Power scaling of AOM-switched lasers with SCPEM-based time-multiplexing

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Abstract: Power Scaling of a Q-switched laser designed for internal frequency conversion is demonstrated by combining two Nd:YVO_4-gain-channels with a time-multiplexing scheme based on a single crystal photo elastic modulator (SCPEM). Both channels are coupled with a polarizer and share an output-coupler and acousto-optic modulator (AOM). In order to combine two channels by time multiplexing, the single crystal photo elastic modulator is used which switches between two channels, while the acousto-optic modulator conducts the Q-switching. This allows almost to double the average output power and repetition rate within a given laser resonator design.

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1. Introduction

Frequency doubled or tripled solid state lasers based on Nd:YVO_4 and Nd:YAG are very important for material processing in many areas of the micro-electronic and photovoltaic industry. VIS and UV is usually addressed with external [1–4] or internal [5–8] frequency conversion. Intra-cavity frequency doubling/tripling is normally preferred due to high conversion efficiency and excellent stability.

The need for high processing speed constantly requires scaling of average output power [3,4,7–9]. It is usually important that higher processing speed is achieved with unchanged pulse parameters (duration and energy) that have already been optimized for the specific process. Therefore the average power and repetition rate have to be scaled simultaneously, which of course makes only sense, if the distance between the pulses becomes not too short, as the higher repetition rate (approx. 1 MHz) can change the process condition for some applications.

In general, there are two ways in which to increase the power and repetition rate. The first possibility is to increase pumping power, which has several serious limitations due to surface damage, thermal lensing and other thermal effects. The second possibility is to use more gain mediums with corresponding pump modules [6]. This approach requires significant prolongation of the resonator length that leads to a change in the pulse parameters, especially increasing pulse duration. Furthermore in both cases there is a change of thermal lensing, requiring additional optimization of the resonator in order to keep it stable and to maintain adequate beam quality.

To avoid the abovementioned problems, we demonstrated another approach based on a dual channel resonator. Several dual channel configurations have already been proposed, mostly for measuring application, e.g. having a Pockels-cell or acousto-optics modulator (AOM) in each channel and a single gain medium in the common part of the resonator [10,11]. Several other configurations are based on one or two gain mediums, and AOMs were proposed for the generation of special tailored laser pulses for micro-processing [12]. Furthermore a configuration for power and repetition rate scaling was proposed [13], based on a dual channel resonator and a single electro-optical modulator (EOM). Its task was to Q-switch both channels in turn, therefore to double the frequency and power. However since the EOM requires a high driving voltage (kV- range) it is not suitable for the high repetition rates typically used in material processing (10-500 kHz range).

As an alternative we demonstrated a new approach based on the combination of two channels and two gain mediums and a type of time-multiplexing similar to that proposed in [14]. The basic idea is that the original single channel resonator is upgraded to two channels. However, in principle each single channel has the same structure and therefore the same optical properties as the original resonator. The Q-switching is carried out by one AOM in the common part of the resonator. Switching between the two channels is performed with a Single Crystal Photo-Elastic Modulator (SCPEM [14–17]) that is suitable for high frequency operation and requires just a few volts for driving.

2. The experimental setup

The setup is based on an industrial ns-pulsed laser that is designed for intra-cavity frequency up conversion. It has a Nd:YVO_4-gain-medium, longitudinally pumped at 808 nm, with a fiber coupled diode laser. Q-switching is based on an AOM. The output-coupler has 80% reflectivity.

In order to increase the power we upgraded the existing laser by adding an additional channel to the resonator with its own gain medium and pumping system. Figure 1 shows the adapted setup with the two channels that share a common out-coupler. The beams of both channels are spatially combined, with a thin film polarizer (POL1) transmitting the p-polarized light of channel 1 and reflecting the s-polarized light of channel 2. The key element of the system is a SCPEM, a resonantly excited piezoelectric crystal (here $LiTaO_3$), that is inserted into the common part of the laser. Its task is to temporally combine the laser pulses

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from both gain media by polarization switching. Each resonator channel exhibits exactly the same dimensions and characteristics as the basic laser design. This means that the single pulse parameters remain the same, however due to time multiplexing, the repetition rate of the laser pulses and consequently the output power is doubled. Therefore the upgraded laser can be equipped with the same frequency conversion unit as the original laser without any change to the laser resonator. In our case this unit is omitted, since it is considered to be of no relevance to the proof of the concept.

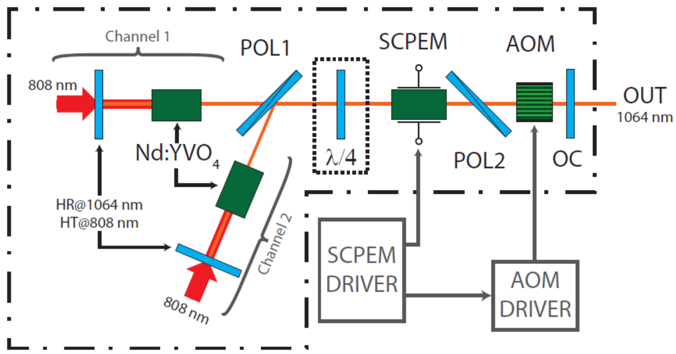

Fig. 1. Scheme of the setup based on a diode-pumped Nd:YVO_4-laser.

In the common laser channel an acousto-optic modulator (AOM) has been installed to Q-switch the lasers, while the SCPEM together with two polarizers (POL1 and POL2 in Fig. 1) switches between both channels. As will be explained later, the SCPEM can work with or without an additional λ/4-plate. Its operation is based on polarization modulation utilizing the photo-elastic effect caused by an electrically induced mechanical oscillation of the crystal. The modulator retardation $\delta(t)$ [rad] is [14–17]:

$$\delta(t) = \delta_1 \sin(2\pi f_R t)$$

δ_1 is the retardation amplitude related to the driving current. f_R is the fixed resonance frequency of the modulator (91.5 kHz, corresponding to a period of 10.9 µs, in our case for a $LiTaO_3$-crystal with dimensions 28.7 x 9.5 x 4mm in the x-, y-, z-directions). Two configurations are possible: with and without a λ/4-plate (retarder) in the common branch. In channel 1 the polarization is p-polarized (horizontal polarization), in channel 2 the polarization is s-polarized (vertical polarization), and in the common part of the resonator only p-polarization can propagate. Therefore when the modulator (together with the optional λ/4-plate) is in neutral position (no rotation of the polarization) channel 1 is switched on. In order to switch to channel 2 the modulator (together with the optional λ/4-plate) has to rotate the polarization by 90°. The transmission T for channel 1 through a SCPEM (optical axis oriented at 45°) is:

$$T = \frac{1}{2}\left(1+\cos\left(\delta\right)\right) = \frac{1}{2}\left(1+\cos\left(\delta_1 \sin\left(2\pi f_R t\right)\right)\right) \tag{1}$$

without a λ/4-plate and

$$T = \frac{1}{2}\left(1+\cos\left(\delta \pm \pi/2\right)\right) = \frac{1}{2}\left(1+\cos\left(\delta_1 \sin\left(2\pi f_R t\right) \pm \pi/2\right)\right) \tag{2}$$

with the retarder. With $\delta_1 = \pi$ in Eq. (1), the transmission curve shown in the Fig. 2(a) can be obtained. In the case of using a λ/4-plate (Eq. (2), the retardation amplitude should be $\delta_1 = \pi/2$. The transmission curve is now slightly different as shown in the Fig. 2(b). Without the retarder the required SCPEM retardation amplitude doubles and the switching frequency between the two channels is a factor 2 higher. Channel 1 also gets a shorter opening time,

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which turned out to be of no relevance to the results. However proper synchronization and adjustment of the delay between the AOM temporal window and SCPEM temporal window as well as the retardation amplitude of the SCPEM is very important.

Overall transmission of one single channel depends on the SCPEM and on the AOM. The principle of operation can be explained as follows. As previously mentioned, the SCPEM alternately selects channel 1 and 2, however the selected channel is in a transmission state and generates a laser pulse only when the AOM is simultaneously open. The repetition rate is therefore still controlled by the AOM as in the original single channel version. However due to the fixed frequency of the SCPEM, only discrete values of the output repetition rate are possible. Figure 3 represents the highest first four values of the repetition rates for the two options.

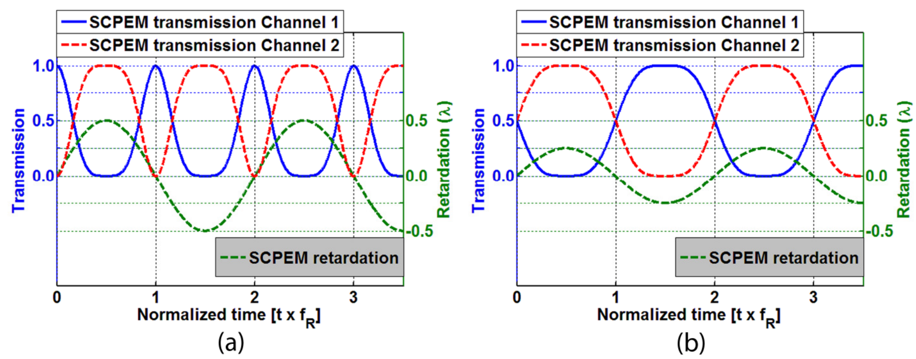

Fig. 2. The SCPEM can operate without or with the λ/4-plate. The graph (a) and (b) show the retardation (green curve) and transmission of the SCPEM without and with a λ/4-plate, respectively. The blue curve is the SCPEM transmission curve for channel 1 and the red curve is the SCPEM transmission curve for channel 2.

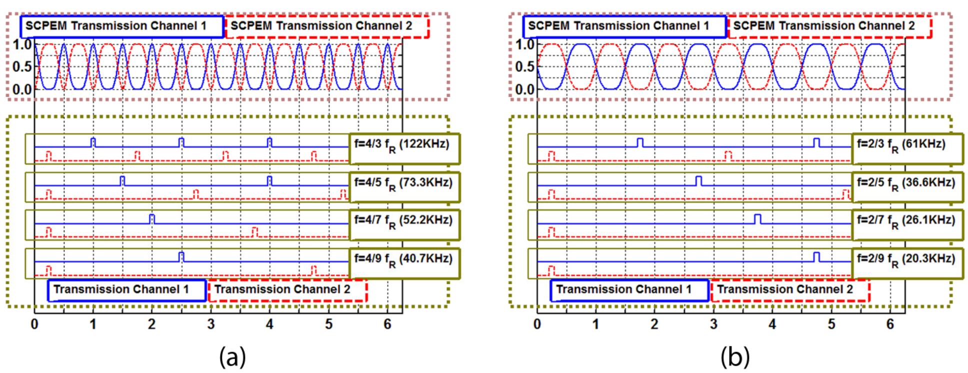

Fig. 3. Principle of operation and available repetition rates for the setup without (a) and with λ/4-plate (b). The two upper curves represent SCPEM-transmission. The pairs of curves below represent the overall transmission of channel 1 (blue curves) and 2 (red curves) for four particular repetition frequencies. The overall transmission is obtained as a combination of SCPEM and AOM transmission. Horizontal axis represents normalized time: $t \times f_R$.

Only combinations with equidistant pulses are shown, since this is usually required for standard applications (e.g. micro-processing). The lower pairs of blue and red curves correspond to the overall transmission window of the particular channel, determined by the combination of the transmission of the SCPEM and AOM which have to be precisely synchronized. The duration of the overall transmission window was fixed at 900 ns. The available repetition rates are $f = 4f_R/(2n\text{-}1)$ without λ/4 plate and half of that $f = 2f_R/(2n\text{-}1)$ with the plate, where n is a positive integer.

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3. Results and discussion

Figure 4 shows typical results for the laser output without (a) and with a λ/4-plate (b), showing little difference between the operations of both setups. The pulse parameters at similar repetition frequencies are the same within measurement accuracy.

The maximum pulse repetition frequency of $4f_R$ (setup without λ/4-plate) showed an unsatisfying pulse-to-pulse-stability or showed even missing pulses and is therefore not shown. However this effect is an intrinsic "problem" of the given laser resonator as it appears even in single channel operation without any additional elements of dual channel operation and is therefore not related to our concept.

Table 1 shows an overview of the pulse parameters and the average power for a repetition rate of 41 kHz to 122 kHz. There is no significant difference for the average power between the two channels, showing that their optical properties are nearly equal. Obviously the modulator does not introduce any significant asymmetry. The average power for a particular channel was measured by switching off the pumping diode of the other channel.

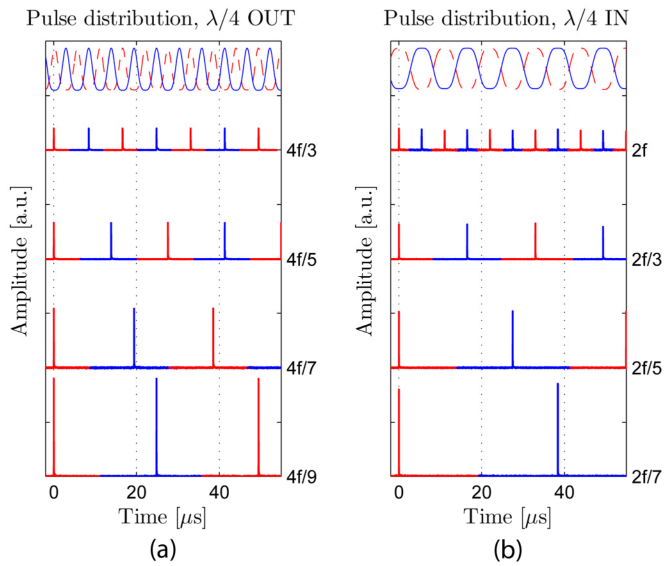

Fig. 4. Pulse operation for the setup without (left graph) and with a λ/4-plate (right graph). The two upper curves correspond to SCPEM transmission. Lower curves correspond to the measured output laser pulses from channel 1 (blue) and channel 2 (red) for four different repetition rates as marked in the graph.

For comparison, the parameters are presented for a single channel laser in Table 2. In order to see the difference between the single and dual channel resonator, the pulse parameters have to be compared at the same single channel repetition rate. As expected for single channel resonators, pulse energy decreases and pulse duration increases with increasing repetition rate.

Table 1. Laser pulse parameters of dual channel laser for four highest repetition rate of the SCPEM with a resonance frequency of 91.5 kHz and setup without λ/4 plate.

Single channel repetition rate (kHz)	Dual channel repetition rate (kHz)	Average power ch1 (W)	Average power ch2 (W)	Average power ch1 + ch2 (W)	Pulse duration (ns)	Peak power (kW)
61	122	10.8	10.2	21.0	42.2	4.1
36.5	73	10.0	10.1	20.1	31.5	8.7
26	52	9.2	9.5	18.7	27.1	13.2
20.5	41	8.9	9.2	18.1	24.7	18.0

For dual channel operation, the average power per channel is ~12% lower, the pulse duration is longer for 2% and consequently the peak power is 14% lower than for the single laser. As solid state lasers are very sensitive to any resonator losses the lower average power is a direct consequence of the additional optical elements: combining polarizers, λ/4-plate and SCPEM. The loss due to the λ/4-plate is less critical and appears mostly due to reflection at the AR-coating which is relatively low (0.2%). Furthermore, the losses due to the SCPEM come from three main parts: reflection from the AR coating (0.2%), intrinsic absorption of the crystal, and non-perfect polarization rotation. The absorption coefficient of lithium tantalate is $\alpha \sim 0.2\ m^{-1}$ [18]. Therefore at a given crystal thickness (4 mm) the contribution of the absorption is low: $(1- \exp(-0.2 \times 0.004)) = 0.08\%$. The major part of the losses comes from a combination of non-ideal operation of the SCPEM and losses on the combining polarizer. Therefore the modulator during operation is never the ideal λ/2 plate, which at the right orientation rotates incoming light by 90° and therefore makes the two perpendicular polarizers transparent (channel 2). Furthermore it is also never the ideal 0-plate which should transmit the light undisturbed (channel 1). We estimate that the losses in both cases mentioned above are approximately 3-4%.

Table 2. Laser pulse parameters of the single channel laser for the same single channel frequency as in Table 1

Repetition rate (kHz)	Average. power (W)	Pulse duration (ns)	Peak power (kW)
61	11.8	40.8	4.7
36.5	11.4	30.7	10.3
26	10.7	26.4	15.6
20.5	10.1	24.5	20.2

4. Conclusion

We successfully demonstrated the concept of power and repetition rate scaling of an AOM-Q-switched longitudinal pumped solid state laser consisting of a two channel resonator. We achieved an efficiency of approximately 90% in each channel, therefore we increased the power by ~80%. The simplicity of the setup allows for easy application to lasers that are not too sensitive to the losses induced by the additional elements. One disadvantage, however, is the fixed multiplexing frequency which allows only certain pulse repetition frequencies.

The concept also allows further scaling of the power and repetition rate. Each of the two channels can be split into two parts by introducing an additional polarizer and modulator. In principle there is no limitation to further channel splitting, however, since the insertion of additional optical elements into the resonators increases the losses, four combined channels probably represent the practical limit.

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