High peak power Q-switched Er:YAG laser with two polarizers and its ablation performance for hard dental tissues

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Abstract: An electro-optically Q-switched high-energy Er:YAG laser with two polarizers is proposed. By using two Al2O3 polarizing plates and a LiNbO3 crystal with Brewster angle, the polarization efficiency is significantly improved. As a result, 226 mJ pulse energy with 62 ns pulse width is achieved at the repetition rate of 3 Hz, the corresponding peak power is 3.6 MW. To our knowledge, such a high peak power has not been reported in literature. With our designed laser, in-vitro teeth were irradiated under Q-switched and free-running modes. Results of a laser ablation experiment on hard dental tissue with the high-peak-power laser demonstrates that the Q-switched Er:YAG laser has higher ablation precision and less thermal damage than the free-running Er:YAG laser.

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References and links

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at the repetition rate of 3 Hz, the corresponding peak power was 1.5 MW [11]. Meanwhile, Zajac et al. used LN as a Q-switch crystal because of its high transmittance. Zajac et al. used LN as a Q-switch in a flashlamp-pumped Er:YAG laser, 137 mJ pulse energy with 91.2 ns pulse width was obtained at the repetition rate of 3 Hz, the corresponding peak power was 1.5 MW [11]. Meanwhile, Koranda et al. utilized a LN Pockels cell in a flashlamp-pumped 2.94 μm Er:YAG laser, 60 mJ pulse energy with 60 ns pulse width was accomplished at the repetition rate of 1 Hz, the corresponding peak power reached 1 MW [12]. In the case of investigations on ablation and thermal effects, it is necessary to limit the single pulse duration less than 1 μs to reduce thermal diffusion during the laser pulse, and therefore minimize the thermal damage zone [7, 13]. Jelinkova et al. observed obvious thermal damage when a free-running erbium laser with a pulse energy of 75 mJ and a pulse width of 200 μs was applied to ablate the hard dental tissues [14]. They found that, when employing a Q-switched erbium laser with 40 μJ pulse energy and 80 ns pulse width, there existed much higher efficiency and less thermal damage. The ablation and dental bio-thermal effects of Q-switched Er:YAG lasers, particularly with higher peak power and shorter pulse width, have not yet been reported.


1. Introduction

Erbium:yttrium-aluminum-garnet (Er:YAG) laser crystals can be used to produce a laser radiation at 2.94 μm, which is closed to the infrared absorption peaks of water and hydroxyapatite. The laser radiation at 2.94 μm is more suitable to ablate biological hard tissues, compared with other wavelengths. Er:YAG laser has been widely applied in the dental fields, such as dental ablation [1], cavity preparation [2, 3], caries removal [1, 4] and root canal treatment [5]. Normally, the free-running Er:YAG laser designed for clinical use typically has a pulse width of a few hundred microseconds. When such a long-pulsed radiation is applied to the affected areas, the excess heat diffuses into the surrounding healthy tissues, causing damage or necrosis [6, 7]. In order to avoid the thermal damages, a water-cooling spray must be used during surgery [8, 9]. However, the high peak power and short pulse width (nanosecond) of a Q-switched laser can very effectively prevent the thermal damage [10]. Therefore, it is important to develop a high-energy high-peak-power Q-switched Er:YAG laser for the treatment of hard tissue diseases.

Nanosecond pulses at a wavelength of 3 μm can be obtained by electro-optic (EO) Q-switching technique that plays an important role in a high-energy laser due to its advantages of effective controllability, high stability, and fast switching. To obtain a high-energy short-pulse Q-switched Er:YAG laser at 2.94 μm, researchers have used LiNbO₃ (LN) as a Q-switch crystal because of its high transmittance. Zajac et al. used LN as a Q-switch in a flashlamp-pumped Er:YAG laser, 137 mJ pulse energy with 91.2 ns pulse width was obtained at the repetition rate of 3 Hz, the corresponding peak power was 1.5 MW [11]. Meanwhile, Koranda et al. utilized a LN Pockels cell in a flashlamp-pumped 2.94 μm Er:YAG laser, 60 mJ pulse energy with 60 ns pulse width was accomplished at the repetition rate of 1 Hz, the corresponding peak power reached 1 MW [12]. In the case of investigations on ablation and thermal effects, it is necessary to limit the single pulse duration less than 1 μs to reduce thermal diffusion during the laser pulse, and therefore minimize the thermal damage zone [7, 13]. Jelinkova et al. observed obvious thermal damage when a free-running erbium laser with a pulse energy of 75 mJ and a pulse width of 200 μs was applied to ablate the hard dental tissues [14]. They found that, when employing a Q-switched erbium laser with 40 mJ pulse energy and 80 ns pulse width, there existed much higher efficiency and less thermal damage. The ablation and dental bio-thermal effects of Q-switched Er:YAG lasers, particularly with higher peak power and shorter pulse width, have not yet been reported.
This paper presents a flashlamp-pumped EO Q-switched Er:YAG laser by using two Al₂O₃ polarizing plates and a LN crystal with end cut at Brewster angle. This combination effectively improves the laser polarization efficiency and achieves excellent Q-switching effect. With this laser, in-vitro teeth were irradiated under two modes of Q-switched and free-running operations so as to compare the crater morphologies and temperature distribution variations during hard dental tissue ablation. The results demonstrate that the Q-switched Er:YAG laser exhibits higher ablation precision and less thermal damage to the surrounding tissues than the free-running Er:YAG laser. This study provides a basis for further investigation on the biological effects of high-energy and high-peak-power Q-switched Er:YAG laser, especially for hard tissue ablation experiments.

2. Er:YAG laser experimental setup

The schematic diagram of the flashlamp-pumped EO Q-switched Er:YAG laser is presented in Fig. 1. An Er:YAG crystal rod with 5 mm diameter and 125 mm length was used as an active medium. The doping concentration of the Er:YAG crystal was 50 at.% for Er³⁺. The two facets of the Er:YAG rod were antireflection coated at 2.94 μm. The laser crystal was pumped by a xenon flashlamp with pulse duration of 200 μs. The laser crystal and the xenon flashlamp were placed inside a reflector, which was cooled by circulating the deionized water flow at a rate of 33 L/min at a temperature of 287 ± 0.5 K. To compensate the thermal depolarization losses, a MgF₂ quarter-wave plate was inserted between the laser rod and the output coupling (OC) mirror. A resonator was formed by two plane mirrors separated by 340 mm. The reflectivity of the high reflective (HR) mirror exceeds 99% and the reflectivity of the OC mirror is 80%. A LN crystal was prepared and cut in a size of 7 mm x 13 mm x 25 mm, with the ends cut at Brewster angle (65°10'). Between the Q-switching crystal and the laser rod, two 1 mm thick Al₂O₃ plates were placed at Brewster angle as the polarizer to improve the polarization efficiency.

Since dielectric-film-based polarizer at 2.94 μm is immature and costly, a LN crystal with the two ends cut at Brewster angle is often used as the polarization and Q-switching. A single cut surface of LN crystal has a reflectivity of 42% to the s-polarized light at the wavelength of 2.94 μm, it can be calculated that the two cut surfaces will have a reflectivity of only 66.36%. With the increase in laser power, part of the laser radiation feeds back from the Q-switch because of the poor polarization efficiency, which causes the weak laser oscillation. In such a case, the Q-switching crystal cannot act as a perfect shutter, thereby it decreases the Q-switched laser output efficiency. In order to solve this problem, two Al₂O₃ plates are placed at Brewster angle in front of the Q-switching crystal. Together with the Brewster angle cut Q-switching crystal, these plates further improve the laser polarization efficiency in the resonator, the effect of polarizers in Q-switched laser has been calculated by Podgaetskii [15]. In addition, this combination can effectively inhibit the weak laser oscillation, because Al₂O₃ plate has a single-surface reflectivity of 24% to the s-polarized light at 2.94 μm. The total reflectivity of the combination can reach 88.78%, so the polarization efficiency inside the cavity was improved effectively.
In the Er:YAG laser system experiment, the EO Q-switch was operated in pulse-off mode. Although the quarter-wave voltage is calculated to be 3674 V (EO coefficient $\gamma_{11} = 5.6 \times 10^{-12}$ m/V), the EO Q-switch can operate properly when a voltage of 2950 V was applied. Koranda et al. [12] found the similar phenomenon in their experiment of EO Q-switched Er:YAG laser. The lower voltage on the Q-switch generator improves the response speed of the EO Q-switch, and subsequently decreases the effect of electric polarization on the crystal, which extends the service life of the Q-switch. The under voltage operation mechanism can be explained as follows. When the EO Q-switch is operated in the pulse-off mode, the high voltage applied on the crystal rotates the polarization direction. Energy loss occurs when the polarized light returns to the polarizer, so the laser cannot oscillate in cavity. In the Er:YAG laser system with a high oscillation threshold, the energy loss caused by the 2950 V high voltage is sufficient to stop the laser oscillation at the maximum pump energy, which makes the laser operating at a low Q state [16, 17].

3. The experimental results: Er:YAG laser

3.1 The Q-switched Er:YAG laser experiment: two polarizers consisting of two Al$_2$O$_3$ plates and a Brewster angle LN

The flashlamp-pumped Er:YAG laser system developed in this study has a Q-switched output threshold about 120 J, and beyond the threshold, the laser output energy increases linearly with the pump energy. In the experiments, high peak power output was obtained by optimizing the delay time of the EO Q-switch when the laser output was 948 mJ/pulse in the free-running mode. When the delay time was increased to 420 $\mu$s, the population inversion reached the maximum, and the pulse was built by the laser with high gain in a short time, the output pulse with high energy and short pulse width was generated. After the opening delay time of the Q-switch was optimized and the thermal depolarization was compensated, pulse energy of 226 mJ with pulse width of 62 ns was obtained with the pump energy of 230 J at the repetition rate of 3 Hz, and the corresponding peak power was 3.6 MW. The pulse energy was measured with an energy meter (COHERENT J-50MB-IR) and the pulse width was measured with a detector (VIGO PVI-ZTE-10.6) at FWHM. The output beam pattern was multi-transverse mode with a diameter of 3 mm at the output coupler. As shown in Fig. 2, the pulse width decreases and the output energy keeps increase with the pump energy. In our experiment, the pump energy did not be further increased so as to avoid the possible damage of the optical components. However, it can be seen that the present output energy does not reach the saturation situation. If the pump energy continues to increase, it is possible to achieve a higher output energy.

![Fig. 2. Influence of pump energy on output energy and pulse width with two polarizers.](image)
3.2 The Q-switched Er:YAG laser experiment: single polarizer containing only a Brewster angle LN

As described in the experimental setup, two Al₂O₃ polarizing plates at Brewster angle were inserted into the cavity as a polarizer to prevent the weak laser oscillation that may occurred at high pump energy. When the Al₂O₃ plates are removed, only the LN crystal acts as the polarizer and the Q-switching crystal. Since the two cutting surfaces of the LN crystal only have a reflectivity of 66.36% to the s-polarized light at the wavelength of 2.94 μm, the laser polarization efficiency decreases in the cavity. Once this phenomenon occurs, the perfect shutter function cannot be achieved, and the extinction ratio is reduced, which results in weak laser oscillation in the cavity. The weak oscillation subsequently depletes the population inversion, leading to a reduction of the output pulse energy. It can be seen in Fig. 3 that when the pump energy reaches 180 J, the output energy and the pulse width are nearly saturated because less energy is stored. The corresponding output pulse energy is only 135 mJ and the pulse width is 92 ns, comparing with the Er:YAG laser system with the Al₂O₃ polarizing plates, which are reduced by 42.5% and 32.6%, respectively.

![Fig. 3. Influence of pump energy on output energy and pulse width with single polarizer.](image)

3.3 The Q-switched Er:YAG laser experiment: a quarter-wave plate compensated the thermal depolarization

The uniformity of the beam pattern and output energy were severely affected by the thermal depolarization under a high pumping flux. The laser oscillates in p-polarization for the polarizer with the Brewster angle, but the polarization state changes to elliptical polarization as a result of the thermally induced stress birefringence in the rod. Then the laser suffers depolarization loss at the polarizer, especially at the angle of 45° to the polarization direction [16–18]. The facula of the depolarization is shown in Fig. 4(a), where the shape of the facula resembles a Maltese cross with lower output energy. To solve this problem, a quarter-wave plate was inserted between the laser rod and the output coupling mirror. After the beam passes the quarter-wave plate twice, the radial component of the light at the angle of 45° to the polarization direction is rotated 90° and becomes the tangential component. Thus, the phase difference between the two components is counteracted when the beam passes through the rod again and the polarization state is restored to p-polarization. The laser facula after compensation is shown in Fig. 4(b), where the beam pattern became uniform, and the output energy is improved. The pulse energy curve is shown in Fig. 5. At a pump energy of 230 J, before thermal depolarization compensation, the pulse energy is 151.6 mJ, which after
compensation increases by 49% and reaches 226 mJ. It can be concluded that the pulse laser with thermal depolarization compensation has a more complete facula and the pulse energy is also improved significantly.

Fig. 4. Comparison of the faculae (a) before compensation and (b) after compensation.

Fig. 5. The outputs of the Q-switched Er:YAG laser with and without compensation.

4. The experimental results: dentine ablation with Er:YAG laser

4.1 Crater structures of dental tissues ablated with free-running and Q-switched Er:YAG laser

With the above described Er:YAG laser system working in Q-switched and free-running modes, in-vitro teeth were irradiated to observe the ablation characteristics. The experimental setup is shown in Fig. 6. The laser radiation is generated by the Er:YAG laser and the beam is reflected by a 45° reflection mirror. After being focused by a lens (f = 50 mm), the beam vertically irradiates the teeth sample surface and the diameter of the facula is 1 mm. For the Q-switched and the free-running lasers, the pulse energy is both 70 mJ at 3 Hz, with a corresponding energy density of 8.92 J/cm², and the pulse number of 15. No spray is applied in the ablation process.
Fig. 6. Experimental setup for dentine ablation study under two laser modes.

The ablation craters of the dental tissues were observed with a scanning electron microscope (SEM). The top view in Fig. 7(a) and cross-section view in Fig. 7(b) of the ablated dental tissues with the free-running mode laser are shown. The crater wall is not smooth and clean, with debris and carbonization. On the contrary, using the Q-switched mode laser with the same repetition rate and pulses number, as shown in Fig. 8(a) and Fig. 8(b), the dental tissues show smooth morphologies without melting in the ablation crater, and the crater wall is clean almost without debris or carbonization, which means a higher ablation precision.

Fig. 7. SEM micrographs of an ablation crater on the dental tissues with free-running laser: (a) top view, (b) cross-section view, the crater wall is not smooth, with debris and carbonization. The dentine is irradiated by 15 pulses with per pulse energy of 70 mJ and pulse width of 200 μs.

Fig. 8. SEM micrographs of an ablation crater on the dental tissues with Q-switched laser: (a) top view and (b) cross-section view, the crater wall is smooth, without debris and carbonization. The dentine is irradiated by 15 pulses with per pulse energy of 70 mJ and pulse width of 62 ns.
4.2 Temperature distributions in dental tissues ablated with free-running and Q-switched Er:YAG laser

To describe the thermal distribution in dentine during the ablation process, theoretical analysis was carried out. The one-dimension heat conduction Eq. (1) can be used to describe this process, which has been proved to have a good agreement with the experimental results [19].

\[
\rho c \frac{\partial T(x,t)}{\partial t} = k \frac{\partial^2 T(x,t)}{\partial x^2} + \mu_e I_o(t) \exp(-\mu_{\text{eff}} x)
\]

(1)

Wherein, the dentine density \( \rho \) is 2.1 g/cm\(^3\), the specific heat \( c \) is 1.17 J/g/K, the thermal conductivity \( k \) is 0.63 W/m/K, the absorption coefficient \( \mu_a \) is 3000 cm\(^{-1}\), the related parameters is form the references [20–22]. \( I_o \) is the incident intensity, \( \mu_{\text{eff}} \) in Eq. (2) is the effective attenuation coefficient defined as:

\[
\mu_{\text{eff}} = (3\mu_s[\mu_a + (1-g)\mu_s])^{1/2}
\]

(2)

where the anisotropy parameter \( g \) is 0.93, the scattering coefficient \( \mu_s \) is 15 cm\(^{-1}\). In the research of Ana et al. [23], the finite element thermal analysis has been used to simulated the temperature distribution of the dental tissues irradiated with Er,Cr:YSGG laser. The simulated results are coincident well with the experimental data, and our parameters are similar with theirs. According to the equations above, the temperature distribution in dentine during the Er:YAG laser irradiation of dentine surface can be simulated with the finite element analysis and the result is shown in Fig. 9. The simulation is under 200\( \mu \)s pulse width for easy comparison with the data from thermography. It can be seen that the dentine temperature is increasing with the number of the pulse, the temperature increments is about 12°C, which is higher than that of the simulated result in dental tissues irradiated with Er,Cr:YSGG laser. The simulated temperature increment is relatively high, because we assume the pulse energy of 70mJ has all been used to heat the dentine in the simulation. In fact, most of the energy is consumed in vaporization, liquefaction and scattering during the ablation process. If we assume that about 30% pulse energy is used to heat the dentine, the results will be in good agreement with the simulated data in in dental tissues irradiated with Er,Cr:YSGG laser. Our simulation is confirmed by the following experimental result shown in Fig. 10. Meanwhile, the simulation under nanosecond level has also been carried out. However, limited by the temporal resolution of the thermography, the simulated results under nanosecond duration cannot be confirmed with experimental data, so the simulated results do not be presented here.

Fig. 9. The simulated result under 200\( \mu \)s pulse width performed with the finite element method.
To confirm the theoretical simulation, the dentine ablation experiment was performed. By means of an infrared thermography (InfraTec VH-620), the temperature distributions over the irradiated areas of the dental sample tissues were measured when using the two Q-switched Er:YAG modes and the free-running Er:YAG mode respectively and the results are given in Fig. 11. It can be seen that the heat produces by laser irradiation mainly concentrate around the irradiated points in the dental tissues. Within the irradiated regions, the hard dental tissues absorb the laser energy and formed high-temperature area, which expands from the irradiated point to the teeth inner and the surrounding tissues. It is clear that the temperatures at the top edge of cavity indicated with dotted line are 42.31°C, 48.05°C and 61.55°C under 62ns, 110ns and 200μs, respectively. The data shown in Fig. 9 were the average results obtained from ten samples, the standard deviations of temperature under the free-running and two Q-switched modes are 1.35, 1.08 and 1.09°C. When the pulse energy is 70mJ@62 ns, the temperature of the dental cavity wall is 42.31°C, which is significantly lower than that of the other two modes, and also lower than the thermal damage critical temperature of 47°C [10]. The experimental results clearly indicate that the shorter pulse and higher peak power has more advantages and lower thermal effect. The Q-switched mode has a low thermal affecting. The free-running mode has much larger thermal damage area about 50 μm outside the cavity wall and higher temperature, which also exceeds the thermal damage critical temperature in dental treatment.
Fig. 11. Temperature distribution around the dental cavity top irradiated with the two Q-switched modes and the free-running mode. Infrared thermal images of the dental cavity are shown in a, b and c on the top, the corresponding temperature distribution is plotted in A, B and C below. The dentine is irradiated by 15 pulses with per pulse energy of 70 mJ, the temperatures at the cavity edge indicated with dotted line are 42.31 °C, 48.05 °C and 61.55 °C under 62 ns, 110 ns and 200 μs, respectively.

The partial energy of the laser irradiate the dentine will diffuse in the dentine, the diffusion process is similar to the thermal diffusion of the laser pulsed heating, which can be described with thermal diffusion formula. The formula to calculate thermal relaxation time of biological tissues are as follows [14]:

$$\tau = \frac{1}{(4\alpha^2 \kappa)^{-1}}$$

(3)

where \(\tau\) is the thermal relaxation time of biological tissues, \(\alpha\) is the absorption coefficient of the dentine to the Er:YAG laser radiation and its value is 0.2x10^6 m^-1, \(\kappa\) is the thermal diffusivity which is 1.92x10^-7 m^2/s [24, 25]. Using Eq. (3), it can be calculated that the thermal relaxation time is 32.6 μs, which is much greater than the pulse width of the Q-switched Er:YAG laser. In such cases, there is no sufficient time for the excess heat to diffuse into the surrounding tissues, thus the high-temperature zone in the irradiated area is smaller. Therefore, the possibility of thermal damage is reduced. In contrast, the pulse width of the free-running laser is greater than the thermal relaxation time, allowing sufficient time for the excess heat to diffuse into the surrounding tissues [26]. The high-temperature zone in the irradiated area enlarges due to the excess heat diffusion, which may cause serious thermal damage.

The dental tissue ablation experimental results reveal that the ablation effect is essentially different between the free-running laser and the Q-switched laser. The free-running laser has a long pulse in the range of hundreds of microseconds, during its ablation the excess heat will diffuse into the surrounding tissue, resulting in very obvious debris and carbonization. On the contrary, the pulse width of the Q-switched laser is much shorter than the tissue thermal relaxation time. Because the tissue melting occurs almost instantaneously, this momentary interaction reduces the debris in the dental tissue. Thus, the Q-switched laser exhibits prominent technique superiority over the free-running laser in the hard dental tissue ablation.
5. Conclusion

In conclusion, a flashlamp-pumped electro-optically Q-switched Er:YAG laser with two polarizers is demonstrated. It has been proved that the dual-polarizer design can increase the polarization efficiency to improve the output performance of the Q-switched Er:YAG laser. At a repetition rate of 3 Hz, 226 mJ pulse energy with 62 ns pulse width has been successfully accomplished, which should be the best results at 2.94 µm. It has been demonstrated that, with the Q-switched Er:YAG laser, the crater wall of dental ablation is more smooth indicating a higher ablation precision, meanwhile the thermal damage can be effectively avoided during the hard dental tissue ablation. The free-running laser ablated dental cavity has a larger thermal damage area over the Q-switched laser. Thus, the Q-switched Er:YAG laser will be very promising to replace the free running Er:YAG laser as a potential tool for the hard dental tissue ablation.

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