Self Q-switching effect in a Nd:YVO$_4$/KTP lasing unit

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Abstract. We report and present an experimental investigation of spatially and thermally dependent self Q-switching effects generated in Nd:YVO$_4$ cavity. The main application for the investigated effect is generation of an efficient Q-switched lasing in a Nd:YVO$_4$ crystal that may be realized without the need for a saturable absorber module.
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[DOI: 10.1117/1.2219976]

1 Introduction

The Casix DPM 1102 hybrid crystal unit includes a lasing crystal Nd:YVO$_4$ followed by a nonlinear KTP crystal used for frequency doubling. The Nd:YVO$_4$ is pumped by a laser diode (LD) at 808 nm and produces a main spectral lasing line at 1064 nm. The KTP crystal doubles the lasing frequency and generates output radiation at 532 nm. This hybrid unit has become quite popular in various research applications. In this unit, the Nd:YVO$_4$ crystal is already glued to the KTP crystal, and proper mirror coatings are deposited on the external surface of the YVO$_4$ and the KTP. The entire unit occupies a volume of several cubic millimeters. Exploring the properties of Nd:YVO$_4$ lasers has became very common in the scientific literature in the last decade (e.g., Refs. 1–4). One important direction that is very popular is related to Q-switching of Nd:YVO$_4$ and microchip lasers.[5–8]

Generally speaking, Q-switching is an effect in which pulses of light appear at the output of the laser while continuous pumping is applied. Such an effect is obtained by insertion of time-dependent losses into the cavity or by varying the transmission coefficient of the mirrors, which can be done in an active manner (electro-optical modulators) or passively. Usually, passive Q-switching includes insertion of an additional crystal into the resonator. Such a crystal is called a saturable absorber. In the experiment presented in this letter, we have managed to obtain self Q-switching without the insertion of such a crystal. In our case, the YVO$_4$ acts not only as the lasing substrate but also as the saturable absorber. In this letter, we present the effect in the Casix DPM unit and experimentally explore its spatial and thermal dependence. We show that when the YVO$_4$ crystal is pumped at its edges, slow-rate temporal modulation appears at the output of the laser. The extinction ratio of this modulation is temperature dependent.

2 Theory and Experimental Investigation of the Self Q-Switching Effect

In Q-switching, a temporally pulsed beam is obtained at the output of a laser. The technique allows the production of light pulses with high peak intensity, much higher than the intensity produced by the same laser when operated in its continuous wave (constant output) mode.

The basis of Q-switching is to have a periodical temporal affect on the Q factor (quality factor) of the optical resonator of the laser. The Q factor is a measure of how much light from the gain medium of the laser is fed back into itself by the resonator:

$$Q = \nu_0/\Delta\nu, \tag{1}$$

where ν_0 is the resonant frequency and $\Delta\nu$ is the bandwidth defined as full width at half maximum.

The explanation of the Q-switching process may be as follows: Initially, the laser medium is pumped while the Q-switch device (e.g., a saturable absorber placed inside the resonator) prevents feedback of light into the gain medium (producing an optical resonator with low Q). This produces a population inversion, but laser operation cannot yet occur because there is no feedback from the resonator. Because the rate of stimulated emission depends on the amount of light entering the medium, the amount of energy stored in the gain medium will increase as the medium is pumped. Due to losses from spontaneous emission and other processes, after a certain time the stored energy will reach some maximum level; the medium is then said to be gain saturated. At this point, the Q-switch device is changed from low to high Q, allowing optical feedback and the process of optical amplification by stimulated emission begins.

Because of the large amount of energy already stored in the gain medium, the intensity of light in the laser resonator builds up very quickly; this also causes the energy stored in the medium to be depleted almost as quickly. The net result is a short pulse of light output from the laser, known as a giant pulse, which may have very high peak intensity. The Q-switch device itself may be a mechanical device (e.g., a shutter, chopper wheel, or spinning mirror placed inside the cavity), some form of modulator such as an acousto-optic or electro-optic device, or a passive saturable absorbing
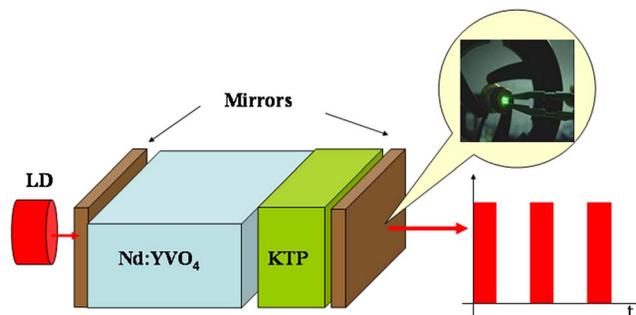

Fig. 1 Schematic sketch of the setup.

material that is a different crystal than the one used for the lasing operation. In this section, we demonstrate how the Nd:YVO$_4$ is used not only to lase but also as the saturable absorber medium, i.e., the device responsible for the Q-switching.

How can such an effect occur? One possible explanation of the detected effect may be related to gain-induced Q-switching through the effect of refractive-index-related gain guiding and saturation.[8] Note that from observation in Ref. 9, at room temperature the Nd:YVO$_4$ reaches first the lasing threshold of its first longitudinal mode at 1063.4 nm and at approximately twice the threshold of the first mode a second longitudinal mode reaches its threshold with a wavelength of 1064.2 nm. We assume that a Gaussian inversion density is generated in the four-level laser system when it is pumped by Gaussian intensity profile. The lasing of the first longitudinal mode will saturate the gain and leave residual spatially varied population inversion. In certain spatial conditions of pumping, this remaining population inversion is still peaked at the center. This gain will induce a distortion in the refraction index experienced by the second mode below the threshold:

$$\Delta n(r,z,\nu_2) = \frac{c(\nu_2 - \nu_0)g_2(r,z,\nu_2)}{2\pi\nu_2\Delta\nu}, \qquad (2)$$

where ν_2 is the frequency of the second mode, ν_0 is the center of the gain profile, $\Delta\nu$ is the gain bandwidth, and g_2 is the gain function of mode 2 after mode 1 partially depleted the population inversion. r and z are the transversal and the longitudinal coordinates, respectively. Therefore, in the presence of population inversion, longitudinal modes at a higher frequency than the center of the gain will experience increased refraction index. Because the magnitude of the residual population inversion is greater in the center of the beam than at the edges, these higher-frequency longitudinal modes will be more positively guided. This is in contrast with longitudinal modes with frequencies lower than the central gain frequency, which will be anti-guided. This effect will prevent mode 2 from lasing first, although it is closer than mode 1 to the center of the gain profile.

In our experiments, the optimized Q-switching performance was obtained in the cases where the pumping LD was close to one of the edges of the YVO$_4$ crystal. The explanation of this effect may be related to Fresnel coefficients. For s-polarized light, the reflection coefficient is:

$$R_s = \left[\frac{n_1\cos\theta_i - n_2\cos\theta_t}{n_1\cos\theta_i + n_2\cos\theta_t}\right]^2, \qquad (3)$$

where θ_t is the angle of the transmitted radiation and θ_i is the incident one. Note that θ_t can be derived from θ_i by Snell's law. If the incident light is polarized in the plane of the diagram (p-polarized), the reflection coefficient is given by:

$$R_p = \left[\frac{n_2\cos\theta_i - n_1\cos\theta_t}{n_2\cos\theta_i + n_1\cos\theta_t}\right]^2. \qquad (4)$$

The transmission coefficient in each case is given by $T_s = 1 - R_s$ and $T_p = 1 - R_p$. Because, close to the edges of the crystal on one side of the generated guiding or anti-guiding channel there is air (having a refraction index of 1), the
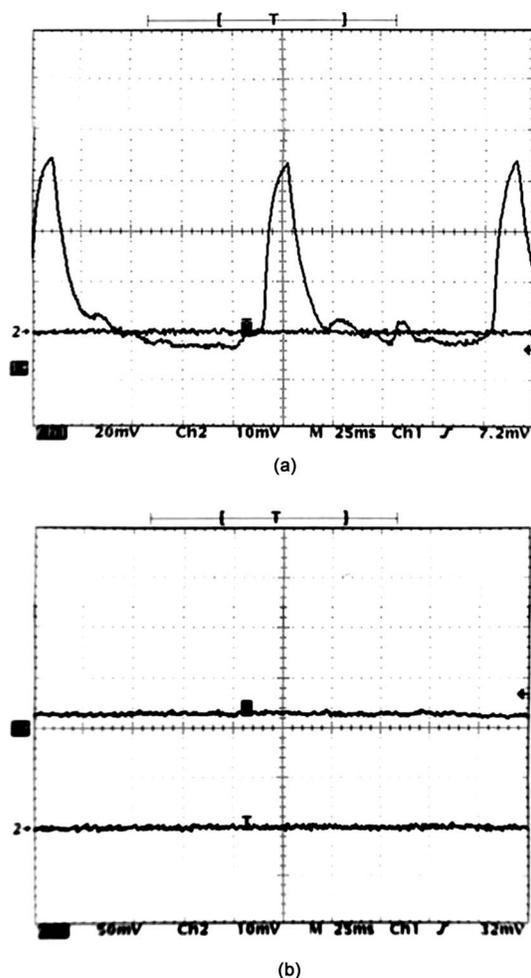

(a)

(b)

Fig. 2 Self Q-switching of Nd:YVO$_4$. (a) The output of the crystal with continuous pumping. (b) The output without Q-switching.

Fresnel reflection coefficient is much larger [since it is computed for the case of $n_1 = n_0 + \Delta n$ and $n_2 = 1$, while if the illumination is in the center rather than at the edge, the two refraction indexes in Eqs. (3) and (4) will be $n_1 = n_0 + \Delta n$ and $n_2 = n_0$). This means that more intensity is bounced back and captured in the guiding channel, and thus Δn is larger and the effect of refractive-index-related gain guiding and saturation is amplified and reinforced.

Our experiment included usage of a Casix DPM 1102 hybrid crystal unit consisting of a Nd:YVO$_4$ crystal that was pumped by LD at 808 nm and generated lasing at 1064 nm. Following the Nd:YVO$_4$, a nonlinear KTP crystal is placed in order to convert the 1064 nm wavelength to 532 nm by frequency doubling effect. The unit was pumped with continuous pumping. We spatially moved the pumping LD and discovered a certain spatial position close to the corner of the crystal at which strong and short pulses are generated at the output. The spatial scanning of the optimal pumping position was done by special mechanical stage. A photodetector that was placed at the output of the module was connected to a scope. At proper spatial position of the pumping (close to the corner of the crystal), temporal fluctuations were measured. The ratio between the power of the continuous lasing obtained for continuous pumping
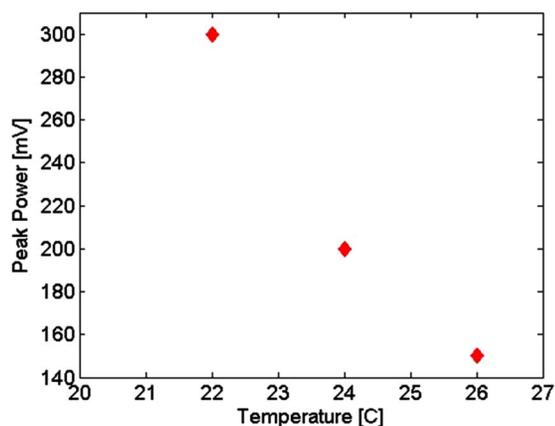
Fig. 3 Self Q-switching of Nd:YVO$_4$. Dependence of the peak on the temperature.

Fig. 4 Fiber-coupled LD of 2W at 808 nm that generates a self Q-switching obtained at temperatures of (b) T=24°C.

without Q-switching and the peak power of the produced peaks was approximately 1:35 (at a temperature of 22°C). This ratio is related to the extinction ratio between the peak of the generated pulses and the energy level between the peaks and is temperature dependent. The room temperature for the initial experiments was 27 to 28 degrees.

Figure 1 presents the schematic configuration and the measurement arrangement. Figure 2(a) illustrates the generated self Q-switching pulses. Their periodicity was approximately every 112 ms. Each pulse had a peak power of 80 mV (at the detector). The YVO$_4$ atoms in this case were used not only to allow the lasing process but also as the saturable absorber. A much stronger peak of approximately 150 mV was obtained when the temperature was decreased by 1 to 2°C. Figure 2(b) presents the lasing continuous output when the pumping is shifted to a different spatial position that does not initiate the self Q-switching effect. The readout in this case is approximately a continuous readout of 10 mV. In Fig. 3, one sees the dependence of the peak on the operation temperature. The results presented in Fig. 3 were obtained by placing the crystal on top of a thermo-electric cooler (TEC), controlling its temperature and measuring the optical intensity generated at the detector positioned at the output of the unit.

An additional example of the thermal dependence of self Q-switching process is depicted in Fig. 4, where the fiber-coupled LD of 2W at 808 nm that manages to deliver 600 mW was used. The measurements were performed for temperatures of 24°C, 27°C, and 31°C. Figure 4 presents an example of such a result obtained for a temperature of 24°C. The peak of the pulses was temperature dependent as measured in Fig. 3 (decrease in temperature increases the efficiency of the effect).

Baer[10] has discussed temporal instabilities and fluctuations in the Nd:YAG module due to a slightly different effect than the one we used to explain the measurements we obtained. In that paper, the output of a Nd:YAG pumped laser with an intra-cavity doubling KTP crystal was temporally fluctuated due to the coupling of longitudinal modes of the laser oscillator by sum-frequency generation as well as frequency doubling in the KTP crystal. Since the frequency separation of the two lasing longitudinal modes is only 50 GHz, it is small in comparison to the phase match-

ing bandwidth of the doubling KTP crystal; both the sum frequency and the second harmonic generation satisfy the phase matching condition in the crystal. Obviously, this effect is thermally dependent, and thus thermal variations can affect the temporal fluctuations in the lasing crystal. This effect may be related to the measured phenomena that we obtained because the thermal operation point of our crystal is dependent on the spatial position of the pumping source. Future similar experiments repeated with Nd:YVO$_4$ unit without the KTP doubling crystal are required in order to have a more decisive explanation of the contribution of each of the two mentioned effects to the experimentally obtained results.

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