. Bowman, "Nonradiative losses in Yb:$KGd(WO_4)_2$ and Yb:$Y_3Al_5O_{12}$," Appl. Phys. Lett. **89**, 091911 (2006).
8. O. Efimov, L. Glebov, L. Glebova, K. Richardson and V. Smirnov, "High-Efficiency Bragg Gratings in Photothermorefractive Glass," Appl. Opt. **38**, 619-627 (1999).
9. B. Volodin, S. Dolgy, E. Melnik, E. Downs, J. Shaw and V. Ban, "Wavelength stabilization and spectrum narrowing of high-power multimode laser diodes and arrays by use of volume Bragg gratings," Opt. Lett. **29**, 1891-1893 (2004).
10. B. Jacobsson, M. Tiihonen, V. Pasiskevicius and F. Laurell, "Narrowband bulk Bragg grating optical parametric oscillator," Opt. Lett. **30**, 2281-2283 (2005).
11. T. Chung, A. Rapaport, V. Smirnov, L. B. Glebov, M. C. Richardson and M. Bass, "Solid-state laser spectral narrowing using a volumetric photothermal refractive Bragg grating cavity mirror," Opt. Lett. **31**, 229-231 (2006).
12. B. Jacobsson, V. Pasiskevicius and F. Laurell, "Tunable single-longitudinal-mode ErYb:glass laser locked by a bulk glass Bragg grating," Opt. Lett. **31**, 1663-1665 (2006).
13. B. Jacobsson, V. Pasiskevicius and F. Laurell, "Single-longitudinal-mode Nd-laser with a Bragg-grating Fabry-Perot cavity," Opt. Express **14**, 9284-9292 (2006).
14. B. Jacobsson, J. E. Hellström, V. Pasiskevicius and F. Laurell, "Widely tunable Yb:KYW laser with a volume Bragg grating," Opt. Express **15**, 1003-1005 (2007).
15. J. Petit, P. Goldner, B. Viana, J. Didierjean, F. Balembois, F. Druon and P. Georges, "Quest of Athermal Solid-State Laser: Case of Yb:$CaGdAlO_4$," in Advanced Solid-State Photonics, Technical Digest (Optical Society of America, 2006), paper WD1.
16. M. Jacquemet, F. Balembois, S. Chénais, F. Druon, P. Georges, R. Gaumé and B. Ferrand, "First diode-pumped Yb-doped solid-state laser continuously tunable between 1000 and 1010 nm," Appl. Phys. B **78**, 13-18 (2004).
17. L. McDonagh, R. Wallenstein, R. Knappe and A. Nebel, "High-efficiency 60 W TEM_{00} Nd:YVO_4 oscillator pumped at 888 nm," Opt. Lett. **31**, 3297-3299 (2006).
18. M. Castaing, E. Hérault, F. Balembois, P. Georges, C. Varona, P. Loiseau and G. Aka, "Diode-pumped Nd:YAG laser emitting at 899 nm and below," Opt. Lett. **32**, 799-801 (2007).

#86928 - $15.00 USD Received 28 Aug 2007; revised 3 Oct 2007; accepted 3 Oct 2007; published 8 Oct 2007

19. E. Hérault, F. Balembois and P. Georges, “Nd:GdVO$_4$ as a three-level laser at 879 nm,” Opt. Lett. **31**, 2731-2733 (2006).
20. J. E. Hellström, S. Bjurshagen, V. Pasiskevicius, J. Liu, V. Petrov and U. Griebner, “Efficient Yb:KGW lasers end-pumped by high-power diode bars,” Appl. Phys. B **83**, 235-239 (2006).

1. Introduction

A main purpose of diode-pumped solid-states lasers is conversion from a low brightness, spectrally broadband pump into a high brightness, narrowband laser beam. Moreover, in the solid-state laser cavity, additional elements can provide reshaping of the laser field in form of Q-switching, mode-locking, intracavity second harmonic generation, etc. The main limitation on the performance of diode-pumped solid-state lasers is the heat that is generated in the conversion from pump to laser, stemming from both the the laser’s quantum defect, i.e. the energy difference between the pump and laser wavelengths, as well as nonradiative processes. Various ways to amend the heat problem have been presented, mostly by adjusting the geometry of the gain medium, e.g. shape it as a fiber [1] or a thin disk [2], to be able to efficiently remove the generated heat. The attention of this paper is instead on reducing the heat generation itself. This is done both by working with a material where the nonradiative losses are small, and foremost by significantly reducing the quantum defect. A laser with a very small quantum defect is a three-level laser where two of the energy levels almost coincide, why we denote such a laser a quasi-two-level laser.

A useful laser material for realization of a quasi-two-level laser is Yb-doped double tungstates, such as Yb:KY(WO$_4$)$_2$ (Yb:KYW), that was used in this work. The energy level structure of the Yb^{3+} ion is very simple [3], with only the two $^2F_{5/2}$ and $^2F_{7/2}$ energy levels, which are Stark split and thermally broadened by interaction with the host crystal, see Fig. 1. Since the energy gap between the lowest two Stark levels of the $^2F_{7/2}$ manifold in Yb:KYW is exceptionally small compared to many other Yb^{3+} hosts, the cross-sections are suitable for lasing close to the pump wavelength. This is shown for N_m polarization (defined in [4]) in Fig. 1(b). The absorption cross section was measured directly with a Ti:sapphire laser and the emission cross-sections calculated from these values using the reciprocity method [5]. Furthermore, in Yb the nonradiative losses are small [6,7], due to the simple two-level system, meaning there are no significant parasitic processes that could relax the excited state.

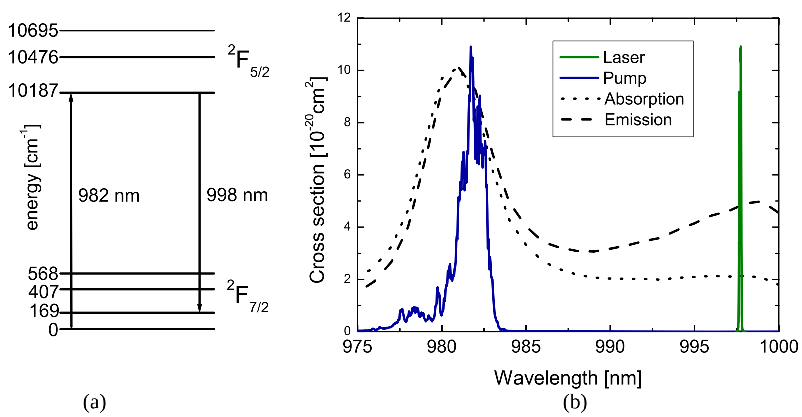

Fig. 1. Spectroscopic properties of Yb:KYW, showing (a) energy levels and (b) cross sections in N_m-polarization. The laser and pump wavelengths are also shown.

The laser was pumped at 982 nm and lased at 998 nm, which yields a very low quantum defect of 1.6%. Compared to conventional Yb-lasers at ~1030 nm, this gives several advantages. First, with a reduced quantum defect, the laser’s slope efficiency could potentially be increased. Second, the reduced thermal load will lead to reduced thermal gradients in the laser crystal, allowing higher pump powers before crystal damage. Third, the thermal lensing

#86928 - $15.00 USD Received 28 Aug 2007; revised 3 Oct 2007; accepted 3 Oct 2007; published 8 Oct 2007

will be reduced, leading to a better beam quality. However, the proximity of the laser wavelength to the pump wavelength inevitably leads to an increased laser threshold, due to a reduced ratio of emission over absorption cross section, illustrated in Fig 1(b). Therefore, the benfits of a low quantum defect will be most prominent at high pump powers. Eventually, for a given pump power and brightness, the optimal laser design should be given by a balance. On one hand, for shorter wavelengths, the heat is decreased, leading to increased beam quality and tolerance to high pump intensities. On the other hand, longer wavelengths yield a decreased laser threshold. The presented laser setup gives access to the laser wavelength as a design parameter, and low quantum defects can conveniently be achieved.

To be able to maintain lasing in a quasi-two-level laser, a few things have to be considered. First, since the lower laser level will be significantly thermally populated, it is important to have high pump intensity, so that net gain can be reached despite considerable reabsorption losses. To maximize the conversion from pump to laser energy, it is desirable to have a good spatial overlap between the pump beam and the laser cavity mode. This is most easily achieved by longitudinal pumping. However, strict requirements are then put on the input coupling mirror that should transmit and reflect the closely spaced pump and laser wavelengths, respectively. Furthermore, a spectrally selective element is needed to enforce lasing at a wavelength close to the pump wavelength, far away from the low loss/high gain region at 1030 nm. By use of a reflective volume Bragg grating [8] as input coupler in a longitudinally pumped laser, all of the above requirements can be fulfilled in a very simple way. A Bragg grating input coupler will reflect only the desired wavelength, thereby transmitting all pump light while at the same time locking the laser wavelength.

Volume Bragg gratings are manufactured in a photosensitive glass by exposure at UV wavelengths and subsequent thermal development [8]. Typically, reflectivities above 99% and bandwidths below 0.3 nm can be achieved in devices of a few millimetres size. Previous work on volume Bragg gratings include locking of high power diode lasers [9], optical parametric oscillators [10] and various solid state lasers: Ti:sapphire [11], ErYb:glass [12], $Nd:GdVO_4$ [13] and Yb:KGW [14]. With the grating at an angle, significant tuning has also been demonstrated [10,14].

The idea to reduce the quantum defect to get quasi-two-level lasers is not new. The lowest reported quantum defect to our knowledge of 0.8% was reported in [15], though at a mere power of 20 mW. There, Yb:CALGO was pumped by a 2 W Ti:sapphire at a skew angle, a method described in [16]. Furthermore, in a thin disk laser setup [2], a quantum defect of 1.4% at an output power of 2.5 W was recently achieved. In comparison, we use a longitudinally diode-pumped laser, a simpler technology, to reach equivalent quantum defect and laser power. Measures to reduce the quantum defect has also been taken in Nd-doped systems, though those quantum defects still remain significantly higher. The quantum defect reduction has been carried out along two separate paths. Either the lasers have been resonantly pumped directly into the upper laser level at 888 nm and operated at the standard 1.06 µm wavelength [17], or they have been pumped at 808 nm and operated at 899 nm [19] or 879 nm [20], both transitions terminating at Stark levels in the lowest energy manifold.

#86928 - $15.00 USD Received 28 Aug 2007; revised 3 Oct 2007; accepted 3 Oct 2007; published 8 Oct 2007

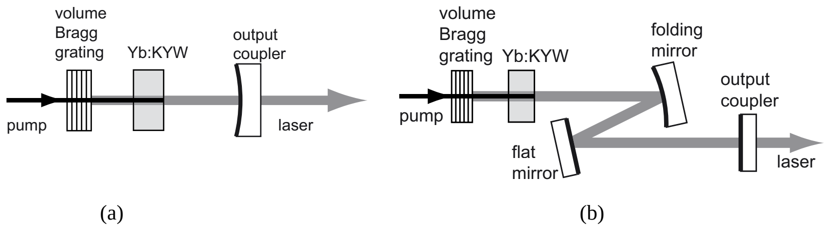

Fig. 2. Experimental set-up, showing (a) the linear and (b) the folded cavity.

2. Experiments and results

The general setup of the laser experiments is illustrated in Fig. 2(a). The pump source was a free space diode-bar with a maximum output power of 19.1 W and a spectrum as shown in Fig. 1(b), which was linearly polarized along the N_m-direction of the crystal. The pump had M^2-values of 35 × 5 and was focussed into a spot with radii ($1/e^2$) of 100 µm × 80 µm in the crystal. As outlined above, a volume Bragg grating (Optigrate, FL) was used as input coupler. From a transmission measurement of the antireflection-coated grating using a Ti:sapphire laser, we determined a maximum reflectivity of 99.9% at 997.5 nm with a bandwidth at half maximum of 0.25 nm. In addition, there were some scattering losses of ~2% at wavelengths off the peak. However, since most of the beam is reflected in the first ~10% of the grating length, the scattering at the peak is only ~0.2%. The laser crystal was a 3×3×3 mm^3 cube of 5 at.% Yb:KYW, which was b-cut, antireflection-coated and clamped from two sides in a water-cooled (16 °C) copper holder, with indium foil in between to increase the thermal contact. With a 20 mm long cavity using an output coupler of 85% reflectivity and 50 mm radius of curvature (ROC), resulting in a mode radius in the crystal of ~75 µm, we obtained a maximum output power of 2.5 W. As shown in Fig. 1(b), the laser was locked to the Bragg grating wavelength.

However, due to the relatively high reabsorption losses in the wings of the transverse mode at the laser wavelength, a lower reflectivity output coupler and a smaller cavity mode waist in the crystal would be advantageous. Since no appropriate concave mirror was available, we had to construct a longer, folded cavity with a plane output coupler. This cavity is depicted in Fig. 2(b). Initially, using a folding mirror with ROC = 200 mm and arm lengths of 114 mm and 355 mm, respectively, the cavity mode waist in the crystal was still ~75 µm. Trying output couplers with different reflectivies, R, we found that R = 77% gave the maximum output power of 3.0 W, see Fig. 3. The beam was diffraction-limited with $M^2 = 1$ for all power levels. By changing to a folding mirror with ROC = 150 mm and with 84 mm and 360 mm long arms, respectively, the waist in the crystal was decreased to ~55 µm. Consequently, the reabsorption loss in the wings was reduced and the maximum output power increased to 3.6 W using the same R = 77% output coupler, see Fig. 3. At the same time, the reduced mode overlap resulted in a slightly degraded beam quality and the M^2-value at maximum power was 1.7 by 1.3. Since about 27% of the Yb ions are initially in the lower laser level due to thermal population, a substantial excitation into the upper level is necessary. This results in a significant bleaching of the material. We measured a pump absorption of ~70% under lasing conditions, as compared with 94% when lasing around 1030 nm.

#86928 - $15.00 USD Received 28 Aug 2007; revised 3 Oct 2007; accepted 3 Oct 2007; published 8 Oct 2007

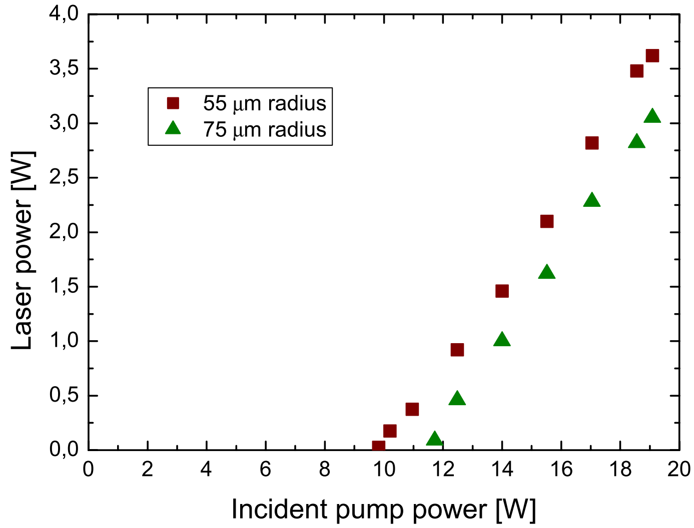

Fig. 3. Pump power versus laser power for different transverse mode sizes, slope efficiency of 40% in both cases.

The laser bandwidth at maximum power in the folded cavity was measured with a flat-flat scanning Fabry-Perot interferometer to be 10 GHz (33 pm), see Fig. 4. Similar to other volume Bragg grating locked lasers, the emission wavelength varied slightly with output power, due to some absorption and the temperature dependence of the grating. In our laser, the wavelength was 997.68 nm near threshold and increased to 997.77 nm at full power.

The power handling capability of the grating was also investigated by using highly reflective output couplers up to R = 99% in the cavity depicted in Fig. 2(a). A maximum circulating intensity of 45 W for a 75 µm beam, i.e. 0.25 MW/cm^2 was reached without any indication of fracture in the grating. However, for circulating powers above ~30 W we did see some roll-off in the laser power, which we potentially attribute to distortion of the grating due to absorption and local heating, as indicated by the laser wavelength drift discussed above.

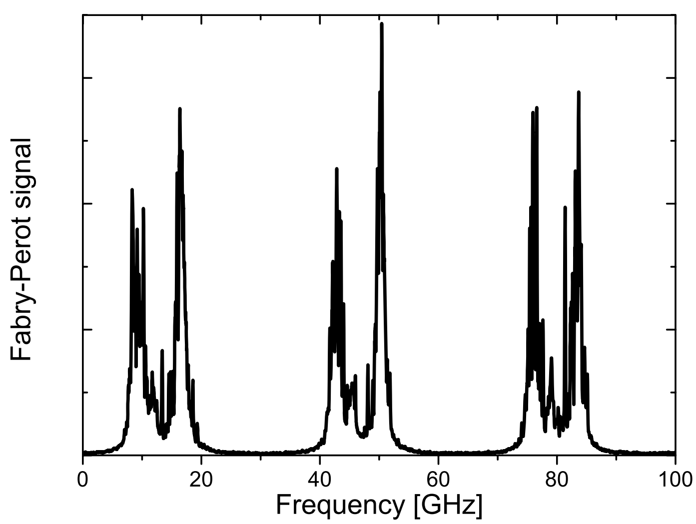

Fig. 4. Fabry-Perot signal.

#86928 - $15.00 USD Received 28 Aug 2007; revised 3 Oct 2007; accepted 3 Oct 2007; published 8 Oct 2007

3. Discussion

The lower laser level thermal population in our laser results in relatively high thresholds, but once these thresholds are reached, there are good power scaling possibilities due to the low heat load, as shown by the following estimation. The fracture limit of the crystal is approximately 1.1 W of absorbed heat power for a 100 µm beam waist at focus [20]. This absorbed heat in a crystal with negligible defects originates mainly from three sources. The first is nonradiative decay corresponding to the quantum radiative efficiency, η_r, and the threshold absorbed pump power, P_{th}, as given by $(1-\eta_r)P_{th}$. The second is the fluorescence quantum defect corresponding to $\eta_r P_{th}(1-\lambda_p/\lambda_f)$ where λ_p and λ_f are the pump and fluorescence wavelengths, respectively. Finally, the third source is the lasing quantum defect corresponding to $(P-P_{th})(1-\lambda_l/\lambda_f)$ where λ_l is the laser wavelength and P is the total absorbed pump power. Next we assume that η_r is similar to the value for Yb:KGW, reported to be between $\eta_r = 0.96$ [6] and $\eta_r = 0.99$ [7], where we use the former one for a more conseravtive estimation. In addition, we assume that the fluorescence is centered at $\lambda_f = 998$ nm and that $P_{th} = 2$ W for 1030 nm [20] while $P_{th} = 7$ W for 998 nm, as in our experiments. The fracture limit then gives a maximum absorbed pump power of just above 20 W for lasing around 1030 nm, while lasing around 998 nm increases this limit to 45 W. Further assuming 57% slope efficiency versus absorbed power, again as in our experiments, this promises a laser output power of 22 W, to be compared with 12 W for a conventional laser [20]. With further optimization of this proof-of-concept cavity, higher power should become possible. One way would be to reduce the mode volume in the transverse wings of the pump region, where the pumping locally is not strong enough to reach threshold. This can be achieved for a pump laser with higher brightness, or by use of a shorter, more heavily doped Yb-crystal. Also, as outlined in the introduction paragraph, the laser wavelength should be optimized to reach a compromise between the generated heat at longer wavelengths and the increased laser threshold at shorter wavelengths.

4. Conclusions

To conclude, we have demonstrated a novel laser design with a volume Bragg grating as input coupler, by which it is possible to pump and lase at closely spaced wavelengths, in a quasi-two-level scheme. In Yb:KYW, we pump at 982 nm and lase at 998 nm with a quantum defect of only 1.6%, reaching powers of 3.6 W. Still we believe further power scaling is possible, since the low quantum defect gives drastically reduced thermal problems. The method we have shown could also be used for quasi-two-level lasers in other ions, such as Nd^{3+} between the $^4F_{3/2}$ and $^4I_{9/2}$ manifolds. Furthermore, the design we present is not restricted to usage at low quantum defects, but would be useful to lock the laser anywhere in the gain spectrum.

Acknowledgements

We acknowledge financial support from the Carl Trygger foundation and the Göran Gustafsson foundation.