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30 mJ, TEM_{00}, high repetition rate, mechanically Q-switched Er:YAG laser operating at 2940 nm

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The 2940 nm Er:YAG laser Q-switched mechanically by means of a rotating mirror was developed. It generated the output pulses of up to 30 mJ energy, below 300 ns duration and record repetition rate of 25 Hz. The developed laser was effectively used for the investigation of laser beam interaction with selected organic matter simulants.

Keywords: erbium lasers, Q-switched lasers, medical applications of lasers.

1. Introduction

In this paper we focused on the 3-μm wavelength range, for which strong, resonant absorption in matters containing OH^- ions (mainly in water present in biological tissues) reveals. Lasers operating at this wavelength range are desired and sought-after in many various fields of medicine [1].

Monopulse generation in a laser systems based on Er:YAG crystals can be obtained by applying commonly known Q-switching methods including active (electro-optic Ref. 2, acusto-optic Ref. 3, mechanical Ref. 4), and passive methods [5]. Cavity Q-switching of erbium lasers results in generation of pulses with time duration below 1 μs, typically in the range of several dozens to hundreds of nanoseconds and peak-power of the order of 1 MW [6].

It seems that electro-optic methods of Q-switching are the most technically advanced. They are very common in lasers operating at around 1-μm wavelength, characterized by a very high gain. However, for 3-μm wavelength range, there is difficulty in finding good Q-switchers. In this wavelength range, most electro-optic crystals have low transmittance. Losses inserted into a laser cavity by a Q-switch should not be higher than several percent – mainly because Er:YAG lasers operating at 2.94 μm have low gain (typical transmission value of an output coupler is about 10%). Electro-optic materials suitable for 3-μm range (e.g. $LiNbO_3$ or RTP crystals) have many drawbacks, like piezoelectric "ringing" effect, limited dimensions, sensitivity to temperature and high price. Additional factor making the use of these Q-switches difficult is the necessity of applying polarizes of low losses or using crystals cut at Brewster angle.

Typical Q-switched erbium lasers work with limited repetition rate – usually below 5 Hz and generate pulses of energy below a few dozens of mJ. Such pulse parameters are inadequate for many practical applications. Therefore, it seems to be reasonable to increase the repetition rate at the cost of pulse energy, ensuring good laser beam quality at the same time. This way undesirable interaction effects (shock wave, for instance) can be reduced.

In 2005, a Q-switched Er:YAG laser generating pulses with record energy of 140 mJ was developed by our team [7]. In 2008, another Er:YAG laser generating pulses with energy of 20 mJ in fundamental TEM_{00} mode, at the repetition rate of up to 10 Hz, was constructed [8]. The lasers were Q-switched electro-optically by means of a Pockels cell made of a $LiNbO_3$ crystal. Although the lasers worked with the repetition rate higher than ever reported, they did not work for a long time. After several hours of operation (about 10^5 pulses), the Pockels cells were damaged. The reason of the damage lies in the properties of the material being used for electro-optic Q-switch manufacturing and it seems to be very difficult to overcome, not to say insurmountable.

Since gain in Er:YAG lasers operating at 2.94 μm is low, the generation of short laser pulses obtained by means of Q-switching methods is difficult to achieve. Generated pulses are relatively long and the power intensity inside the laser cavity is many times higher than that obtained at the laser output. This can lead to damage of optical cavity elements. Furthermore, since firstly inner power (energy) at not so high exceeding of the generation threshold (which usually takes place in an Er:YAG laser Q-switching process) is comparable with the saturation power (energy) and secondly, the power (energy) density at the laser output is at least one order of magnitude lower that the saturation power (energy) (due to low transmission of the output coupler),

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further pulse amplification in such a laser is ineffective. On the other hand, low gain in a laser medium can have also a positive aspect, it allows applying Q-switches with relatively slow switching time, like for instance mechanical modulators.

2. Q-switched Er:YAG laser with a rotating mirror – laser set-up

The laser system was developed with the use of elements utilized in earlier construction of the system presented in Ref. 9 and its set-up is depicted in Fig. 1. A $\phi 4\times 100$ mm Er^{3+}-doped YAG crystal was used as an active medium. The rod had AR-coatings on both end surfaces. The laser was pumped by a single xenon flashlamp (5400X type) with typical pump energy of up to 60 J, housed in a single diffuse (ceramics) head. The 80–cm-long laser cavity was formed by two mirrors, a rotating mirror M1 and an output mirror M2 with reflectivity of 100% and 90%, respectively. The flash-lamp was supplied by a home-made power supply built with the use of IGBT transistors which allowed smooth control of pump pulse duration from 100 μs to several ms at the repetition rate up to 50 Hz. To keep the thermal lensing minimum, the pump pulse duration was set to 300 μs.

Due to strong thermal lensing phenomenon, the compensating element in the form of a convex mirror RM was inserted inside the laser cavity. Such a laser resonator configuration resulted from a limited availability of high quality optical elements dedicated for the spectral range of 2.94 μm. Using ABCD matrix formalism, the resonator was optimized in terms of maximum size of the fundamental mode for the expected range of average pumping power. Selected results of the optimization are shown in Fig. 2. The laser resonator was dynamically stable for the focal length of a thin lens representing the thermal lens of Er:YAG rod in the range of 20–35 cm.

The convex mirror RM had 100% reflectivity at 3 μm and curvature radius of 50 cm. The 100% reflectivity mirror M1 played a role of mechanical Q-switch. It was attached to a motor driven by a suitable microprocessor controller which triggered the pump source according to the chosen repetition rate, pump pulse length and delay time.

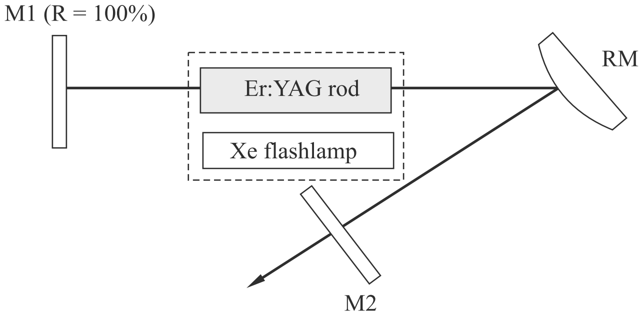


Fig. 1. Q-switched Er:YAG laser set-up with thermal lensing compensation.

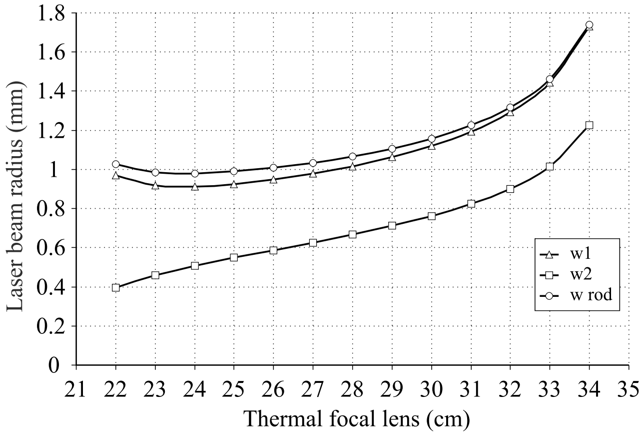


Fig. 2. Calculated dependence of fundamental mode radius on M1 and M2 mirrors and in a laser rod (for the laser presented in Fig. 1) *vs.* focal length of a thin lens representing a thermal lens of an active laser rod. w1, w2 – radius of a laser beam located on M1 and M2 mirrors, respectively; w rod – radius of a laser beam at the centre of a laser rod.

The main disadvantage of a Q-switch based on a rotating mirror is its limited controllability compared to electro-optic modulators. Every rotational velocity complies with only a certain set of repetition rates. The applied rotational velocity of the motor is directly connected with the pump energy necessary for obtaining the suitable gain level. For a given pump energy, there is only one optimum rotational velocity of the motor, at which the energy of generated pulse is the highest. Therefore, there is no possibility of separate selection of laser parameters, like pumping energy or repetition rate. Furthermore, for each pair of "pump energy-repetition rate" there is usually different average pumping power, which, in turn, is very important for the sake of thermal lensing and consequently diffraction losses of the laser cavity and its stability.

3. Free-running mode of operation

Compared to an electro-optically Q-switched laser, a laser Q-switched mechanically by a rotating mirror has considerably lower internal losses and thank to that the gain value required for obtaining the same pulse energy at the laser output is significantly lower. On the other hand, keeping the same diffraction losses level related to thermal lensing requires increasing the repetition rate so that, the average pumping power is constant. Therefore, increasing the repetition rate is just the necessity. The side effect of this is lengthening of the pulse duration. The stability of the Er:YAG laser in free running mode of operation was achieved by replacing the rotating mirror M1 with a flat stationary total reflection mirror. The laser output energy *vs.* flash-lamp supply voltage for the repetition rates of 10, 15, 20, 25, 30, and 35 Hz are presented in Fig. 3.

The output laser pulse energy was presented as the function of flash-lamp supply voltage instead of pump energy due to measurement difficulties of the latest one. These two quan-

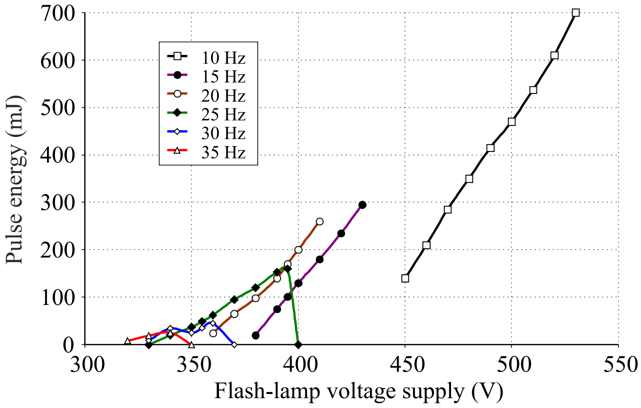


Fig. 3. Output energy of free-running Er:YAG laser *vs*. flash-lamp supply voltage for repetition rates of 10, 15, 20, 25, 30, and 35 Hz. Pump pulse duration – 300 μs.

tities are equivalent and therefore it is possible to use them interchangeably. Based on the results presented in Fig. 3, it can be stated that for the repetition rate below 20 Hz, the thermal focal length in the Er:YAG rod is longer than 20 cm (in the range of applied flash-lamp supply voltage values). For these cases, the laser operation cut-off caused by excessive thermal lensing was not observed. For all the values of the applied repetition rate, the thermal focal lens was shorter than 35 cm and with the repetition rate increase, the threshold value of supply voltage (pump energy) decreases. It is apparent that it results from the fact that the average power causing the losses of resonator stability should be equal in each case. For the repetition rate above 25 Hz, the laser operation cut-off induced by thermal lensing was recorded. Further repetition rate increase caused decreasing the voltage supply (pump energy) range and the voltage supply values for which the resonator was stable. For that reason, also the output pulse energy was lower.

In case of Q-switched erbium lasers operating at 2.94 μm, the energy of single giant pulse constitutes of 30–50% of the energy obtained in free-mode operation [10]. Therefore, to obtain pulse energy of the order of 30 mJ, it is necessary to work in pumping conditions where for free-mode operation the output energy is of the order of 100 mJ. Simultaneously, the working point of the resonator should be located near the centre of its stability range. Hence, the optimum repetition rate value for the laser considered should be 25 Hz and the pump energy should correspond with flash-lamp supply voltage of about 360–380 V. For the chosen supply voltage range and for 25 Hz repetition rate, the output beam profile was very stable and close to a Gaussian distribution.

4. Q-switching mode of operation

Due to limited possibility of a rotating mirror controller, the Q-switched Er:YAG laser presented in Fig. 1 was stable only for a certain values of flash-lamp supply voltage and repetition rate. Moreover, the output pulse energy was to be set in the range of 30 mJ so as not to damage the optical components of the laser cavity. For the supply voltage of 360–380 V and 25 Hz repetition rate corresponding to the resonator stability centre, the optimum rotational velocity of the microprocessor controller was in the range of 85–115 Hz (which corresponded with the discrete laser repetition rate values of 19, 20, 21, 23, 25, 28, 29, and 33 Hz) and its further increasing caused the output pulse energy decrease. The best beam quality was observed at 25 Hz repetition rate. At every repetition rate value, the output pulse energy increased with the flash-lamp supply voltage increase up to a value at which a second pulse appeared.

In the mechanically Q-switched Er:YAG laser, generation of nanosecond pulses at the repetition rate of 25 Hz has been obtained. The pulse energy and the shortest pulse duration (FWHM) recorded equalled 30 mJ and 287 ns (Fig. 4), respectively. The supply voltage in this case was set to 375 V. The laser operated with a stability of several percent for many hours without any damage. It is also worth emphasizing that the beam profile of generated radiation was homogenous and stable. The output beam divergence measured in a far field was 3.125 mrad and the M^2 parameter was 1.54.

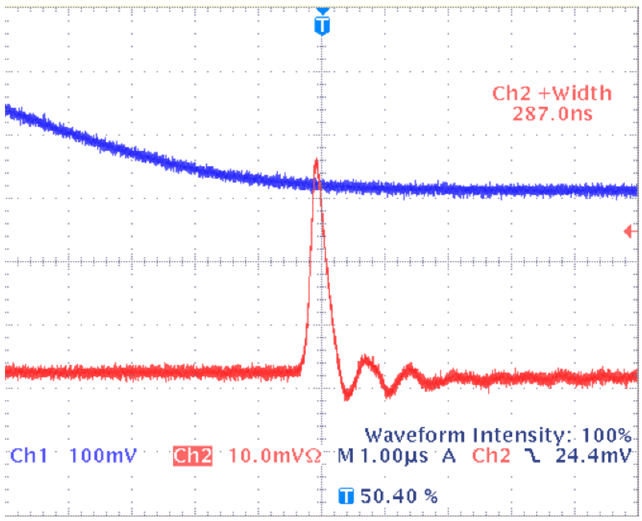


Fig. 4. Oscilloscope pictures of the shortest Q-switch pulse generated by the Er:YAG laser. Lower trace – laser pulse, upper trace – current applied to the pump lamp.

5. Laser pulses interaction with organic matters

The developed Q-switched Er:YAG laser was put to the long-term working test. During the test, the laser generated pulses with energy of 20 mJ (+/–3%) and the repetition rate of 25 Hz. The system operated in sessions lasting for several hours, right up to noticeable laser energetic performance decrease, resulting from flash-lamp ageing (over 10^7 flashes). After the flash-lamp replacement, the output laser parameters returned to the initial state. During the laser operation no any damage of laser cavity components was observed.

The efficiency of laser radiation interaction with selected organic matters (gelatin and plexiglass) was investigated. The laser beam was focused on samples surface by means of a single sapphire AR-coated lens, with effective focal length of 10 cm. The laser spot diameter at the focus region was 70 μm, which corresponded to the power density of several GW/cm^2.

The gelatin samples were prepared in the shape of a rectangular prism with at least one side surface polished – in order to make the interaction process recording by means of a digital camera possible. Three samples with different concentration of gelatine (10, 25, and 50 gram of gelatin per 150 ml of water) were used in the experiment to imitate tissues of various hardness. It is necessary to add here that gelatin is a medium commonly used in laboratory experiments as a substitute of a biological tissue.

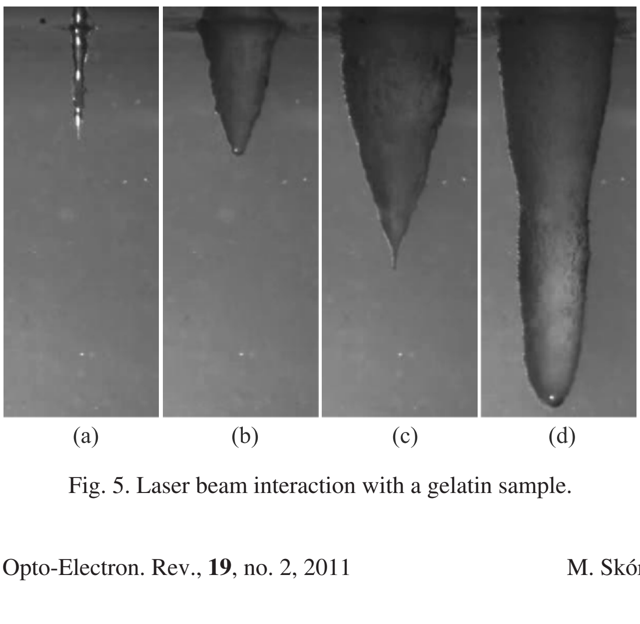
The effects of laser radiation interaction with gelatin samples were different depending on their hardness. The most effective results of fast crater hollowing were observed for low concentration samples. The craters were hollowed relatively quickly in all cases, however, the duration of this process was different in each case.

During the laser radiation interaction with gelatin samples four phases can be distinguished. In the initial phase (a), the hollowing of a narrow crater was observed which then widened (b,c) and at the same time the hollowing velocity decreased. At one moment, the blisters (moving in a way similar to the one observed during liquid boiling) in the crater region were noticeable. It could go to show that the gelatin temperature in the interaction region increased significantly, especially as in the next phase (d) the observed crater hollowing was specific to remelting process. Simultaneously, a very strong evacuation of gelatin (in the form of drops) in the direction of laser optics was observed. It caused very fast covering of the lens surface by gelatin drops and consequently decreasing pulse energy of the consecutive laser pulses applied to the sample.

The hollowing process presented in Fig. 5 is quite complicated and shows the importance of thermal effects occurring during the interaction of relatively long, not so energetic (20 mJ) laser pulses generated at high repetition rate with organic matter. It seems that the main reason of the interaction character is the high repetition rate causing the matter heating. Additionally, the evacuation of ablation products was very limited and the pulse energy had to be dissipated into a limited volume of the crater. Therefore, superficial interaction seems to be much more appropriate. Currently, such an experiment is in preparation.

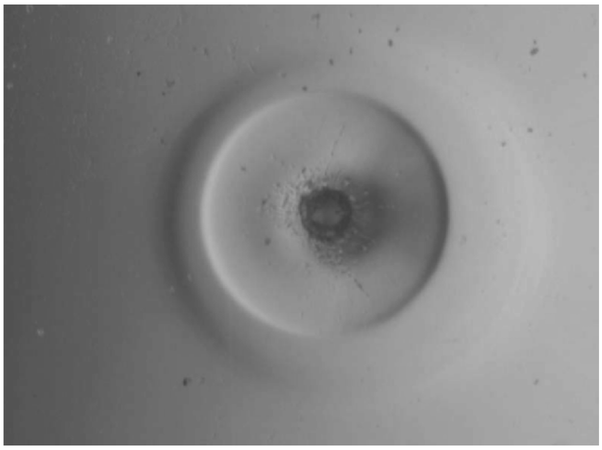
During the experiment, an optically changed layer located around the crater in a gelatin sample was observed. It was visible only during the time of pulse interaction with gelatin and it disappeared after laser switching-off. To show more precisely the effect, the gelatin sample was replaced by a plexiglass plate. Thanks to that it was possible to record it in the permanent way, which is showed in Fig. 6.

Around the crater there is an optically changed zone in the shape of aureole. It is presumed that an acoustic or shock wave generated during interaction or combined thermal and mechanical effects are responsible for that. This aspect of interaction requires further study, especially that possible presence of shock waves generated during the laser beam-matter interaction could be a factor significantly limiting the Q-switched Er:YAG medical applications.

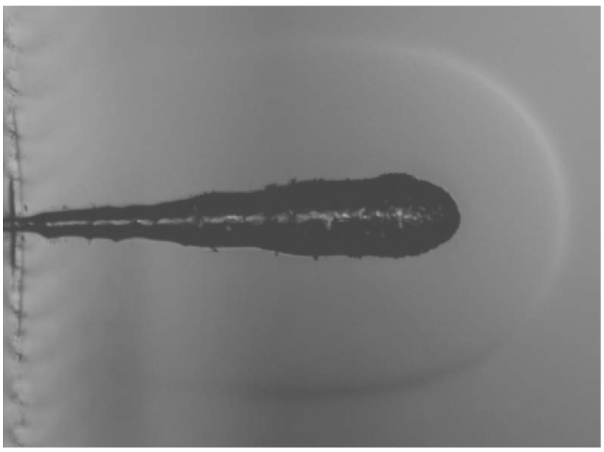


(a) (b) (c) (d)

Fig. 5. Laser beam interaction with a gelatin sample.



(a)



(b)

Fig. 6. (a) View of a crater created by Er:YAG laser radiation in plexiglass: sample surface, (b) View of a crater created by Er:YAG laser radiation in plexiglass: side view.

6. Conclusions

The 2.94-μm Er:YAG laser Q-switched mechanically by means of a rotating mirror and working with the record repetition rate of 25 Hz was developed. It generated the pulses with energy of up to 30 mJ and duration below 300 ns, which corresponds to over 100 kW peak power. The output beam quality was $M^2 = 1.54$. The laser has been working stable and without breakdown for several months and its parameters has only depended on the state of the pumping flash lamp. To our best knowledge, this is the most powerful erbium laser in 3-μm region characterized by so high repetition rate. Furthermore, we believe that further laser rod thermal lens compensation will allow shortening of a laser cavity which, in turn, will result in shortening of output pulse duration. The developed laser was effectively used for the investigation of laser beam interaction with selected organic matter simulants.

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