Appl. Phys. B 61, 213–215 (1995)

Applied Physics B Lasers and Optics



*Rapid communications*

# High-efficiency multicolour Q-switched $Nd^{3+}$:KGd$(WO_4)_2$ laser

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Received: 3 March 1995 / Accepted: 12 June 1995

**Abstract.** Energy output of 400 mJ, an order of magnitude higher than reported previously is obtained in a $Q$-switched flashlamp-pumped $Nd^{3+}$:KGd$(WO_4)_2$ laser. No pronounced saturation of the output energy with respect to the pump energy is observed. Multiwavelength operation due to efficient Stokes conversion in the laser crystal is demonstrated.

**PACS:** 42.55; 42.65

Recently, the neodymium-doped crystal $Nd^{3+}$:KGd$(WO_4)_2$ (or Nd:KGW) lasing at 1067 nm was demonstrated to exhibit highly efficient free-running operation [1]. The host-crystal structure allows high doping (3–8 at.%) without considerable concentration quenching. Thus, 2–3 times higher specific energy as compared to Nd:YAG can be obtained. The laser crystal possesses other attractive features: broad luminescence bandwidth (24 $cm^{-1}$) which is promising for subpicosecond pulse generation, large stimulated Raman gain of the host which allows simultaneous generation of Stokes-shifted lines [2, 3], a strong and broad (> 10 nm) absorption line that makes this laser medium an excellent candidate for efficient diode pumping without temperature control [4, 5].

Although this laser crystal is known since 1972 [6], there are only a few reports in the literature which discuss the properties of this active medium [1–3]. Very recently, investigations by Kushawaha et al. [1] demonstrated that the laser crystal performs quite efficiently in the free-running mode, with a maximum efficiency being higher than 4%. However, operation in a $Q$-switched mode showed that the efficiency at high pump energy is lower than that of Nd:YAG and the laser exhibited pronounced saturation of the output with pump energy. In [1], 40 mJ by pump energy of 30 J in $Q$-switched mode were obtained. Ivanyuk et al. [2] obtained an energy of 18 mJ at a pump energy of 25 J with passive $Q$-switching.

We performed investigations of the lasing properties of the new laser crystal which show that the saturation of the output energy at the fundamental wavelength is apparent because of efficient conversion into Stokes radiation.

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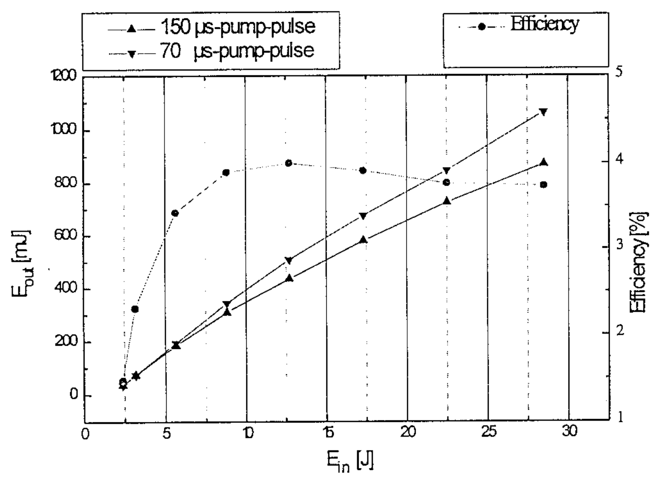


**Fig. 1.** Output energy and efficiency for a flashlamp-pumped Nd:KGW laser in free-running mode as a function of pump energy

## 1 Experimental

### *1.1 Free-running generation*

We used a standard laser design in order to test the lasing properties of the Nd:KGW laser crystal. The laser rod in our experiment was plane/parallel, with AR-coatings, 6.3 mm diameter, 75 mm long, of which only 55 mm length were pumped with the available silver-coated reflector. A proper absorption of the UV radiation was achieved by employing a Ce-doped quartz tube as the light reflector. According to the supplier's data [4], the $Nd^{3+}$ concentration was 3 at.%. The rod was pumped with a single lamp of 55 mm arc length.

First, we studied the free-running mode in a cavity with a highly reflecting concave mirror ($f$ = 3 m) and a flat output coupler ($R$ = 60% at 1067 nm). The available power supply allowed to vary continuously the pulse duration from 70 to 150 $\mu$s. The output energy exceeded 1 J for a pump energy of only 27 J for 150 $\mu$s pump-pulse duration. The maximum conversion efficiency of 4% was achieved at lower pump energies of the order of 12 J as is shown in Fig. 1. We measured an extremely high degree of polarization, better than 1:4000 (probably limited by the analyzing polarizer),

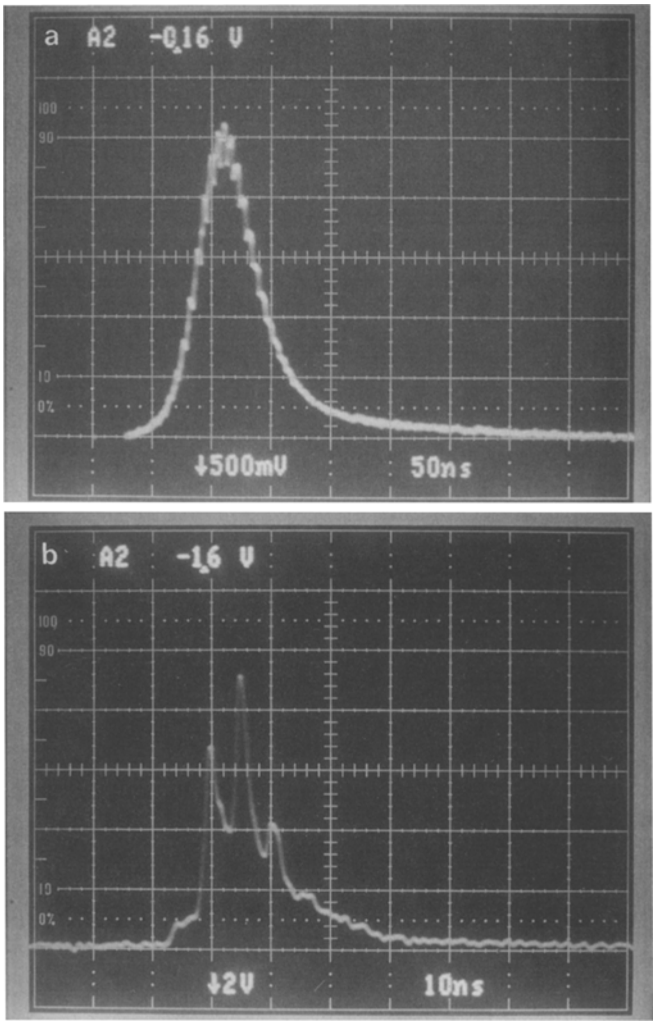


**Fig. 2a,b.** Pulse form in $Q$-switched mode: (**a**) output energy 40 mJ, (**b**) output energy 350 mJ

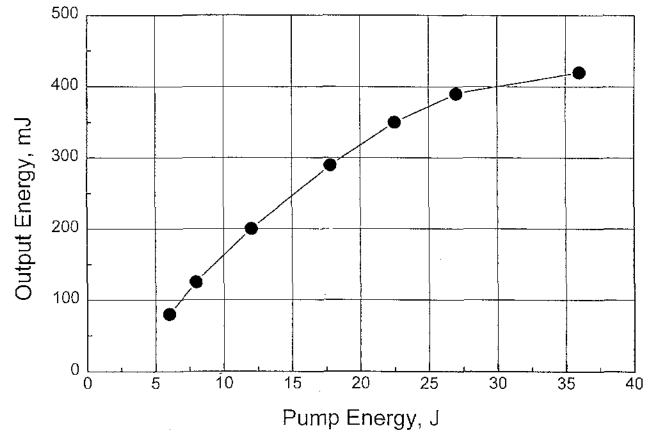


**Fig. 3.** Dependence of the output energy (*all lines*) on pump energy in $Q$-switched mode

indicating high quality of the laser rod. From the available crystal data [4], it is evident that the thermal conductivity of the rod (3.8 W/m·K) is somewhat lower than that of Nd:YAG (9.76 W/m·K) which may result in stronger thermal lensing. We measured, indeed, formation of a negative cylindrical lens of −54 cm focal length for 600 W flashlamp pump power (20 Hz repetition rate and 30 J pump energy per pulse). The cooling rate was in this case 8 l/min. However, for up to 10 Hz repetition rate, only a small decrease of 20% of the output energy was observed. On the other hand, the higher efficiency attainable with this crystal allows pumping with lower energy for the same output power, which may compensate partially for the lower thermal conductivity of the active medium.

The laser was operating multimode with an uniform intensity profile, even though a single lamp was used. The intensity non-uniformity did not exceed 15% at output energies 0.8–1.1 J. For lower pump energy the non-uniformity was found to increase proportionally. In this experiment, we did not attempt to obtain single transversal mode operation.

### *1.2 Q-switched operation*

Since the Nd:KGW laser crystal has a relatively short lifetime of 110 $\mu$s of the upper laser level, in order to increase the laser efficiency in the $Q$-switched mode, we built a special power supply providing close to rectangular pump pulses with a pulse dura tion of 60 $\mu$s. A Pockels cell in combination with an AR-coated Glan-polarizer was used as the $Q$-switch. The introduction of the polarizer and the Pockels cell in the laser cavity decreased the efficiency more than 2 times. The maximum output energy achieved was 400 mJ (multimode) for a pump energy of 36 J (limited by the available power supply). While at lower energies (10–50 mJ), the laser pulse was bell-shaped and had a pulse duration of about 70 ns; at higher energies the pulse form was strongly modulated and the pulse duration was considerably reduced to 10–15 ns (Fig. 2). The modulation period corresponds to the round-trip time (laser cavity length of 80 cm), indicating a mechanism of self-mode-locking. The energy measurements were taken at repetition rates up to 10 Hz.

The output-energy dependence in $Q$-switched mode as a function of the pump energy is presented in Fig. 3. An energy of more than 400 mJ multimode was obtained for the maximum available pump energy of 36 J.

In the $Q$-switched mode, we observed very strong Raman conversion in the laser crystal into first and second Stokes. The Stokes shift with the largest gain for the $KGd(WO_4)_2$ crystal is 901.5 cm$^{-1}$ [2]. The stimulated Raman generation was visualized using an extracavity AR-coated $LiIO_3$ frequency doubler [4]. We observed 5 lines in the visible originating from direct frequency doubling of the fundamental, the first and second Stokes, and from frequency mixing. These lines are as follows: 533.6 nm (second harmonic of the fundamental F = 1067 nm), 590.4 nm (second harmonic of the first Stokes S1 = 1180.8 nm), 560 nm (mixing of F and S1), and 660.7 nm (second harmonic of S2 = 1321.5 nm). Occasionally, we observed also the frequency-doubled first anti-Stokes (973.5 nm) line at 487 nm. We measured the total conversion into Stokes lines using a dichroic mirror totally reflecting the fundamental radiation and transmitting $>$ 90% the Stokes-shifted lines. At the highest pump power, the energy in the Stokes components exceeded 60% of the total output.

## 2 Discussion

In contrast to the investigations of Kushawaha et al., the energy in the $Q$-switched mode in our experiment did not saturate considerably. We obtained an output energy of 400 mJ as compared to 40 mJ obtained by Kushawaha et al. for the same pump energy of 30 J. The apparent saturation of the output energy observed in [1] may be probably due to the use of a silicon photodetector as the energy meter. This detector is not sensitive above 1100 nm, therefore the strong Stokes lines at 1180.8 nm and 1321.5 nm cannot be detected. In our measurements, we used a pyroelectric energy meter (Gentec, ED 500) with a flat frequency response for all wavelengths in this experiment (F, S1, S2); thus, the total output was measured.

Another possible explanation for the quite different experimental results may be the use of relatively short rectangular pump pulse of 60 $\mu$s pulsewidth in our pulse-forming network which facilitates more efficient $Q$-switched operation for laser crystals with short-living upper level.

A third reason may be that we used efficient cooling due to the special construction of the laser head. With inefficient cooling, the strong thermal lens may reduce considerably the efficiency of the $Q$-switched operation at high pump rates.

Because of lack of mirrors with lower reflectivity, we did not optimize the $Q$-switched operation with respect to output coupling. It is clear that the available outputcoupler with 60% reflectivity was far from the optimum and that one can expect even better results with lower reflectivity of the order of 20%.

An especially attractive feature of the new laser medium is the possibility for simultaneous multiwavelength generation of high power nanosecond pulses. Altogether 12 possible lines can be generated by using only two nonlinear crystals (doubler and mixer): 355.6, 367, 378, 393, 408, 423, 440, 533.5, 560, 590, 623 and 660 nm. All these are combinations $n(\omega - p\Omega)$, $n = 2, 3$; $p = 0$, 1,2), where $\Omega$ is the Raman shift 901.5 cm$^{-1}$. Another five lines are attainable by frequency quadrupling: 267, 280, 295, 312 and 330 nm.

## 3 Conclusion

In conclusion, high energy output of 400 mJ, exceeding by an order of magnitude that of previously reported results, is obtained in the $Q$-switched mode of a flashlamp-pumped $Nd^{3+}$:$KGd(WO_4)_2$ laser. The $Q$-switched operation does not exhibit pronounced saturation of the output energy as was recently reported in other works. Multiwavelength operation is observed due to efficient Stokes conversion in the laser crystal. This feature makes the laser medium attractive for many spectroscopic applications.

*Acknowledgements.* The authors are indebted to F. Simon for the help in the initial stage of the experiment. We thank also Dr. Fröhlich for providing the laser power supply and J. Jethwa for providing the Pockels cell.

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