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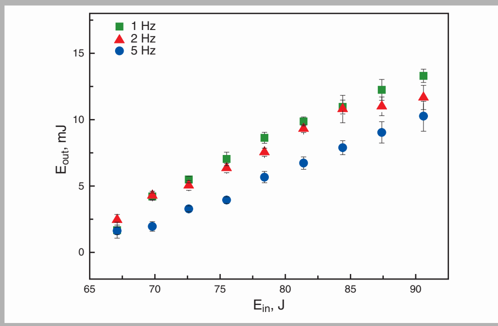
Abstract: In this study, an electro-optically Q-switched 2.70 μm emission Er:Cr:YSGG laser with a $LiNbO_3$ Pockels cell is investigated and compared with a FTIR Q-switched scheme. It can obtain nanosecond pulse at a low voltage of 1.4 kV using a CaF_2 polarizer and a $LiNbO_3$ crystal with Brewster's angle cut ends. Wavelength generation of 2.70 μm was possible with a Fresnel loss at a rear mirror with a dielectric dichroic coating. The maximum output energy of 21.5 mJ (at 1 Hz repetition rate) was achieved in TEM_{21} mode using the output coupler with a reflectivity of 55% at 2.70 μm. The generated maximum pulse energy and pulse width were 13.3 mJ and 159 ns in TEM_{00} mode, respectively. The pulse width was shorter than 1.3 μs of the FTIR Q-switched scheme.



Q-switched pulse energy and pulse width as a function of the electrical input energy (output coupler with 55% reflectivity at 2.70 μm and a switching time of 120 μs) at a repetition rate of 1 Hz

2.70 μm emission Er:Cr:YSGG laser with $LiNbO_3$ Pockels cell

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1. Introduction

Laser radiation in mid-infrared range is of great interests in medical treatments due to high absorption coefficients for tissue-water and hydroxyl-apatite [1,2]. Er:YAG (2.94 μm) lasers have been used as typical laser systems in dental hard tissues [3–9].The Q-switched Er:YAG laser pulses with high intensity is used for a very precise micro surgery [10] and these mid-infrared radiation can be delivered using COP/Ag hollow glass waveguide [11]. However, it is challenging to obtain a giant nanosecond pulse due to the short lifetime of the upper level (100 μs) and has poor transmittance for optical fibers such as Low-Hydroxyl-Fused-Silica (LHFS), which is used with the endoscopic surgery.

A Er:Cr:YSGG laser has a longer lifetime in the upper level (1.3 ms) compared to Er:YAG and has high transmission in the LHFS fiber. Thus, these Er:Cr:YSGG lasers have mainly studied for use in dentistry such as caries removal [12], cavity preparation [13], root canal treatment [14], caries prevention [1,15], and dental ablation [16–19]. One recent research in mid-infrared range demonstrated that tunable mid-infrared laser radiation generation is possible using a Cr:ZnSe prism [20]. In the study, the generated radiation was tunable from 2000 up to 2750 nm, and the maximal output energy of 20 mJ was achieved. In the present study, a 2.70 μm emission Er:Cr:YSGG laser with $LiNbO_3$ Pockels cell is developed. It can address both of these issues.

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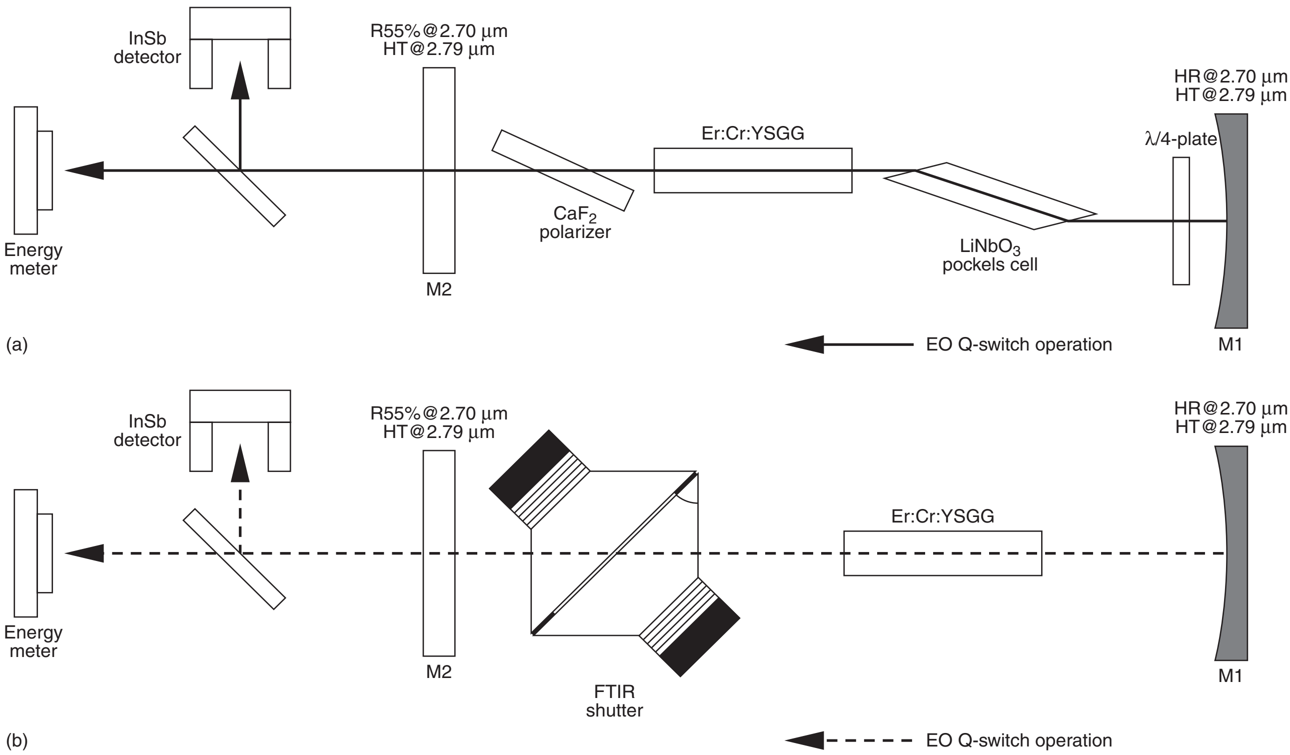

Figure 1 (online color at www.lphys.org) Schematic diagram of the 2.70 μm emission Er:Cr:YSGG laser system with EO Q-switch using a $LiNbO_3$ Pockels cell (a) and with a FTIR Q-switch (b)

The Q-switch techniques researched thus far include saturable absorbers [21,22], mechanical switches [23,24], acousto-optic (AO) Q-switches [25,26], electro-optics (EO) Q-switches [27–30], and Frustrated Total Internal Reflection (FTIR) [31,32]. The EO Q-switch of the $LiNbO_3$ crystal has a non-hygroscopic property, a low half-wave voltage, and has high transparence in a wavelength range of 0.4 μm to 4.5 μm.

Nevertheless, a commonly available polarizer that serves as a switch for wavelengths around 3 μm does not exist. One recent study simply outlined the use of a Pockels cell and polarizer simultaneously using an active Pockels cell crystal with Brewster cut ends [28]. This allowed the use of a lower applied voltage to achieve a giant short pulse.

In the proposed scheme, though the $LiNbO_3$ Pockels cell crystal with Brewster cut ends is used, two orthogonally polarized beams that are not clearly separated; it causes a preleasing problem. Thus, sufficient discrimination between the two polarizations is required under a high level of pump energy. A Er:Cr:YSGG laser with an emission of 2.70 μm with a CaF_2 polarizer and with Brewster cut ends of a $LiNbO_3$ Pockels cell is designed, which allows a feasible arrangement at λ/4 voltage. A CaF_2 window with a Brewster angle of 65.5° is used as an additional polarizer. Generation of a wavelength of 2.70 μm is possible by applying the Fresnel loss method [33]. This is the first known study on the subject of a Er:Cr:YSGG laser with an emission of 2.70 μm with $LiNbO_3$ Pockels cell. The experimental result is compared to that of the FTIR Q-switch scheme.

2. Experimental setups and methods

To obtain a giant short pulse, a Er:Cr:YSGG laser with $LiNbO_3$ Pockels cell with Brewster cut ends and a CaF_2 polarizer was developed. The 2.70 μm emission Er:Cr:YSGG laser system is composed of a Er:Cr:YSGG crystal with a diameter of 5 mm and a length of 80 mm. The dopant concentrations of Er^{3+} and Cr^{3+} are 30 at.% and 1.5 at.%, respectively. The crystal was pumped inside a ceramic pumping cavity using two xenon flash-lamps with a pulse duration of approximately 300 μs. The generation of a wavelength of 2.70 μm is possible between the dichromatic dielectric mirror M1 (99.9% reflectivity at 2.70 μm and 10% reflectivity at 2.79 μm) and the dichromatic dielectric mirror M2 (55% reflectivity at 2.70 μm and 30% reflectivity at 2.79 μm). The mirror M1 acts as a rear mirror with a curvature of 3 m, and the mirror M2 acts as an output coupler. The mirrors consist of CaF_2 material with a high transmittance at 2.79 μm [33]. A schematic experimental setup of the 2.70 μm emission Er:Cr:YSGG laser system with a $LiNbO_3$ Pockels cell EO Q-switch is shown in Fig. 1.

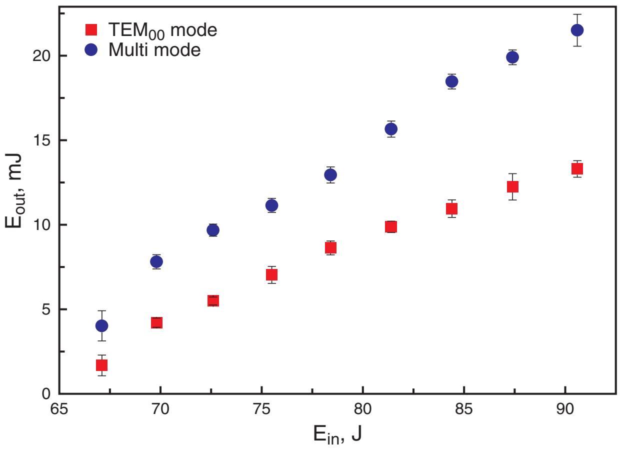

Figure 2 (online color at www.lphys.org) Comparison of the laser output energy in TEM_{00} mode and in TEM_{21} mode (output coupler with 55% reflectivity at 2.70 μm and a switching time of 120 μs) at a repetition rate of 1 Hz

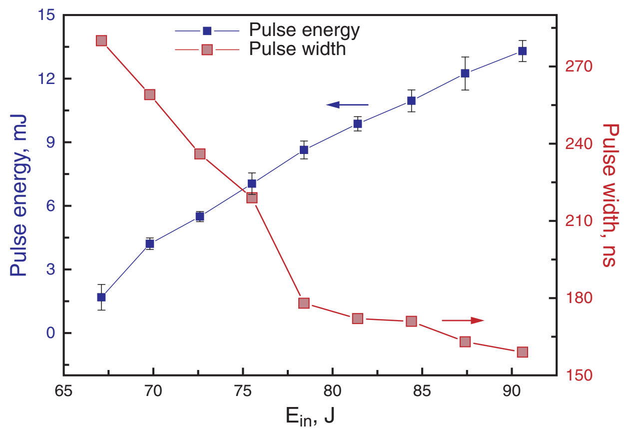

Figure 3 (online color at www.lphys.org) Q-switched pulse energy and pulse width as a function of the electrical input energy (output coupler with 55% reflectivity at 2.70 μm and a switching time of 120 μs) at a repetition rate of 1 Hz

An EO Q-switch with a transverse electric field was assembled. A typical $LiNbO_3$ crystal with dimensions of 7×7×25 mm^3 with a Brewster angle of $\theta_B = 73.5°$ was used. This $LiNbO_3$ crystal and a λ/4-waveplate were placed between the rear mirror (M1) and the Er:Cr:YSGG active medium inside an optical resonator.

To solve the prelasing problem, a CaF_2 polarizer was placed at a Brewster's angle (65.5°) between an output coupler (M2) and a Er:Cr:YSGG active medium. The length of the optical resonator was fixed at 40 cm. A negative trigger voltage with a rising time of less than 400 ns from an electric circuit triggers the high voltage of 1.4 kV on the $LiNbO_3$ crystal. The generated pulse energy was in-

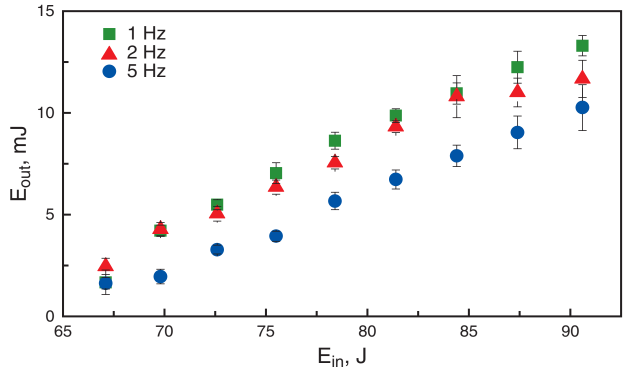

Figure 4 (online color at www.lphys.org) Output energy as a function of the electrical input energy at 2.70 μm for repetition rates of 1 Hz, 2 Hz, and 5 Hz (output coupler with 55% reflectivity at 2.70 μm and a switching time of 120 μs)

vestigated in TEM_{00} mode (transverse) for repetition rates of 1, 2, and 5 Hz. The Q-switched pulse energy and pulse width as a function of the electrical input energy (E_{in}) were also investigated at 1 Hz. With the exception of the λ/4-waveplate inside the resonator, the output was measured with the $LiNbO_3$ Pockels cell and CaF_2 polarizer in a free-running regime. The output energy was measured with an energy meter (Oriel 70273) and the pulse duration was measured with an InSb detector (EOS IS-001/HS) with a response time of 2 – 5 ns in a wavelength range of 2 μm to 12 μm. The measurements were recorded by 54520A (Hewlett Packard) digital storage oscilloscope.

3. Results and discussion

In this section, experimental results of the 2.70 μm Er:Cr:YSGG laser with a $LiNbO_3$ Pockels cell EO Q-switch are represented. By inserting a CaF_2 polarizer in the cavity, the prelasing problem was solved at a high pumping energy. A giant single pulse was achieved after a delay time of 120 μs from a flash-lamp triggering signal. In the proposed scheme, the maximum electrical input energy was 91 J.

Fig. 2 shows the pulse energy as a function of the electrical input energy. The maximum output energy values of 13.3 mJ and 21.5 mJ were achieved in TEM_{00} mode and TEM_{21} mode at E_{in} = 91 J, respectively. It was transferred into the higher mode from cavity misalignment.

The dependency of the output energy and pulse width on the electrical input energy at a repetition rate of 1 Hz is depicted in Fig. 3. When the output energy increases from 1.7 mJ to 13.3 mJ, the pulse width decreases from 280 ns to 159 ns. When higher pumping power is injected, more energy is stored in the gain medium. This increases the gain and shortens the round trip time needed to build up the pulse. Thus, the pulse width became shorter with an increase of the pump energy.

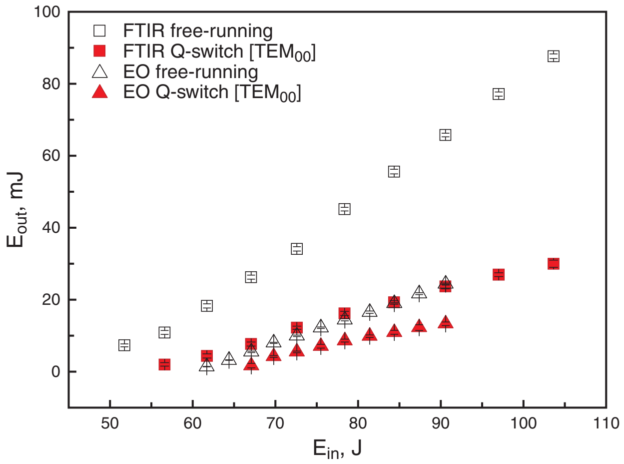

Figure 5 (online color at www.lphys.org) Comparison of the laser output energy in the free-running region and the Q-switch region for FTIR Q-switch operation and EO Q-switch operation (output coupler with 55% reflectivity at 2.70 μm) at a repetition rate 1 Hz

The effect of the repetition rate on the laser output energy was studied using an output coupler with 55% reflectivity at 2.70 μm. Fig. 4 shows that the output energy at a repetition rate of 2 Hz up to an electrical input energy of 84 J was similar to the operation of the device at a repetition rate of 1 Hz. Pulse energy levels of 11 mJ, 10.8 mJ, and 7.9 mJ at E_{in} = 84 J were obtained for 1 Hz, 2 Hz, and 5 Hz, respectively. At a high pumping power greater than E_{in} = 84 J, the output energy falls rapidly when the repetition rate increases from 2 Hz to 5 Hz. The rapid drop of the output energy with the increase of the repetition rate can be attributed to the poor thermal conductivity of the YSGG crystal. The thermal conductivity of YSGG (0.08 $Wcm^{-1}K^{-1}$) is relatively small at merely half for the value of YAG (0.14 $Wcm^{-1}K^{-1}$). This has a considerable thermal lens effect and birefringence effect under a high pumping power. The stored heat in the laser rod induces the thermal lens effect, which reduces the mode volume in the cavity. Thus, the output energy and slope efficiency decrease at high repetition rates.

The output energies at a wavelength of 2.70 μm under both a free-running condition with $LiNbO_3$ Pockels cell inside the cavity and under Q-switched operation as a function of the electrical input energy at 1 Hz are shown in Fig. 5. The output energy levels are compared to that of the FTIR Q-switch operation case shown in Fig. 1.

In the free-running region, the maximum output energy levels of 65.7 mJ and 24.4 mJ were obtained with the FTIR Q-switch and the EO Q-switch, respectively. In the Q-switching region, the maximum output energy of 23.7 mJ with a pulse width of 1.3 μs (FWHM) and of 13.3 mJ with a pulse width of 159 ns (FWHM) were obtained for the FTIR Q-switch and the EO Q-switch, respectively.

In contrast to the FTIR Q-switch scheme, the Pockels cell with double Brewster angles led to inherent passive losses inside the resonator. Thus, the lasing threshold of the EO Q-switch operation was higher compared to that of the FTIR Q-switch operation. The output energy of the EO Q-switch operation decreased considerably relative to the level of the FTIR Q-switch operation. However, a shorter pulse width was achieved at the EO Q-switch operation only at the point of the pulse width.

4. Conclusion

This study demonstrated an electro optically Q-switched 2.70 μm emission Er:Cr:YSGG laser using a $LiNbO_3$ Pockels cell with Brewster angle cut ends and a CaF_2 polarizer. Several properties of the pulsed laser were investigated, including its energy, pulse width, and repetition rate. In addition, the output energy with the scheme using the Brewster angle cut ends of the $LiNbO_3$ Pockels cell was compared to that of the FTIR Q-switch scheme.

With the FTIR Q-switch, a much higher Q-switched single-pulse energy level can be achieved. Additionally, it can be operated under a low Q-switch threshold. The advantage of the EO Q-switched Er:Cr:YSGG laser with this $LiNbO_3$ Pockels cell is that it has a shorter pulse width compared to the operation of the FTIR Q-switch. A maximum output energy of 21.5 mJ (at 1 Hz repetition rate) was achieved in TEM_{21} mode using an output coupler with 55% reflectivity at 2.70 μm. A maximum output energy of 13.3 mJ with pulse width of 159 ns was achieved in TEM_{00} mode.

The laser developed is suitable for the effective ablation of soft tissues and can be used as a pumping source to generate far-infrared wavelengths ranging from 8 μm to 13 μm.

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