Q-switching of a fiber laser with a single crystal photo-elastic modulator

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Abstract: A study of using a single crystal photo-elastic modulator for active Q-switching of a fiber laser is presented. The modulator, which oscillates in a longitudinal eigenmode, was realized with $LiTaO_3$. This induces due to the photo-elastic effect a modulated artificial birefringence which modulates the polarization of passing light. When used together with a polarizer inside a laser cavity the laser photon life time is strongly modulated and the laser may start to emit laser pulses. We realized this with a fiber laser based on a 5m long double clad Nd-doped fiber. The pulse repetition frequency was 400 kHz and the pulse duration 300ns.

OCIS codes: 230.4110 Modulators; 140.3540 Q-switched Lasers; 140.3510 Fiber Lasers; (999.9999) Photo-elastic modulators

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1. Introduction

Pulsed laser operation is of utmost importance for many applications in manufacturing and medicine. One important method to produce short and strong laser pulses is Q-switching. This method uses inside the laser cavity an optical switch, which blocks the optical light path while energy is pumped to the gain medium. When this switch suddenly opens all stored energy is rapidly converted to a strong light pulse. Due to the very fast development of lasers based on an active fiber core there is a profound interest on various techniques for Q-switching of fiber lasers. As well as in case of classical solid state lasers a passive or an active Q-switch can be used. In case of passive Q-switching of fiber lasers different types of elements can be used such as a saturable absorber based on dye [1], crystal [2,3], doped fiber [4] or semiconductor saturable-absorber mirror (SESAM) that incorporates an additional two-photon absorber [5] and others.

Passive Q-switching in general leads to a relatively simple and robust structure, however in some cases, where a higher level of pulse control is necessary, an active Q-switch is needed. For fiber lasers besides the most common based on standard acousto-optic and electro-optic (EO) modulators [6], several alternatives of active Q-switches were proposed as for example: modulators based on Bragg grating modulation [7, 8, 9], a micro-optical waveguide on a micro-actuating platform light modulator [10], an electro-statically actuated micro-mirror system [11] and some others.

For Q-switching we introduce a new kind of photo-elastic modulator based on a single crystal photo-elastic modulator (SCPEM). It relies like acousto-optics modulators on photo-elasticity, but modulates polarization instead of beam direction. This modulator is made of $LiTaO_3$, which is electrically excited to oscillate in a longitudinal eigenmode. An important advantage of using eigenmode oscillations is that there is no need for a high voltage driver as it is in the case of standard EO modulators. In this paper some theory of a SCPEM and the results from an experiment with a SCPEM inside a laser resonator based on a double clad active core fiber are presented.

2. Photo-elastic modulators

2.1 The classic photo-elastic modulator

A typical photo-elastic modulator consists of a piece of glass (e.g. SiO_2, CaF_2, ZnSe), on which a piezoelectric transducer made of SiO_2 is glued [12, 13]. Both pieces are tuned to the same longitudinal eigenfrequency such that when the transducer is electrically excited on this frequency, the whole assembly starts to oscillate with high amplitude in a longitudinal mode. Now due to the photo-elastic effect an artificial birefringence is induced in the initial isotropic glass such that it acts as a wave plate with temporally varying retardation. Hence the polarization of light will be modulated. E.g. when the induced oscillation amplitude corresponds to a quarter-wave-retardation and the incident polarization is inclined 45° to the direction of oscillation, the output-polarization will oscillate between left- and right-circularized light. If the oscillation amplitude corresponds to a half-wave-retardation and the input is again 45°-linear polarized, the output-polarization will oscillate between -45° and again -45° linear polarized light with intermediate states 45°-linearly, left-&right-circularly and elliptically polarized.

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2.2 A single crystal photo-elastic modulator

An obvious disadvantage of the above described scheme is the need for precise adjustment of the frequencies of both pieces. It is therefore desirable to use the induced birefringence of the piezo-electric transducer itself for polarization modulation, i.e. the light is guided through this part and there would be no need to use an additional optical piece of glass. Unfortunately crystalline SiO_2 (crystal class 32) as used for the transducer has a large optical activity and changes therefore the polarization in an undesired way, even if there is no oscillation [14]. Hence we suggest the crystal class 3m to which the well-known $LiNbO_3$ and $LiTaO_3$ belongs [14, 15]. It shows no optical activity and can be transversely excited. In fact a similar crystal orientation like in Pockel's cell can be used. The important difference is that the dimensions are chosen in a way such that a clean longitudinal oscillation is possible.

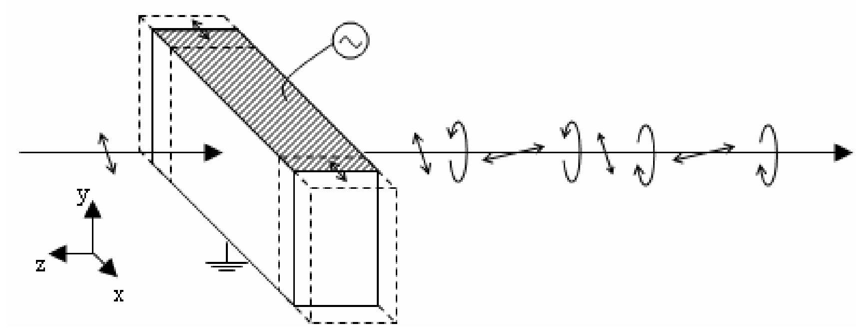

Fig. 1. A single crystal photo-elastic modulator made of a 3m-crystal

Figure 1 shows how it can be used for a SCPEM and how the orientations of the crystal axes have to be chosen. The shown polarization states correspond to half wave retardation, i.e. to the case described in the last line of the previous section.

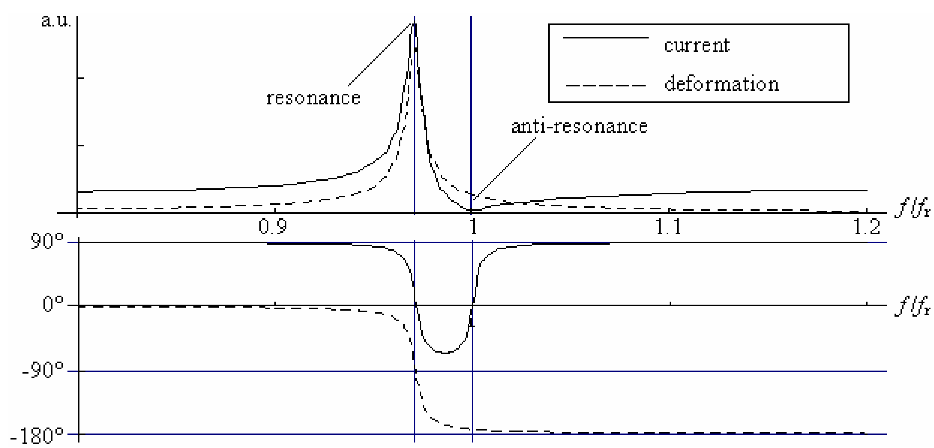

Fig. 2. Course of amplitude (top) and phase (bottom) of current and deformation at one typical resonance of a piezo-electric element against normalized frequency.

Figure 2 shows typical resonance curves for current and deformation which are common to all piezo-electric elements. It can be seen that outside the range of resonance the crystal acts electrically as a capacitor, i.e. the phase shift of the resulting current against the driving voltage is 90°. At resonance current and deformation takes a significant maximum while at the slightly higher frequency of anti-resonance the current amplitude is extremely small (zero in case of a loss-less device). The deformation amplitude in resonance is usually two or three

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orders of magnitude higher than the static deformation. The important advantage is now that the amplitude of the driving voltage is in the order of 10 V, i.e. two orders of magnitude lower than for electro-optic Q-switches.

However this utilization of the resonance behavior of the SCPEM leads to a limited frequency range. A measure for the possible frequency shift is the 3db-bandwidth of the crystal resonance, which is usually below 0.1% of the resonance frequency. Depending on the available driving amplitude the driving frequency can be shifted within this range. Another option is to use other resonance frequencies. In our experiment we used the first resonance frequency at 199 kHz (*x*-longitudinal oscillation). The next useful frequencies can be found at 348 kHz (*y*-thickness oscillation) and 377 kHz (*yz*-shear oscillation).

3. A SCPEM in a laser cavity

The effect of any kind of photo elastic modulator on the polarization of light with wavelength λ can be described by the so called retardation defined as

$$\delta = \frac{L}{\lambda}\left(n_{\mathrm{h}} - n_{\mathrm{v}}\right) \quad , \tag{1}$$

where L is the optical interaction length and n_{h}, n_{v} are the temporally varying refractive indices for horizontally and vertically polarized light. These can be calculated via the time dependent strains $\varepsilon_1 \ldots \varepsilon_6$ and the photo-elastic coefficients $p_{11} \ldots p_{66}$ [14, 15]. For a harmonic excitation at a resonance frequency f_{r} we get a harmonic retardation course

$$\delta = A \sin \omega_{\mathrm{r}} t \quad , \tag{2}$$

where $\omega_{\mathrm{r}} = 2\pi f_{\mathrm{r}}$ and A is the amplitude of the retardation course. For the polarization course sketched in Fig. 1 $A = \lambda/2$ holds.

If a polarizer oriented at 45° is placed behind the SCPEM and 45° linear polarized light is sent on the configuration, the transmission can be calculated by [15]

$$Tr(\delta) = \cos^2\left(\frac{\pi}{2}\delta\right) \tag{3}$$

A typical transmission curve with rather sharp transmission peaks achievable with a harmonic retardation course is shown in the third graph of Fig. 4. Similar considerations can be found in Ref. [17], where a similar type of polarization modulator was used for time-multiplexing of laser pulses emitted by high power laser diodes.

4. Experimental results

The main idea of the experimental setup is to test a SCPEM incorporated into the laser cavity as a Q-switch. The SCPEM is made of $LiTaO_3$ with dimensions 13.15 x 7.15 x 5.5 mm in *x*-, *y*- and *z*-direction. The electrodes are on the *zx*-surfaces and the light travels along the *z*-axis through the *xy*-surfaces. The first resonance frequency is found at $f_{\mathrm{r}} = 199$ kHz and corresponds to a longitudinal oscillation in *x*-direction.

A schematic diagram of the experimental setup is shown in Fig. 3. It is based on a Nd-doped D-shaped double clad fiber (DCF). The concentration of Nd_2O_3 is 1300 mol ppm. The length of the fiber is 5m and the diameter of the active core and inner cladding is 13µm and 400µm, respectively. The corresponding numerical aperture is 0.13 and 0.37.

We measured the laser output pulses and the transmission course of the modulator simultaneously as follows: Pumping light with 808nm from a 5W laser diode is guided through a coupler to the fiber end that also acts as an output mirror (4% of reflectance) of the laser cavity. The output laser light is reflected by the wavelength-sensitive mirror 2 and measured by photodiode 2. On the other end of the fiber the emerging laser light is collimated and then led through a polarizer and a SCPEM and is finally reflected by a highly reflective interference mirror 1 to travel again through the SCPEM and the polarizer back to the fiber. Pumping light that is not absorbed into the fiber and goes through the SCPEM is transmitted

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by mirror 1 and goes through an analyzer and falls onto photo diode 1. With its signal we can deduce the transmission course of the Q-switch for the laser light as explained later.

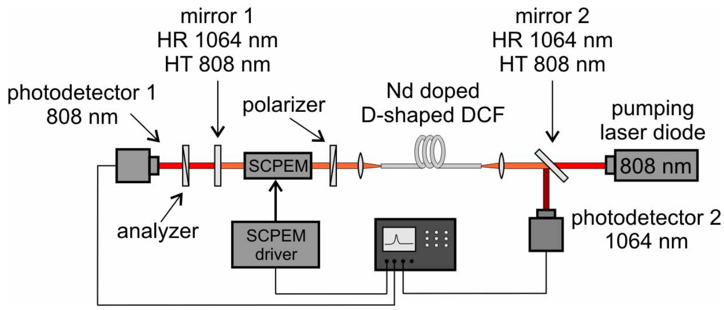

Fig. 3. Setup of a fiber laser with SCPEM Q-switch. Two photo detectors are used simultaneously in order to detect both the transmittance of the SCPEM and the output pulses of the laser.

5. Results and discussion

Figure 4 shows now the results of the measurements. The first graph shows the voltage on the electrodes (note the low amplitude: ~ 3V!), the second one the resulting current generated by the crystal. It is measured with a 100 Ω resistor between the lower crystal electrode and ground (100 Ω are much lower as the absolute value of the crystal impedance in resonance and hence has negligible influence on the resonance behavior). The voltage amplitude is adjusted in order to optimize the output laser pulses. The current signal is in phase to the voltage signal indicating a perfect adjustment to the resonance frequency. The third graph contains the transmittance of the pumping light through the polarizer/SCPEM/analyzer configuration measured by photo diode 1 (blue line). The red line is the estimated transmittance for the laser light when going through the optical elements in the sequence: polarizer/SCPEM (reflection) SCPEM/polarizer. This double pass configuration doubles the retardance induced by the SCPEM.

Now for the transmission of the pumping light Eq. (3) holds with a pumping light retardance δ_p. With estimated retardation amplitude of 0.70 a fit of Eq. (3) to the measured transmission curve (blue line in 3^{rd} graph of Fig. 4) can be obtained. Hence we get:

$$\delta_p(t) = 0.70 \sin(\omega_r t) \tag{4}$$

Now Eq. (1) shows that δ scales with the $1/\lambda$. Further the laser light retardance δ_l is doubled by the double pass configuration. Hence with the wavelengths $\lambda_l = 1064$nm for the laser light and $\lambda_p = 808$nm for the pumping light we estimate, while neglecting the dispersion of refractive index and photo-elastic coefficients, a laser light retardation

$$\delta_l(t) = 2\frac{\lambda_p}{\lambda_l}\delta_p(t) \tag{5}$$

The resulting estimated transmission curve for the laser light (red curve in 3^{rd} graph of Fig. 4) shows between the transmission peaks for ~800ns a complete block of the light path.

The resulting pulsed output of the laser (fourth graph) offers laser pulses with peak powers three to four times above the average power, which is obtained when no voltage is applied on the modulator. It is worth mentioning that the average output of the laser during pulsed mode is very close to that in cw-mode, namely ~200mW. Hence the modulation scheme introduces no significant decrease in efficiency.

It can be seen in the fourth graph of Fig. 4 that the amplitude of the laser pulses varies. We believe that this is related to a phenomenon explained in Ref. [18], where certain repetition rates of externally imposed switching leads to a variation of the pulse energy.

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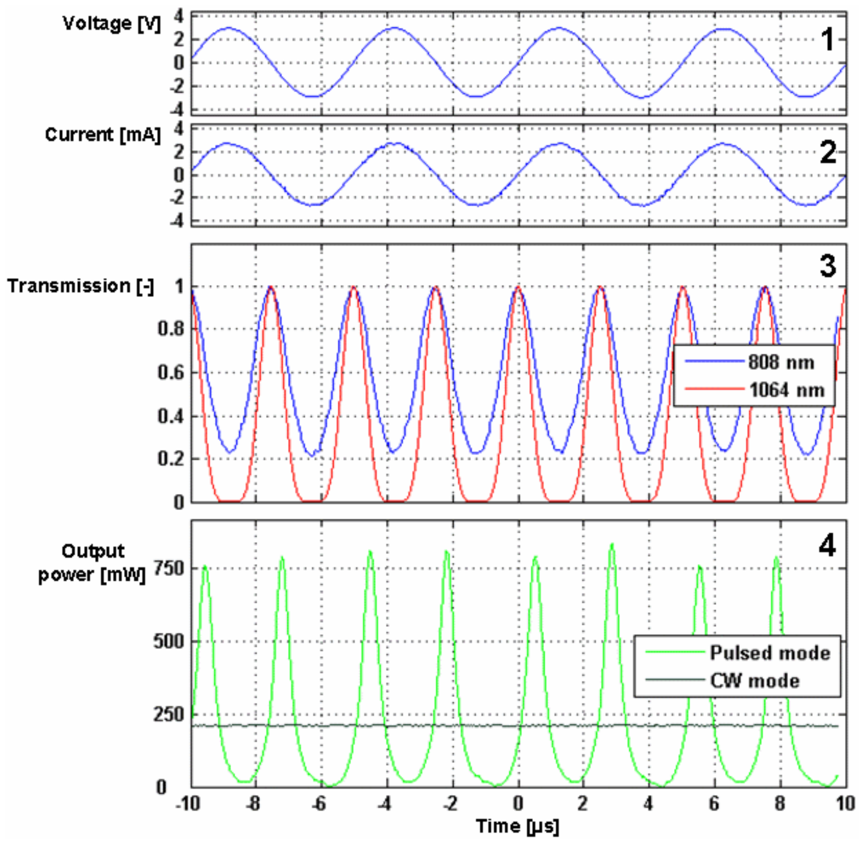

Fig. 4. voltage course on the crystal (1), current signal of the crystal (2), measured transmission for the pumping light (blue) and estimated transmission for the laser light (red) (3), optical output of the laser (4)

6. Conclusion

The presented investigation allows a simple modulation of the output power of a laser, without significant loss of efficiency when compared to cw-operation. We demonstrated this for a 200mW-fiber laser and we believe that there is no hindrance to extend the results to higher powers and other laser types. Possible applications may be found in fields where the simple laser structure is an important advantage and where the fixed pulse frequency does not represent a deficiency such as laser marking and engraving. This could be micro-welding of metals, where pulsed operations sometimes helps to smooth the welding seam surface, rapid prototyping of plastics, where some polymers needs high optical peak powers to harden, and laser range finding, where only small, simple, cheap and robust solutions are possible. We plan our future work to be focused on an even more robust setup with higher output power and shorther pulses, using pulse frequencies adapted for specific applications.

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