Available online at www.sciencedirect.com

SCIENCE DIRECT®

Optics Communications 231 (2004) 319–324

OPTICS COMMUNICATIONS

www.elsevier.com/locate/optcom

Green Q-switched microsecond laser pulses by overcoupled intracavity second harmonic generation

Dietmar Kracht *, Ralf Brinkmann

Medical Laser Center Luebeck, Peter-Monnik-Weg 4, 23562 Luebeck, Germany

Received 12 September 2003; received in revised form 26 November 2003; accepted 26 November 2003

Abstract

In order to achieve laser pulses with microsecond duration in the green spectral range, we investigated the effect of overcoupled intracavity second harmonic generation with a Q-switched transversally diode pumped Nd:YLF laser. KTP and LBO crystals with different lengths were used to study the laser pulse energy, shape and duration at 526.5 nm. A pulse energy of 4.3 mJ was achieved with a FWHM pulse duration of 650 ns using a 5 mm long KTP and 3.4 mJ with 3.2 μs using a 10 mm long crystal. With a 10 mm long LBO a FWHM duration of 600 ns and with a 20 mm LBO 1.5 μs were generated both with a pulse energy of 4 mJ.

PACS: 42.55.Xi; 42.60.Gd; 42.65.Ky

Keywords: Solid state lasers; Harmonic generation; Microsecond laser pulses

1. Introduction

In ophthalmology a variety of retinal diseases are thought to be associated with a decreased function of the retinal pigment epithelium (RPE). In order to selectively target dysfunctional RPE while preserving the adjacent tissues, especially the photoreceptors and the neuronal retina, a train of microsecond laser pulses is most suited. For treatment a pulse energy up to 2 mJ at a repetition rate of 100–500 Hz in the green spectral range is required [1,2]. A laser system with the desired specifications is to the best of our knowledge not described so far. Commercially available green Q-switched solid state lasers are limited to pulse durations up to some hundred nanoseconds, while flashlamp pumped dye lasers are limited in their pulse repetition rate. Several approaches to stretch the duration of Q-switched laser pulses have already been made by using intracavity nonlinear absorbing elements [3,4] or active feedback control systems [2,5]. Nevertheless none of these techniques were converted to a compact and efficient laser system.

* Corresponding author. Address: Department of Laser Development, Laser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hannover, Germany. Tel.: +49-511-2788-261; fax: +49-511-2788-100.

E-mail address: dk@lzh.de (D. Kracht).

0030-4018/$ - see front matter
doi:10.1016/j.optcom.2003.11.064

2. Aim

The aim of this work is to demonstrate a practicable method to generate microsecond laser pulses in the green spectral range with an all solid state laser system, fulfilling the specifications required for the selective retinal treatment. A combination of a low gain laser source with overcoupled intracavity second harmonic generation [6–10] is promising to generate Q-switched laser pulses in the microsecond time regime. A proper solid state laser medium with a low gain is Nd:YLF due to its small stimulated emission cross-section of 1.2×10^{-19} cm^2 on the 1053 nm line [11]. With respect to efficient second harmonic generation, KTP with its high effective nonlinear coefficient of 3.13 pm/V is a suitable crystal for type II critical phase matching. LBO provides temperature tuned noncritical phase matching and thus minimize phase mismatch. This enables the use of long crystals. However, LBO has an effective nonlinear coefficient of only 0.85 pm/V at 1053 nm [12].

3. Theory

In order to describe the effect of overcoupled intracavity second harmonic generation on the laser pulse duration it is necessary to focus on the dynamic behaviour during the pulse emission. The nonlinear crystal inside the cavity acts as a variable output coupler due to the nonlinear power conversion from the fundamental wave to the second harmonic. While the laser power is build up at the beginning of the pulse, the intensity dissipated from the cavity increases linearly with the fundamental intensity due to parasitic losses and with the square of the fundamental power due to the losses from the second harmonic generation. The peak power is reached when the loss equals the gain for the fundamental. Beyond this time the laser power decreases and the remaining inversion is slowly depleted in an extended pulse. If the conversion efficiency becomes much higher than that necessary to generate maximum second harmonic peak power, more of the stored energy is used to lengthen the pulse.

To quantitatively analyse the dependence of the laser pulse energy and duration on the frequency conversion process the rate equations for this laser system have been numerically solved. Using the plane wave approximation the conversion $I_{2\omega}(t)/I_{\omega}(t)$ from the fundamental frequency ω to the second harmonic 2ω mainly depends on the length of the nonlinear crystal l, its effective nonlinear coefficient d_{eff} and the fundamental beam waist within the nonlinear crystal [13]. Further the conversion describes the nonlinear single pass loss factor $\gamma_{\mathrm{NL}}(t)$ of the resonator:

$$\gamma_{\mathrm{NL}}(t) = \frac{I_{2\omega}(t)}{I(t)} = \tanh^2\left(\beta\sqrt{I(t)}\right),$$

with

$$\beta = \sqrt{2\eta^3} d_{\mathrm{eff}}\, l\, \omega_{\mathrm{F}} \sqrt{\frac{A_{\mathrm{L}}}{A_{\mathrm{N}}}} \frac{\sin \Delta k l/2}{\Delta k l/2},$$

η is the plane wave impedance, $A_{\mathrm{L,N}}$ is the area of the fundamental beam inside the laser crystal and nonlinear crystal, Δk is the phase mismatch. The Q-switched rate equations for the inversion density $n(t)$ and laser intensity $I(t)$ are:

$$\frac{\mathrm{d}n(t)}{\mathrm{d}t} = -\frac{\sigma_{\mathrm{SE}}}{h\nu} n(t) I(t),$$

$$\frac{\mathrm{d}I(t)}{\mathrm{d}t} = \frac{2\sigma_{\mathrm{SE}}\, l}{\tau_{\mathrm{R}}} I(t) n(t) - \frac{1}{\tau_{\mathrm{R}}}\left(\ln(1-\gamma_{\mathrm{L}}) + 2\ln(1-\gamma_{\mathrm{NL}}(t))\right) I(t),$$

where τ_{R} is the photon round trip time in the laser resonator, γ_{L} the linear round trip losses and σ_{SE} the cross-section for stimulated emission. To simplify the model a top hat beam profile was assumed.

Fig. 1 shows a calculation of the dependence of the pulse energy and duration on the nonlinear coupling β for different absorbed pump powers of 30, 50 and 70 W. For each pump power the pulse energy rises to a maximum and decreases slowly in the range of overcoupling, while the pulse duration ascends nearly with the square of the nonlinear coupling. According to the simulation the pulse duration of a Q-switched Nd:YLF laser system can be lengthened to the microsecond time regime without significant loss of energy by increasing the second harmonic conversion efficiency respectively the nonlinear coupling.

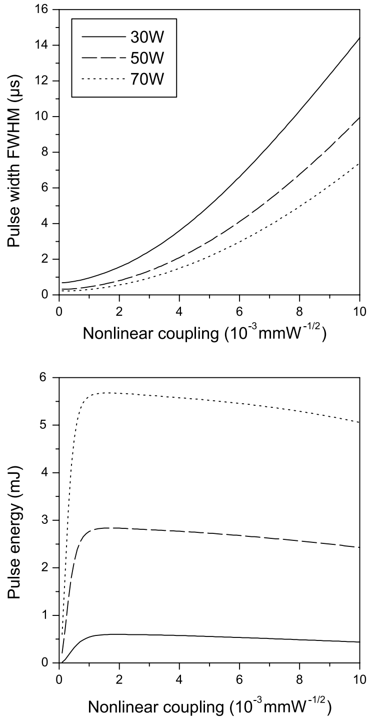

Fig. 1. Calculated dependence of pulse width (FWHM) and energy on the nonlinear coupling for different absorbed pump powers. Simulation parameters: Nd:YLF laser crystal with 50 mm length and 5 mm diameter operated on the 1053 nm line, round trip losses 4%, beam diameter 3.75 mm inside the laser crystal, resonator length 100 cm.

Assuming no phase mismatch the nonlinear coupling per length nonlinear crystal (in mm) is $\beta/l = 0.65 \times 10^{-3}\ \mathrm{W}^{-1/2}$ for KTP and $\beta/l = 0.18 \times 10^{-3}\ \mathrm{W}^{-1/2}$ for LBO respectively. The beam diameter inside the nonlinear crystal was set three times of that inside the laser rod which corresponds to the experimental resonator setup. In practice a perfect phase match is rarely achieveable, so this is only an estimation for the highest possible coupling.

4. Experiments and results

A 70 mm long and 5 mm in diameter 1% doped c-cut Nd:YLF laser rod (Litton Inc.) was continuously transversally pumped by three elements of four laser diodes (Dilas GmbH) each emitting at a wavelength of 795 nm. The pumped rod length was 50 mm. The cw laser performance was measured with a 20 cm long resonator built by a concave high reflective mirror with a radius of 500 mm and different plane output couplers. With a mirror transmission of 3.5% a slope efficiency of 35% and a maximum cw output power of 47 W were achieved at 1053 nm with a pump power of 150 W. 9.5% transmission led to a slope efficiency of 39% and 44 W maximum output power. The threshold pump power was 15 W for 3.5% and 39 W for 9.5% transmission. The absorption efficiency of the pump light was estimated to be 70%.

The resonator with intracavity second harmonic generation is sketched in Fig. 2. It was build by a L-configuration with a plane high reflective mirror for the fundamental, a planoconvex lens with 400 mm focal length and a concave mirror with 250 mm radius, which is high reflective for 527 and 1053 nm. A plane dichroic mirror under 45° separates the fundamental and the second harmonic wave. The laser was acoustooptically Q-switched with an AOM (Gooch & Housego). To match the needs for type I phase matching with LBO the laser is optionally polarized with a Brewster plate.

KTP crystals (gray tracking resistant, $\theta = 90°$, $\varphi = 32.9°$, Crystal Associates Inc.) with an aperture of 4 by 4 mm and different lengths of 3, 5, 7 and 10 mm were used for frequency doubling at room temperature. To specify the optimal phase matching conditions for two LBO crystals ($3\ \mathrm{mm} \times 3\ \mathrm{mm} \times 10\ \mathrm{mm}$, Casix Inc.; and $2.25\ \mathrm{mm} \times 2.75\ \mathrm{mm} \times 20\ \mathrm{mm}$, Castech Crystals Inc.) the green pulse energy was measured varying the temperature of an oven for the crystals over a wide temperature range. To avoid overcoupling for these measurements the laser system was operated with a plane 3.5% transmission mirror instead of the high reflective one. The best phase matching condition, i.e. the highest pulse energies at 527 nm were achieved at 165.1 °C for the 10 mm LBO and at 163.2 °C for the 20 mm LBO.

For the two different LBO crystals the dependence of the pulse energy and duration on the pump power was measured at a repetition rate of 500 Hz as shown in Fig. 3 after replacing the 3.5% transmission mirror with a highly reflective one. The threshold for Q-switched operation for both LBO crystals was around 22 W. The pulse energy

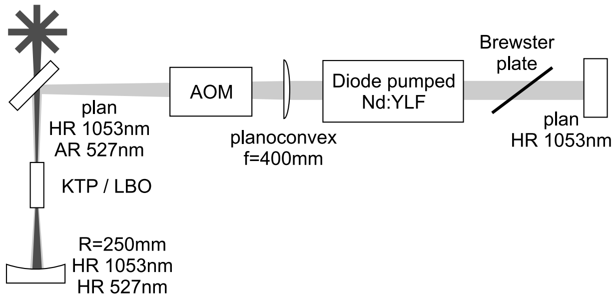

Fig. 2. Schematic diagram of the resonator setup for the intracavity frequency doubled Q-switched Nd:YLF laser.

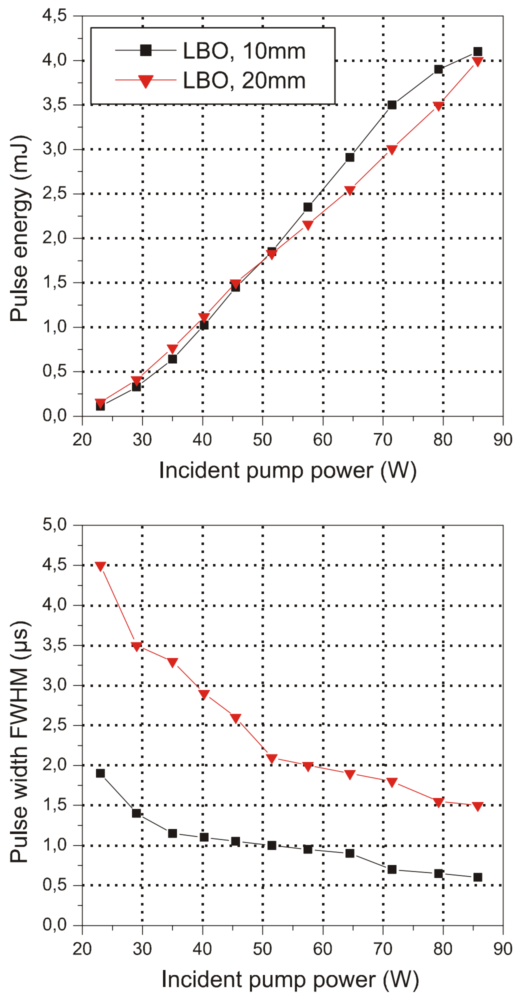

Fig. 3. Measured pulse energies and pulse durations (FWHM) at 527 nm vs. incident pump power using LBO crystals with different lengths.

rose for both crystals nearly linearly up to 4.1 mJ for the 10 mm LBO and 4 mJ for the 20 mm LBO at a pump power of 86 W. The pulse duration (FWHM) was significantly different although the pulse energies were similar. Using the 10 mm LBO the pulse duration was nearly 2 µs at threshold, decreased to 1 µs at a pump power of 51 W and was 600 ns at 86 W. For the 20 mm LBO the pulse duration was between two and three times higher in the whole pump power range. For the 20 mm LBO the duration at threshold was 4.5 µs, at 51 W it was reduced to 2.1 µs and to 1.5 µs at 86 W of pump power. The whole system operated stable and reproducible. Standard deviation of pulse to pulse fluctuations were typically less than 4% for the energy and less than 10% for the duration over a range of 10,000 pulses.

For the four different KTP crystals the dependence of the pulse energy and duration on the incident pump power was measured at a repetition rate of 100 Hz as shown in Fig. 4. The threshold for Q-switched operation was around 22 W for all KTP crystals. The pulse energy rose to the range of 3 mJ at a pump power of 57 W for all crystals. The highest energy was achieved with 4.3 mJ for the 5 mm KTP, while only 3.4 mJ were measured for the 10 mm KTP at the maximal used pump power of 71 W. As expected for the overcoupling range (see Fig. 1) the pulse energies were very similar for all crystals while the pulse durations (FWHM) increased with higher nonlinear coupling. The pulse duration decreased with the pump power for each KTP and increased with the length of the KTP crystal at constant pump power. Using the 3 mm KTP the pulse duration was between 400 ns and 1.2 µs, while the 10 mm KTP led to durations

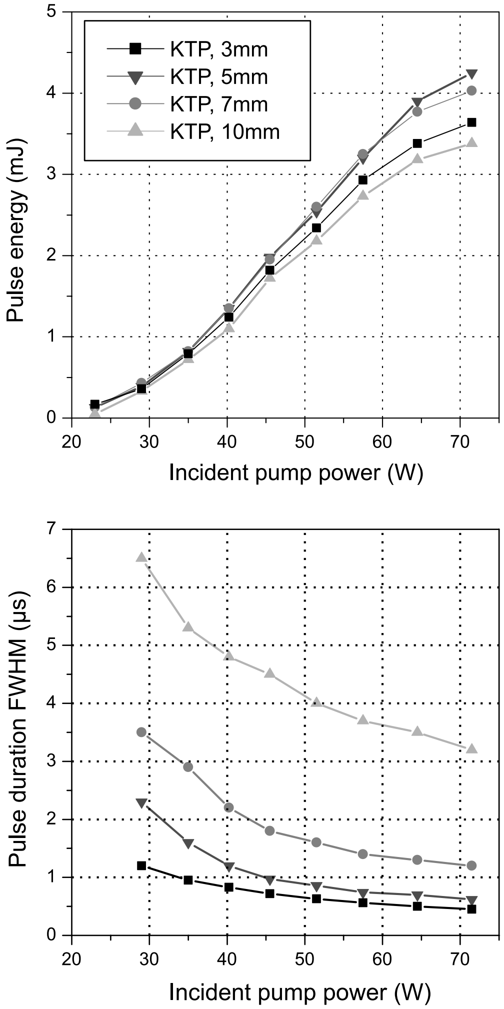

Fig. 4. Measured pulse energies and pulse durations (FWHM) at 527 nm vs. incident pump power using KTP crystals with different lengths.

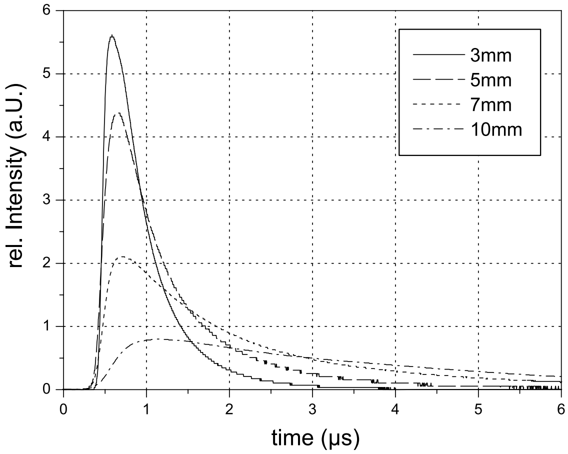

Fig. 5. Measured laser pulses shapes at 527 nm using KTP crystals with different lengths as indicated at an incident pump power of 71 W.

from 3.2 to 6.5 μs, which is more than five times higher than with the 3 mm crystal over the whole pump range. For incident pump powers higher than 35 W the standard deviation of pulse to pulse fluctuations were typically less than 1% for the energy over a range of 10,000 pulses and less than 4% in duration regarding 20 pulses out of the 10,000. The better stability of the system using KTP is thought to be a product of temperature fluctuations of the crystal oven for the LBO. Typical pulse shapes for a pump power of 71 W are shown in Fig. 5 for the laser operating with the different KTP crystals. The asymmetrical pulse shapes are typical for the overcoupling regime. The beam quality of the laser system was measured to have an M^2 below 8 over the whole pump power range.

The experimental results underline the tendencies calculated with the numerical analysis of the rate equations. With both crystals LBO and KTP microsecond pulses can be generated by using the overcoupling effect. The pulse widths achieved experimentally are shorter than expected for maximum nonlinear coupling which is obviously caused by unavoidable phase mismatch.

5. Conclusion

In conclusion we have demonstrated green Q-switched laser pulses of several millijoules energy in the microsecond time regime with a compact all solid state laser system for the first time. The overcoupling effect provides a method to adjust the pulse duration of intracavity frequency doubled laser systems without significant loss of pulse energy. To extend the pulse duration to several microseconds a low amplification laser source is favourable, since it requires a lower nonlinear coupling than a high amplification one.

Acknowledgements

This project was supported by the German Ministry of Education and Research (BMBF), grant no. 13N7309.

References

[1] J. Roider, R. Brinkmann, C. Wirbelauer, H. Laqua, R. Birngruber, Arch. Ophthalmol. 117 (1999) 1028.
[2] R. Brinkmann, G. Hüttmann, J. Rögener, J. Roider, R. Birngruber, C.P. Lin, Laser. Surg. Med. 27 (2000) 451.
[3] A. Hordvik, IEEE J. Quantum Electron. 6 (1970) 199.
[4] V.A. Aleshkevich, V.V. Arsen's, V.N. Dneprovskii, D.N. Klyshko, L.A. Sysoev, Jetp Lett. 9 (1969) 123.
[5] W.E. Schmid, Pulse stretching in a Q-Switched Nd:YAG Laser, IEEE J. Quantum Electron. 16 (1980) 794.
[6] J.E. Murray, S.E. Harris, J. Appl. Phys. 41 (1970) 609.
[7] J.F. Young, J.E. Murray, R.B. Miles, S.E. Harris, Appl. Phys. Lett. 18 (1971) 129.
[8] P.E. Perkins, T.A. Driscoll, J. Opt. Soc. Am. B 4 (1987) 1281.
[9] V.G. Dmitriev, E.A. Shalaev, Sov. J. Quantum Electron. 9 (1979) 123.
[10] P.E. Perkins, T.S. Fahlen, J. Opt. Soc. Am. B 4 (1987) 1066.
[11] E.J. Sharp, D.J. Horowitz, J.E. Miller, J. Appl. Phys. 44 (1973) 5399.
[12] V.G. Dmitriev, G.G. Gurzadyan, D.N. Nikogosyan, Handbook of Nonlinear Optical Crystals, Springer, Berlin, New York, 1999.
[13] W. Koechner, Solid-state Laser Engineering, Springer, Berlin, New York, 1999.