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Active and passive Q-switching of a diode pumped Nd:KGW-laser

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Abstract. Efficient operation of a pulsed diode-pumped Nd:KGW laser is reported in actively and passively Q-switched operation. A 6 mm long laser rod was end pumped by a 4-bar stacked quasi-CW laser diode array. Q-switched pulses of 2.7 mJ and 8 ns duration were generated and externally upconverted to 140 μJ, 7 ns pulses at 267 nm.

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There has been considerable interest in the development of diode pumped pulsed solid state lasers for many applications including environmental monitoring, metrology, materials processing, etc. The reason is the high efficiency, compactness and high reliability of these systems. The progress in this field has been possible due to the development of high power laser diodes and diode arrays as efficient pumping sources [1–3]. With these devices the design of battery powered laser systems without water cooling for field applications becomes possible. Our goal was the construction of a pulsed UV-laser for a fluorimetric analytical system for environmental monitoring of water pollutants [4]. The specifications for such a system are: pulse duration less than 10 ns for time-resolved studies, pulse energies of 50–100 μJ in the UV (limited by the UV-transmission properties of optical fibers [5]), moderate repetition rate (50–100 Hz) and low average power consumption (line-independent supply).

We decided to use a single laser diode array in the end-pumping configuration, since this has proved advantageous in the medium power regime [6, 7]. The main problem in this case is the high divergence and extended emitting area of these arrays which results in a bad focusability of the pump radiation leading to a bad mode overlap. An approach to overcome this drawback is to use a laser material with higher Nd-ion concentration and therefore shorter absorption length.

Apart from expensive Nd:YVO$_4$ with short upper level storage time [8], a very promising material is Nd-doped potassium gadolinium tungstate KGd(WO$_4$)$_2$ (abbreviated Nd:KGW). Up to now only few publications exist about this material and most of them are concerned with the flashlamp-pumped operation [9–12]. Recently, successful diode-pumped operation of a Nd:KGW-laser was reported [13, 14].

1 Properties of Nd:KGW

Earlier work showed that Nd:KGW has low intra-cavity loss and high efficiency [12]. Values of crystal properties can be found in [9, 12, 14]. Because of its anisotropy the output of a Nd:KGW laser is polarized. Since the ionic radius of the Gd^{3+} is very close to that of Nd^{3+} [10] high doping is possible. In Nd:YAG concentration quenching of the fluorescence due to the transition Nd^{3+}($^4F_{3/2}$–$^4I_{11/2}$) is a problem that limits Nd-concentration to 1.0 or 1.1 at.%. In the case of Nd:KGW, Nd concentrations as high as 3–8 at.% show no significant quenching effect on the fluorescent emissions [9, 12]. For flashlamp-pumped operation doping of 5 at.% was reported to result in optimum operation. In our experiments too high doping (8 at.%) led to the destruction of the crystal front surface at high pump intensities (> 1 kW/cm^2). A moderate doping level of 3 at.% proved well suited to quasi-CW diode pumping. Another advantage of Nd:KGW is its comparatively wide absorption band (> 10 nm) [12] around 810 nm, which simplifies diode pumped operation.

2 Free-running operation

In our setup we use a high power quasi-CW diode array (SDL 3231-A4 with 240 W peak power, 2% duty cycle by Spectra Diode Labs) as pump source. The array consists of four 10 mm long, 1 μm high bars with a spacing of 0.4 mm. The beam divergence is 40° perpendicular to the bars and 10° FWHM parallel to the bars of the array (according to the manufacturers). The pump beam was shaped by cylindrical optics and then focused into the

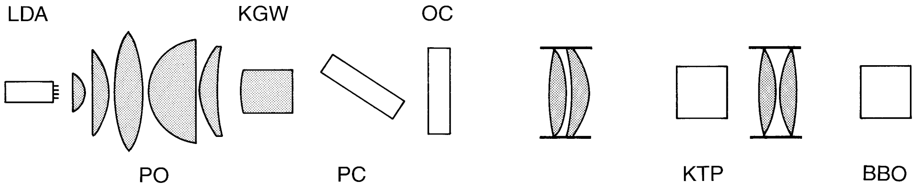

Fig. 1. Experimental setup, LDA: laser diode array, PO: pump optics, KGW: laser crystal, PC: pockels cell, OC: output coupler, KTP: second harmonic generation, BBO: third/fourth harmonic generation

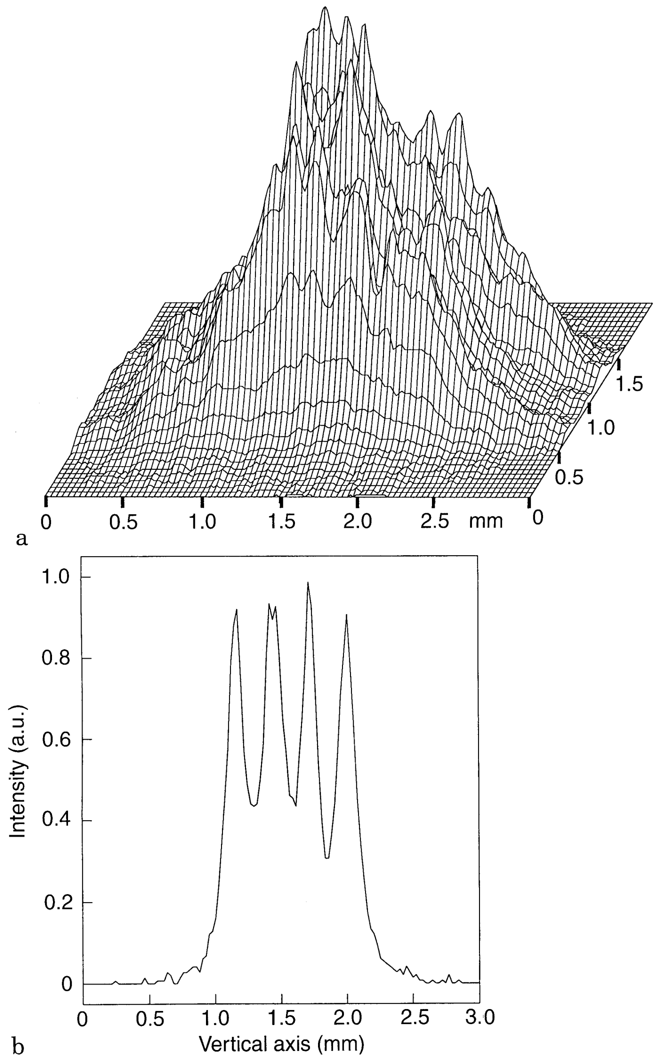

Fig. 2a, b. Pump beam characteristics at the crystal surface when pumped with the 4 bar array. **a** three dimensional distribution, **b** vertical cross-section

laser crystal (Fig. 1). The pump beam distribution on the crystal surface is shown in Fig. 2. The dimensions of the spot are ca. 2 × 1 mm (FWHM). Approximately 80% of the pump radiation is collected by the optics and about 72% passes through an aperture of 3 mm diameter. The arrays were mounted on a thermoelectric cooler and kept at optimum temperature to match the absorption bands of either Nd:YAG or Nd:KGW. For the experiments we used Nd:KGW-crystals with 3 at.% doping level, 6.2 mm diameter, and 6.3 mm, length. While one side was flat, the pump side was curved with different radii of curvature (50, 108, and 148 mm r.o.c.). The Nd:YAG crystal used for comparison in our experiments had a diameter of 3 mm and a length of 10 mm and was doped at a level of 1.1 at.%. The crystal surface had a radius of curvature of 100 mm on the pump side and a flat surface on the other side. The pump side was AR coated for the pump wavelength and HR coated for the laser wavelength. The resonator was of the hemispherical type with a flat output coupler of 95% reflectivity. The input–output-curves for free-running operation in Fig. 3 show the clearly higher efficiency of Nd:KGW when pumped with 200 μs pulses at 20 Hz repetition rate, which is in agreement with [14]. The slope efficiency of Nd:KGW and Nd:YAG was found to be 45% and 37%, respectively. The laser slope efficiency can be expressed as follows:

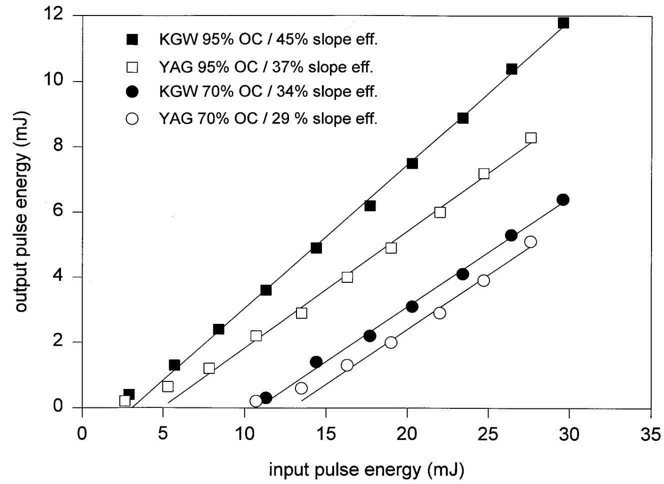

Fig. 3. Free-running performance of Nd:YAG and Nd:KGW at different output coupler reflectivities

$$\eta_{sl} = \eta_p \eta_{st} \eta_{qe} \eta_{abs} \times (-\ln R_{oc}) / (L - \ln R_{oc}), \qquad (1)$$

where η_{sl} refers to the optical slope efficiency, η_p the geometrical factor describing pump and resonator mode overlap, $\eta_{st} = 0.76$ the stokes loss, $\eta_{qe} = 0.95$ [15] for Nd:YAG and $\eta_{qe} = 1$ (assumed for Nd:KGW) the quantum efficiency, $\eta_{abs} = 1$ the absorption of pump radiation, R_{oc} the reflectivity of the output coupler and L the resonator loss. With these values we obtain $\eta_p = 0.76$ for Nd:YAG and 0.99 for Nd:KGW which shows a rather poor matching in the first case and a nearly perfect matching in the second case. This can be explained by the very short absorption length of Nd:KGW and plays an important role when using diode laser arrays with their poor beam quality as pumping sources. The intracavity losses of the two lasers were determined by a Findlay–Clay

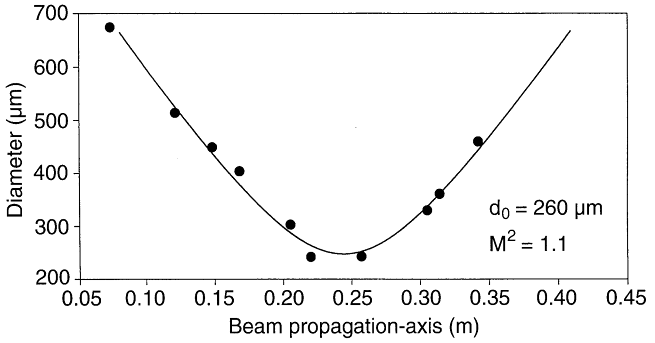

Fig. 4. Beam characteristics of an Nd: KGW laser with 148 mm roc hemi-spherical resonator in the direction parallel to the slow axis of the pump array. Beam diameters along propagation axis, focussed with an achromatic $f = 60$ mm lens

Table 1. Beam propagation parameters of different resonators at a pumping level of 28 mJ. Directions parallel and perpendicular to the slow axis of the diode laser array

Crystal	Nd:YAG	Nd:KGW		
Radius [mm]	100	50	108	148
Res.length [mm]	55	27.5	56.5	75
$M^2\|$	5.3	4.0	3.5	1.1
$M^2\perp$	3.2	1.8	2.2	1.0

analysis [16]. The calculated values were 2.5% for Nd:YAG and 3.5% for Nd:KGW.

We also compared the mode structure of the different lasers by measuring the 2-D beam profile with a CCD-based system (LLG-Beam Profiler). The beam was focussed with an achromatic lens of 60 mm focal length. The diameter in two perpendicular dimensions was measured for a number of points along the beam propagation axis in front of and behind the focus. With a hyperbolic fit the beam propagation parameters were determined (according to the draft of the European standard prEN ISO 11146). Figure 4 shows the TEM_{00} beam of a resonator with Nd:KGW and 148 mm radius of curvature. The results of the measurements are shown in Table 1. The resonators were aligned for optimum output energy. When the resonator length is increased slightly, TEM_{00} operation is possible in either case at the expense of output energy. In the case of 100 mm Nd:YAG, approximately 50% of the energy is TEM_{00} radiation, whereas, from 108 mm Nd:KGW, approximately 75% can be extracted in the TEM_{00} mode. In multimode operation Nd:KGW shows better beam profile than Nd:YAG. This results again mainly from the shorter absorption length of the Nd:KGW crystals.

3 Actively *Q*-switched operation

For active *Q*-switching of the laser we used a KDD*P-Pockels-cell with 99% deuteration and Brewster-windows for low losses. A Findlay–Clay analysis of the free-running performance of the resonators with Pockelscell delivered the insertion losses in both cases. For Nd:YAG the value is 7.7% and for Nd:KGW it is 3.1%. The much better value for Nd:KGW results from the polarized radiation of the crystal that can be matched to the Brewster's angle of the Pockelscell. The *Q*-switched operation at 200 µs pump pulses with a 70% output coupler is shown in Fig. 5. We obtained slope efficiencies of 11% for Nd:YAG and 13% for Nd:KGW. Naturally Nd:YAG is advantageous for *Q*-switching, since the storage time in the upper level is longer, but lower threshold and better pump overlap lead to similar performance at pumping levels up to 30 mJ. So the maximum multimode energy extracted (70% O.C.) was 2.5 mJ in 7 ns pulses for Nd:YAG with 300 µs pump duration and 2.7 mJ in 8 ns pulses for Nd:KGW with 200 µs pump duration. Compared to literature values of a side-pumped Nd:YAG laser system at similar pumping levels [17], the performance is fairly good. The beam quality in the vertical direction remains nearly as good as it is without the Pockels-cell in the resonator, whereas in the horizontal direction the beam profile is elongated.

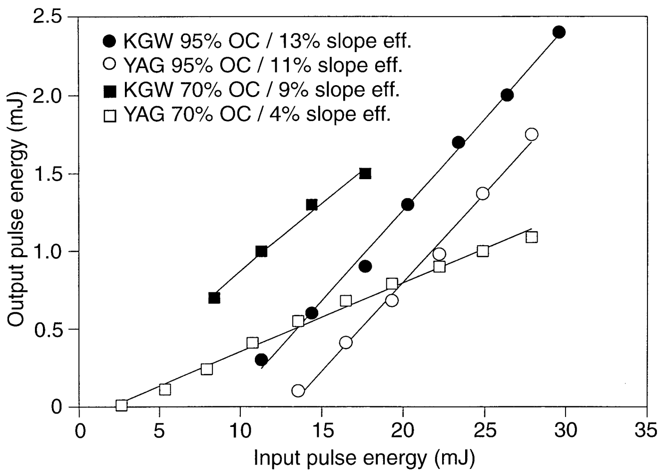

Fig. 5. Actively q-switched performance of Nd:YAG and Nd:KGW at different output coupler reflectivities

4 Passively *Q*-switched operation

For both crystals, the passively *Q*-switched operation was tested with a Cr^{4+}:YAG-crystal. The crystal had a thickness of 0.65 mm and an initial transmission of 85%. The crystal was inserted into the resonator and aligned at the Brewster's angle. By proper adjustment of the angle, single pulse operation was achieved in both cases. With Nd:YAG pulse energies of 1.9 mJ and pulse duration of 13 ns were achieved (250 µs pump pulses) and with Nd:KGW energies of 1.5 mJ in 9 ns pulses (200 µs pump). Compared to the empty cavities, *Q*-switch efficiencies of 29% and 23% can be calculated. Although the alignment of the passive *Q*-switch is critical, very stable operation was achieved. We measured a pulse to pulse energy stability of 1.3% (3 times standard deviation). The pulse uncertainty (time jitter) was about 1 μs. To our knowledge this is the first report on passively *Q*-switched operation of a diode pumped Nd:KGW-laser.

5 Frequency upconversion

For the generation of UV-pulses the radiation of either actively or passively *Q*-switched Nd:KGW was first upconverted to 534 nm. Therefore the beam, emitted from the laser, passed a half wave plate and was focussed into a 5 mm long KTP crystal that was cut for Type II phasematching. Energies of 870 μJ in 8 ns were achieved with active *Q*- switching and 560 μJ in 7.5 ns with passive *Q*- switching (ca. 37% efficiency). The wave plate was used to rotate the polarisation so that the high divergence direction of the 1067 nm beam corresponded to the noncritical phasematching direction of the crystal. Behind the doubler stage the beam passed a half-waveplate and was focussed again into a 7 mm long BBO crystal cut for Type I phasematching. 267 nm pulses of 140 μJ, 7 ns (act. *Q*-switch) and 75 μJ, 6 ns (pass. *Q*-switch) were reached, with 16% and 13% conversion efficiency, respectively. For third harmonics generation a 7 mm long BBO crystal cut for Type I phasematching was placed directly behind the KTP crystal. The results were 180 μJ, 7 ns (act. *Q*-switch) and 120 μJ, 6 ns (pass, *Q*-switch) at 356 nm.

6 Conclusions

In conclusion we have shown that Nd:KGW is well suited for end-pumping with high peak power laser diode arrays. The comparison of different resonator geometries showed that efficient TEM_{00}-operation is possible with hemispherical resonators of less than 10 cm length. Because of Nd:KGW's short absorption length, the beam quality of very short resonators is better than that of a similar Nd:YAG laser. Despite its short storage time Nd:KGW performs very good in actively and passively *Q*-switched operation, leading to high peak powers that are favourable for efficient upconversion. In effect we could generate 140 μJ, 7 ns-pulses at 267 nm at 100 Hz repetition rate. Because of the relatively low electrical power consumption and thermoelectric cooling the laser is an attractive source for field applications in environmental sensing.

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