

# 1.7MW Nd:YAG Laser Pulse Generation by A Passive BDN Q-switch

M. Dezhkam<sup>a</sup> and M. Soltanolkotabi<sup>b</sup>

<sup>a</sup>Department of Physics, University of Shiraz, Shiraz, Iran

<sup>b</sup>Quantum Optics Group, Department of Physics, University of Isfahan, Isfahan, Iran

**Abstract**— This paper describes the passive Q-switch, based on polymer and organic dye BDN, of a pulsed Nd:YAG laser. Pulses of 27ns duration and peak power of 1.7MW for initial transmission of Q-switch  $T_0 = 18.4\%$  have been obtained. We have obtained Q-switching efficiency of 77% for train of pulses of 31 and  $T_0 = 76.2\%$  at the pump energy of 98J. We have also obtained the dependency of laser pulse characteristics on pump energy and initial transmission of Q-switch. We have obtained the damage threshold of this Q-switch at the pulse duration of 27ns to be  $13J/cm^2$ .

**Keywords:** Dye, Nd:YAG laser, passive Q-switching, polymer.

## I. INTRODUCTION

The Neodymium-doped yttrium aluminum garnet (Nd:YAG) laser is one of the most commonly used type of solid-state laser. It is a four level system having a wavelength of 1064nm in the infrared. Nd:YAG lasers are optically pumped using a flashlamp or laser diodes. They operate in both pulsed and continuous mode. Pulsed Nd:YAG lasers are typically operated in the so called Q-switching mode [1]. They are used in applications such as scribing, drilling, marking, surface doping and heat treatment of refractory materials [2].

Q-switching is one way of obtaining short and powerful pulses of laser radiation. There are two main types of Q-switching: active and passive. Active Q-switching is an externally - controlled variable attenuator. The technique of active Q-switching (such as acousto-optic or electro-optic device) is rather complicated. In passive Q-switching, the Q-switch is a

saturable absorber, a material whose transmission increases when the intensity of light exceeds some threshold [1].

The passive Q-switching technique is usually accomplished with dyes, color centers such as  $LiF:F_2^-$ , semiconductors and  $Cr^{4+}:YAG$  crystals as saturable absorbers [3].

Using dye as a Q-switch is one of the most important examples of Q-switching, especially in miniature Q-switched lasers [4]. A suitable dye as saturable absorber for Nd:YAG lasers, is Bis (4-dimethylamino dithiobenzil) nickel (BDN). Because BDN in 1, 2-Dichloroethane solvent absorbs wavelength 1064nm (neodymium lasers wavelength), furthermore the dye lifetime is nanosecond and suitable for Q-switching.

## II. THEORETICAL BACKGROUND

The rate equations of Q-switched laser can be written as:

$$\frac{\partial \Phi}{\partial t} = \Phi \left( c \sigma n \frac{l}{l'} - \frac{\varepsilon}{t_R} \right) \quad (1)$$

$$\frac{\partial n}{\partial t} = -\gamma \Phi \sigma c \quad (2)$$

where  $\Phi$  is the photon density,  $c$  is the speed of light in vacuum,  $\sigma$  is the stimulated emission cross section,  $n$  is the population inversion density,  $l$  is the length of the active material,  $l'$  is the length of the resonator,  $\varepsilon$  is the losses in a cavity,  $t_R = 2l'/c$  is the round-trip time and  $\gamma$  is the inversion reduction factor.

Using these rate equations one obtains the expressions for the output energy  $E$ , the peak power  $P$  and the pulse width  $\tau$  of a Q-switched laser:

$$E = \frac{Vh\nu}{\gamma} (n_i - n_f) \frac{\ln\left(\frac{1}{R}\right)}{\varepsilon} \quad (3)$$

$$P = \frac{Vh\nu \ln\left(\frac{1}{R}\right)}{\gamma \tau_R} \left\{ n_i - n_t \left( 1 + \ln \frac{n_i}{n_t} \right) \right\} \quad (4)$$

$$\tau = \frac{t_R}{\varepsilon} \frac{n_i - n_f}{n_i - n_t \left( 1 + \ln \frac{n_i}{n_t} \right)} \quad (5)$$

where  $V$  is the active volume of the laser medium,  $h\nu$  is the photon energy,  $n_i$  and  $n_f$  are the initial and final population inversion densities,  $n_t$  is the population inversion density at threshold and  $R$  is the reflectivity of the output mirror [1].

A saturable dye can be represented by a four-level model such as that shown in Fig. 1. Absorption at the laser wavelength occurs for both the 1-3 and the 2-4 transitions. These are the ground state and excited state absorptions, respectively. The absorption cross sections for the 1-3 and 2-4 transitions are denoted by  $\sigma_{13}$  and  $\sigma_{24}$ . On the other hand,  $\tau_{21}$ ,  $\tau_{32}$  and  $\tau_{42}$  are the lifetimes of energy level 2, 3 and 4 respectively and  $\tau_{32} \ll \tau_{21}$ ,  $\tau_{42} \ll \tau_{21}$  [4].

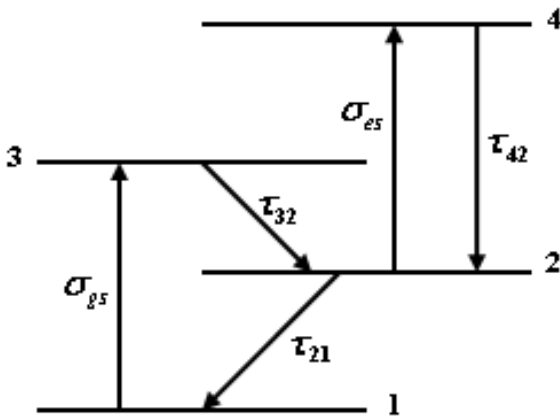


Fig. 1. The four-level model of the saturable dye.

The transmission of the dye can be written as:

$$\ln T - \ln T_0 = \left( \frac{1}{\delta} - 1 \right) \ln \left( \frac{\frac{1}{\delta} + \frac{I}{I_s}}{\frac{1}{\delta} + \frac{IT}{I_s}} \right) \quad (6)$$

where  $T$  is the transmission of dye at the laser intensity of  $I$ ,  $T_0$  is the small-signal transmission (initial transmission),  $\delta = \frac{\sigma_{24}}{\sigma_{13}}$ ,

where  $\delta$  for BDN is 0.24,  $I_s = \frac{h\nu}{\sigma_{13}\tau_{21}}$ ,  $I_s$  is called the saturation intensity [4,5].

For  $I \ll I_s$ , the transmission  $T$  is close to  $T_0$ , but for  $I \gg I_s$ ,

$$T = T_0^\delta \quad (7)$$

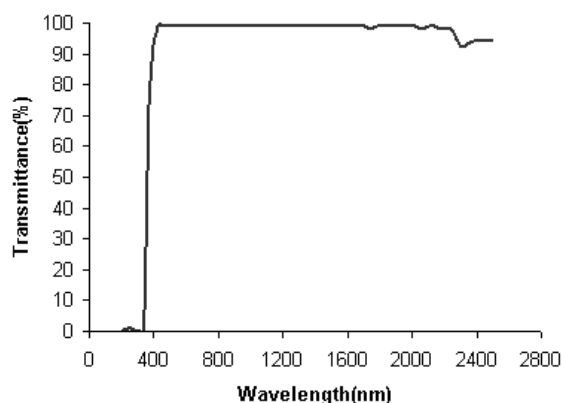
This expression shows two things: first, if  $\sigma_{13} > \sigma_{24}$ , then we have  $T > T_0$  (It is obvious if  $\sigma_{13} < \sigma_{24}$  then transmission will be less than  $T_0$  which is not favorable), second  $T < 1$  that means we have absorption even when the Q-switch is saturated [5].

### III. BDN Q-SWITCH PREPARATION

Dye Q-switches are used in the forms of liquid solutions and solid solutions. For making solid-state Q-switches, dyes are doped in transparent polymers. Among polymers, polystyrene, polymethyl methacrylate, polyvinyl alcohol and epoxy have low radiation damage threshold, on the other hand, elastic polymers have high radiation damage threshold. Polyurethane acrylate and polyurethane are two examples of elastic polymers. Polyurethane acrylate is not suitable because it is formed by radical polymerization and interaction between chemically active free radicals and dye molecules causes dyes to be decomposed. Polyurethane is formed by polycondensation reaction in the neutral medium so it is qualified for making dye Q-switches [2].

To make Q-switch we have used polyether-based, aliphatic, thermoplastic polyurethane

which is plasticizer-free. The transmission of polymer film as a function of wavelength is shown in Fig. 2, using Shimadzu UV-3100 spectrophotometer. As shown in this figure the transmission coefficient of this polymer in the region 420-2260 nm is approximately 100% ( $T \approx 100\%$ ), so its loss at laser wavelength 1064nm is low. Also, ultimate elongation of this polymer is  $\frac{\Delta l}{l} = 500\%$ .



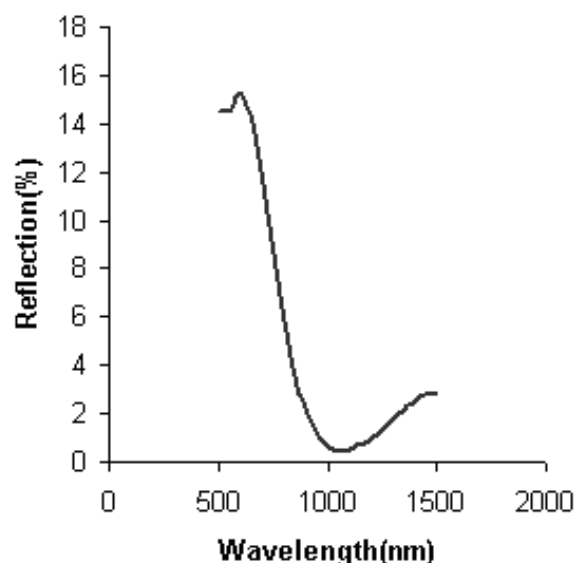
**Fig. 2.** Optical transmission as a function of wavelength for the polymer film.

As mentioned above, we have used organic dye Bis (4-dimethylamino dithiobenzil) nickel (BDN) as saturable absorber in this Q-switch. Because BDN in 1, 2-Dichloroethane solvent absorbs wavelength 1064nm (neodymium lasers wavelength), furthermore the dye lifetime is nanosecond and suitable for Q-switching.

We have dissolved polymer and dye in methylene chloride solvent, and then we have poured out this solution on the optical glass BK7 and put the similar glass on top of it. We have pressed them with a gadget and heated it for an hour at  $40^\circ\text{C}$ . The polymer adhesion characteristic joins the glasses.

The reason of using glass for polymer film is to protect it against mechanical damages and oxygen. In order to decrease the losses caused by light reflection, we have antireflection-coated the outer surface of the glasses. Coating has been done by  $\text{MgF}_2$  and  $\text{Ta}_2\text{O}_5$ , in this way the glass reflection at wavelength 1064nm was decreased to 0.43%. We have measured the

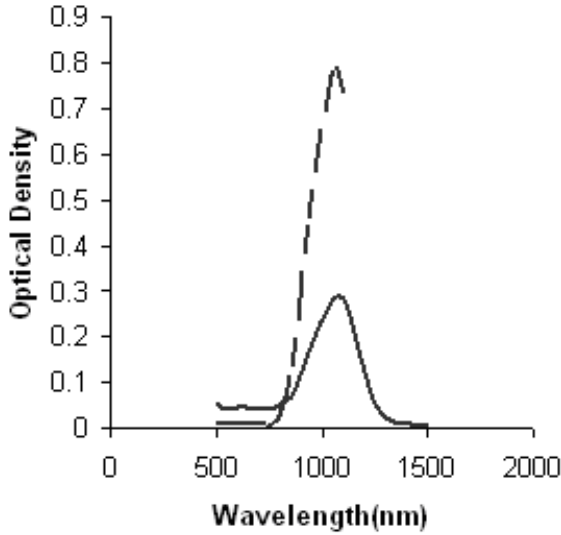
glass reflection spectrum –as shown in Fig. 3- using Shimadzu UV 3100 spectrophotometer.



**Fig. 3.** The coated BK7 glass reflection spectrum.

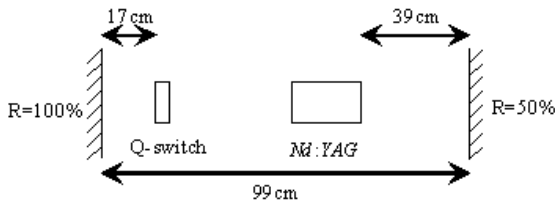
The absorption spectrum of the BDN dye in the polymer (solid line) and the BDN dye in methylene chloride solvent (dashed line) is shown in Fig. 4. To obtain the absorption spectrum of the BDN dye in the polymer, we have used Shimadzu UV 3100 spectrophotometer whereas for the absorption spectrum of the BDN dye in methylene chloride we have used Perkin Elmer Lambda2 spectrophotometer. Unfortunately, this spectrophotometer range was limited to 1100nm and we could not obtain the full spectrum. The maximum absorption of colored polymer is at  $\lambda = 1075\text{nm}$  and the main absorption of the BDN dye in methylene chloride is  $\lambda = 1060\text{nm}$ . It means in comparison with liquid solution the maximum absorption occurs in the higher wavelength for colored polymer.

By changing concentration of the dye, the initial transmission  $T_0$  of Q-switch can be changed. In this way we have produced different Q-switches with different initial transmissions  $T_0$  (from 18.4% to 76.2%). We have measured the initial transmission of Q-switches using Perkin Elmer Lambda2 spectrophotometer with 0.1% accuracy at wavelength 1064nm.



**Fig. 4.** The absorption spectrum of the BDN dye in polymer film (solid line) and in methylene chloride (dashed line).

We have used these Q-switches to Q-switching our Nd:YAG laser. This laser has the following specification: laser rod diameter of 6.3mm with the length of 100mm, pumped by flash lamp with a repetition rate of 1Hz, the resonator is plane-plane mirror and 99cm long. The reflectivity of back mirror is 100% whereas for the front mirror is 50%. The output pulse duration of this laser without Q-switching was  $100\mu s$ . The Q-switch located at 17cm from the back mirror and laser active medium is at 39cm from output mirror (see Fig. 5). For pulse measurement, we have used HAMEG Digital Oscilloscope, Gentec Joulemeter and FK-19 photodetector.



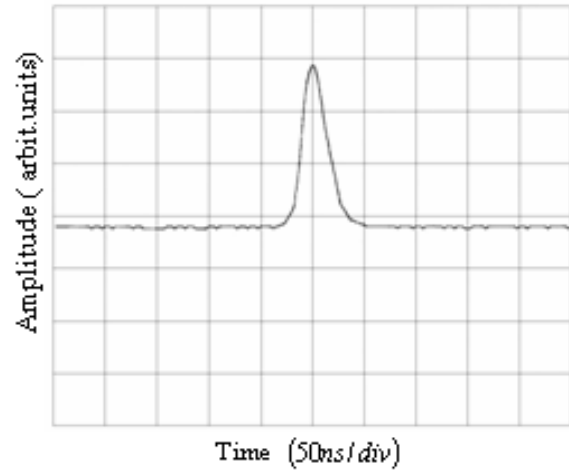
**Fig. 5.** The laser cavity and location of Q-switch.

In a Q-switched mode, we have increased pump energy  $E_p$  from threshold up to 98Joules. For various input pump energies, we have measured the train energy  $E_o$ , the number of pulses in a train  $N$ , single spike duration  $\tau$  and train time pulses  $T$ . By using these measurements, we have determined peak

power of pulse  $P_p = \frac{E_o}{N\tau}$  and average power  $P_m = \frac{E_o}{T}$ . We have also measured energy  $E_{f,r}$  of this laser for different pump energies without Q-switching. Then, we have obtained Q-switching efficiency, defined as the ratio of the train energy to the free-running energy at a fixed pump energy,  $\eta = \frac{E_o}{E_{f,r}}$ .

#### IV. RESULTS AND DISCUSSION

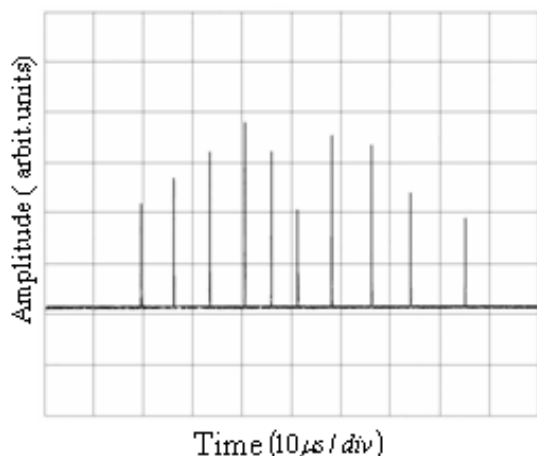
We have prepared our Q-switch with various initial transmissions. For example, with the initial transmission 18.4%, we have obtained the threshold pump energy of 21J, single pulses of 45 mJ and pulse duration of 27 ns (Fig. 6). This pulse is approximately Gaussian shape and had peak power of 1.7MW. When the Q-switch initial transmission was 59.3%, at the pump energy of 41J, we have obtained a train of pulses with 196mJ energy with time interval of  $66\mu s$ . This train had 10 pulses with time duration of 94ns for each pulse (Fig. 7).



**Fig. 6.** Oscillogram of a single output pulse,  $T_0 = 18.4\%$  and pulse pump energy 21J.

Under different initial transmissions, we have noticed the dependence of output pulse characteristics on these parameters. For fixed initial transmission, by increasing pump energy, the number of pulses in a train,  $N$ , has increased linearly. Since, as the pump energy increases, the gain increases as well therefore

pulses generated. Also, as the pump energy increases, the train energy  $E_o$  increases approximately linearly and Q-switching efficiency,  $\eta$ , increases. However, by increasing pump energy no changes have been seen in pulse duration and peak power.



**Fig. 7.** Oscillogram of a train of output pulses,  $T_0 = 59.3\%$  and pulse pump energy 41J.

Next, we have examined the pulse characteristic for various initial transmissions of Q-switches. For fixed pump energy, by increasing Q-switch initial transmission, pulse duration,  $\tau$ , increases. This is because, as the initial transmission increases, the absorption decreases and that delay the saturation. Also, by increasing the initial transmission, the number of pulses,  $N$ , in a train increases, because loss is less and the gain enhances and that lets more pulses to be generated. Moreover, by increasing initial transmission, the cavity loss be less and that increases the train energy  $E_o$  and consequently more Q-switching efficiency,  $\eta$ , expected. Increasing initial transmission leads to average power enhancement and reduction of peak power. It is worth mentioning that initial transmission enhancement of Q-switch, cause less threshold pump energy as a result of less cavity losses.

To summarize, at the initial transmission 18.4%, we have obtained the least pulse duration of 27ns with the peak power of 1.7MW. We have obtained the best Q-switched efficiency of 77% with the 31 pulses

in a train for  $T_0 = 76.2\%$  at the pump energy of 98J.

To determine the damage threshold of Q-switch, we did the following: by using Q-switched Nd:YAG laser with  $T_0 = 18.4\%$  and generation of 27ns pulse and focusing this laser beam (using a lens with focal length of 107mm) on a Q-switch located at 82mm from this lens and producing a beam diameter of approximately 1.5mm, we have gradually increased the laser energy up to the point in which polymer film start to damage. We have obtained a high damage threshold of  $13 \text{ J/cm}^2$ . This comparatively large damage threshold is due to highly elastic property of polymer film  $\left(\frac{\Delta l}{l} = 500\%\right)$ .

## V. CONCLUSION

We have implemented the passive Q-switch based on organic dye BDN and a kind of polymer for pulse Nd:YAG laser. Then we have used this BDN Q-switch for Q-switching the laser and we have obtained the pulses of 27ns duration and 1.7MW peak power.

## ACKNOWLEDGMENT

The authors are thankful to Mr. Ebadian and Mr. Atabaki for helping to prepare the sample and setting up the laser system. This work was supported by University of Isfahan graduate office.

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