SCPEM-Q-switching of a fiber-rod-laser

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Abstract: We demonstrate high-frequency Q-switching of a fiber rod laser with a Single-Crystal Photo-Elastic Modulator (SCPEM) made of a $LiTaO_3$-crystal. This type of photo-elastic modulator can be driven simultaneously with two different eigenmodes to achieve a shorter rise time, which is essential for high-power operation. When operated in the laser cavity, a pulse repetition frequency of 183.6 kHz with an average power of 47 W, a pulse duration of 26 ns, and a peak power of 10.5 kW was achieved.

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1. Introduction

Rod-type active optical fibers have attracted a lot of attention in recent years [1,2]. They have proved to be appropriate for high-power continuous wave (cw)-operation [2–4] and especially for high average and high-peak-power pulsed operations [5–7]. The lasers based on fiber rods combine some advantages of fiber lasers with the advantages of classical laser concepts. This enables a very high active core diameter in the range of 100 µm while still maintaining single-mode or quasi-single-mode output, as reported in some theoretical as well as experimental analyses [2,7,8]. Because of its high power capability, rod-type fibers are perfectly suited for single-stage high-power Q-switch lasers [6]. In contrast to the standard setups in which an acousto-optic modulator is used for Q-switching, we describe in this paper a different approach based on photo-elastic modulators (PEM). According to our knowledge Q-switching has never been performed with a conventional PEM, however, there is a report that only mentions this possibility [9]. In general the PEM is based on a resonantly oscillating glass with a driving amplitude in the range of 10 Volts or even below. The PEM is excited with an actuator (Fig. 1(a)) [9]. The most common resonance frequency is 50 kHz. Like acousto-optic modulators, the PEM is based on photo-elasticity, but it modulates polarization instead of beam direction.

For Q-switching we introduced the SCPEM (Single Crystal PEM) using one single piezoelectric crystal (Fig. 1(b)) [10–13].

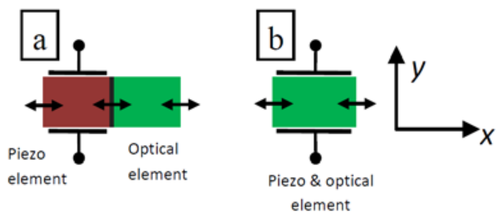

Fig. 1. Standard PEM (a) and SCPEM (b); Arrows indicate main oscillation.

Our concept relies on the SCPEM which is based on a 3m-crystal (e.g., $LiTaO_3$, $LiNbO_3$, BBO), cut along the crystallographic axis, with electrodes on the y-facets and light propagation along the z-axis (optical axis). This new design enables design simplification, cost and size reduction and differs (regarding crystal class and orientation) from designs described in older reports of SCPEM-operation [14,15]. Even more importantly, many mechanical eigenmodes can be excited in such a crystal. For y-excitation (i.e. the electrical field is oriented along the y-axis - see Fig. 2), the most useful ones being the x-longitudinal, y-longitudinal and yz-shear-modes. These modes can be frequency matched and superposed on each other, to achieve shorter switching times. There is report on such a frequency matching and superposition of the x- and yz-shear-mode [16], while in this study we describe the combination of the 1^{st} x- and a y-mode (Figs. 2(a) and 2(b)). This superposition of frequency-tuned eigenmodes is not possible with a classical PEM unless it is excited with additional actuators that would lead to a more complex design. Dual-mode operation of a traditional PEM was reported in [17], but without the possibility of frequency-matching.

Resonant operation of a $LiNbO_3$-crystal was also reported [18], where a 33 MHz-standing-wave was induced for active mode-coupling of a laser, using the acousto-optic effect.

An important advantage of this is that there is no need for a high-voltage or high-power driver, as needed for standard acousto-optic or electro-optic modulators.

In this paper some theory about SCPEMs dual mode operation for high power Q-switching and the results from experiments with an SCPEM inside a laser resonator based on a rod–type active core fiber are presented.

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2. Operation of a single-crystal photo-elastic modulator

The orientation of the coordinate axes and the crystal are as in Fig. 2(a). We assume linear polarized monochromatic light traveling through the crystal along the z-axis. The polarization is oriented at 45° measured from the x-axis. Further we assume a polarizer (analyzer) behind the crystal with polarization orientation parallel to the initial polarization. When the SCPEM is oscillating the light is split in the crystal into x- and y-polarized light with different phase velocities. After passing the crystal a time-dependent retardation $\delta = 2\pi L (n_x - n_y)/\lambda$ has built up ($n_{x/y}$ … refractive index for x-/y-polarized light, L…crystal-z-dimension, λ…wavelength of light). The transmission through the analyzer is now given by

$$T(\delta) = \cos^2\left(\frac{\delta}{2}\right) = \frac{1}{2}(1+\cos\delta). \quad (1)$$

The retardation δ depends linearly on the strain in the crystal. If we assume that the crystal oscillates simultaneously with two eigenmodes the time-dependence of δ can be described by

$$\delta(t) = \delta_1 \sin(2\pi f_{R1} t) + \delta_3 \sin(2\pi f_{R3} t), \quad (2)$$

with $\delta_{1,3}$ and $f_{R1,3}$ representing the retardation amplitudes and the resonance frequencies of the two modes. We assume in the following discussion that the frequency relation f_{R3}/f_{R1} is exactly 3, which can be achieved by a proper adjustment of the crystal dimensions, as explained later, and by phase-locking both modes with a proper driver. We assume further that $\delta_{1,3}$ are real, which means that both eigenmodes are exactly phase-matched

To achieve fast optical switching, which is needed for Q-switching, the retardation $\delta(\underline{t})$ should be a square wave function oscillating between π and –π (dashed line in Figs. 3(a) and 3(b)). The retardation values π and –π correspond to zero-transmission for the optical configuration mentioned above. The switch opens twice every period during the fast transition through $\delta = 0$. This desired function can be relatively poorly approximated with one term in Eq. (2), namely with $\delta_1 = \pi$ and $\delta_3 = 0$ corresponding to mono-mode operation (solid line in Fig. 3(a)). The approximation is much better with the two terms of a Fourier series in Eq. (2) with $\delta_1 = 4$ and $\delta_3 = 4/3$ (solid line in Fig. 3(b)), which requires the activation of two eigenmodes.

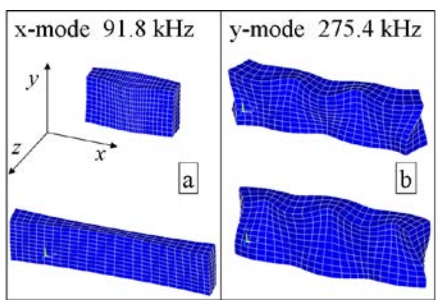

Fig. 2. Finite-element-simulation (with the program ANSYS) of two different eigenmodes of a y-excited $LiTaO_3$-crystal with dimensions of 28.6x9.5x4 mm: x-eigenmode at 91.8 kHz (a) and y-eigenmode at 275.4 kHz (b).

In order to see the advantage of the dual mode operation one can check first the conventional operation (mono-mode). For this case the transmission curve shown in Fig. 3(c) can be obtained. It shows very broad peaks with rise-time from 20% to 80% transmission 0.84 µs @ f_{R1} = 91.8 kHz. Figure 3(d) shows the possible outcome that corresponds to dual mode operation. This mode yields much sharper transmission peaks and faster optical response: 20%-80%-rise-time = 0.32 µs @ f_{R1} = 91.8 kHz, with 3 small ~10%-transmission peaks in the off-phase.

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A dual-mode SCPEM in a laser cavity (as in Fig. 4) should force the laser to pulsed operation. The necessary retardation amplitudes are halved in this case, because of the double pass of the light after reflection from the end mirror.

Figure 2 shows a finite-element simulation of the two modes: the basic x-mode and one of the y-modes, having resonance frequency at 91.8 kHz (Fig. 2(a)) and 275.4 kHz (Fig. 2(b)), respectively. For mode combination it is essential that both oscillations induce the same kind of birefringence, which is indeed the case here. Dual-mode operation requires a crystal with carefully adjusted dimensions. By adjusting the crystal to a certain x-length, the basic x-mode frequency was tuned to one-third of the frequency of the y-resonant oscillation (tuned within the resonance bandwidth, which is ~1/2000 of the frequency, i.e. ~50 Hz for the x-mode).

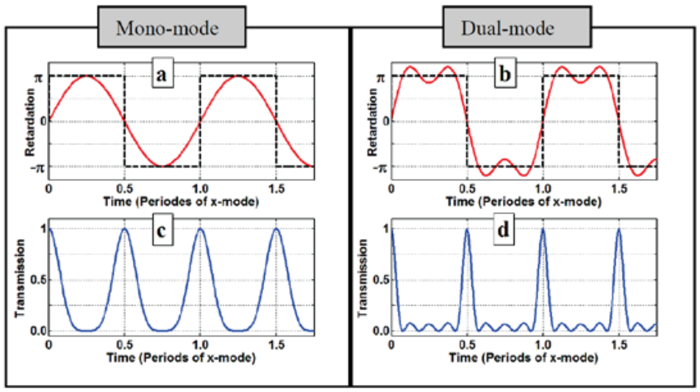

Fig. 3. Theoretical retardation ((a) and (b)) and transmission curves ((c) and (d)) for a SCPEM with a polarizer for mono-mode-operation ((a) and (c)) and dual-mode- operation ((b) and (d)).

Dual-mode operation requires a special driver, which in our case is based on a custom-made controller that locks with a phase-locked loop to one resonance and adds the 2nd frequency with adjustable phase and amplitude. The driver operates with low voltage amplitudes (< 15V) and low power (< 100mW).

3. The setup

The setup (Fig. 4) is based on an end-pumped PCF-fiber-rod laser with a 50 µm core and a 200 µm pump clad-diameter with 1 mm outer diameter and a length of 750 mm.

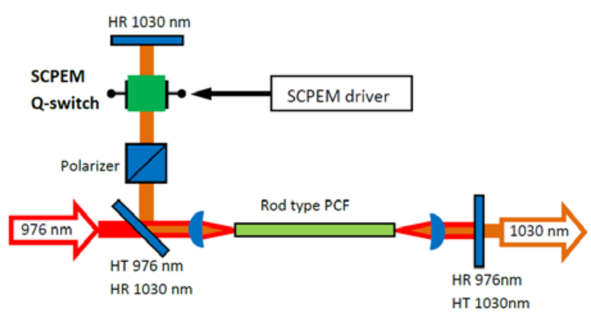

Fig. 4. Scheme of the setup based on a fiber-rod-laser.

The laser cavity uses the Fresnel reflection at the uncoated right end of the fiber rod for out-coupling and optical feedback. On this side, there is also an HR-mirror for the non-absorbed pump-light. The cavity is L-shaped via a dichroic mirror highly reflective for the laser wavelength 1030 nm, while it is transparent for the pumping wavelength 976 nm.

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Between this element and the back mirror, a polarizer and the SCPEM (z-axis parallel to the optical path, x-axis tilted 45° to the paper plane) are placed. The insertion of the SCPEM reduces the laser output power by less than 2%.

4. Results and discussion

During the test of the laser, in addition to dual-mode-operation, we also examined mono-mode-operation of the SCPEM to evaluate the advantages of dual-mode-operation with much faster switching times. Until the average output power reaches 30 W stable pulsed operation is found and, apart from approximately 5% higher output power for the dual-mode, there is no significant difference between the two modes. At higher output power with mono-mode-operation an additional small pulse appears after the main pulse, as shown in Fig. 5. Obviously, because too much gain has been built up, the main laser pulse occurs too early, before the peak transmission is reached. Consequently, further secondary smaller pulses are emitted. Obviously, the switching speed is too slow with the mono-mode approach. The driving voltage in this case corresponds to the single sinusoidal curve whose frequency corresponds to the resonance frequency of the x-eigen mode (91.8 kHz). The voltage amplitude is adjusted such that the amplitude of the phase shift corresponds to π.

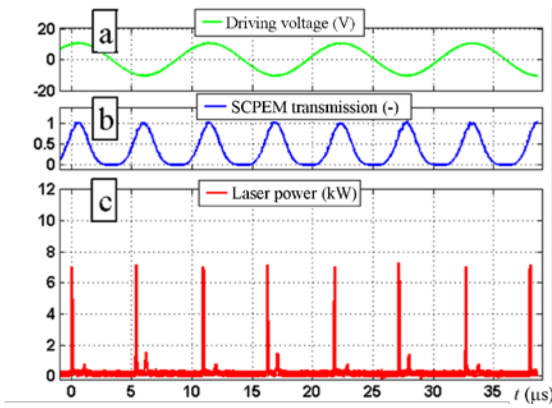

Fig. 5. Experimental results for SCPEM mono-mode-operation. Driving voltage (a), relative optical transmission (b) and laser output pulses (c). Pulse repetition frequency 183.6 kHz.

Figure 6 shows the experimental results for dual-mode operation. The x-mode at 91.8 kHz is combined with the y-mode at 275.4 kHz; therefore, the waveform of the driving voltage is a superposition of two sinusoidal curves. Now, the transmission of the modulator is shown in Fig. 3(b). As expected it exhibits much faster optical response in comparison to mono-mode.

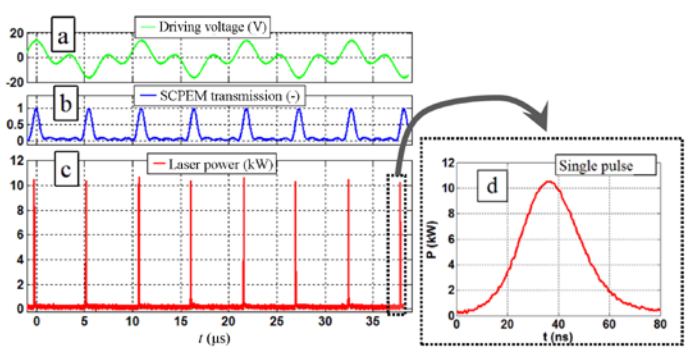

Fig. 6. Experimental results for SCPEM dual-mode operation: driving voltage (a), relative transmission (b), laser output pulses (c). Pulse repetition frequency 183.6 kHz, peak power 10.5 kW, pulse width 26 ns, pulse energy 257 µJ, and average power 47 W. A single pulse is shown in graph (d).

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As a result, no post-lasing is found for any output power when dual-mode is used. In this case, we achieved an average power of 47 W, a pulse duration of 26 ns, a peak power of 10.5 kW, a pulse energy of 260 µJ, and a pulse-to-pulse stability of 2.4%.

Figure 7 shows a comparison of cw-power and the average power in pulsed mode against the driving current of the pumping source. Both curves are equal at the beginning and deviate at around 30W average power. While the cw-power increases linearly, the average power of the pulsed mode levels up, indicating that saturation effects limit further increases of power. This effect is related to the high inversion population due to increasing pump power, which leads to an increase in gain. Because of this and the finite switching time the pulse appears before the modulator reaches its full transmission. This means that a part of the light is reflected by the polarizer out from the resonator and therefore is lost to the laser pulse. Consequently, the efficiency is reduced. In the case that higher power is needed, a modulator with a higher eigen-frequency should be used. A higher frequency would decrease the switching time and reduce the population inversion between the pulses and would therefore lead to stable pulsing at higher average power.

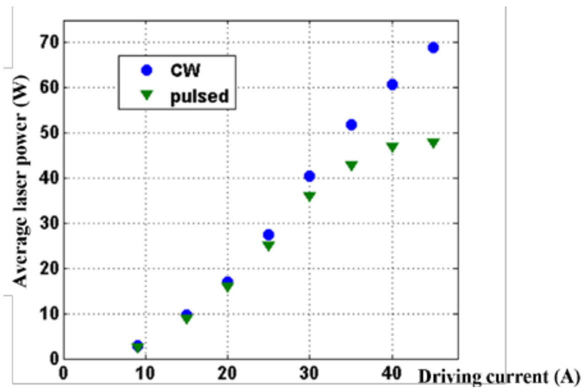

Fig. 7. cw-power and average power in pulsed mode against pump-current.

At last we mention that the beam quality is in all cases diffraction limited and that the laser spectrum has a narrow bandwidth of 0.7 nm centered at 1033nm. This means that for one important possible application of this kind of Q switching, namely external second harmonic generation, a high conversion efficiency is to be expected because a sufficiently narrow bandwidth together with good beam quality and high peak power is achieved.

5. Conclusion and outlook

For the first time, a fiber rod laser was Q-switched with a single crystal photo-elastic modulator producing pulses with a peak power > 10 kW and a pulse duration < 30 ns. The maximum average power (47 W) is at present the highest ever recorded for SCPEM-Q-switching, and it seems to scale with the frequency. To further increase the average output power, we plan to test a dual-mode SCPEM working at around 125 kHz. With this SCPEM in the given laser in dual-mode operation, we expect a 250 kHz pulse repetition rate. The simplicity of the setup allows easy application to every kind of laser for high-frequency Q-switching.

Generally, SCPEM-Q-switching is especially appropriate for fiber lasers because of their high gain per pass. This allows high output coupling and therefore low internal light intensity and low average/peak powers on the crystals. This means that a modulator can also be made from an optical material that intrinsically does not show extreme resistance to high optical intensity, such as the $LiTaO_3$ used in our experiment. However, for classical fiber lasers, SCPEMs are difficult to integrate into the resonator. In contrast, fiber rod lasers are free space devices, and together with their high gain, they seem therefore to be the ideal medium for SCPEM-Q-switching.

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