Black YAG crystal and BDN dye as passive Q-switched laser modulators
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Received 2 January 2002, revised 26 August 2003, accepted 2 December 2003

Passive Q-switching has been done in Nd:YAG laser transmitter using Black YAG crystal and BDN dye as saturable absorbers. The results have been obtained for two different cases (i) at free running laser threshold and (ii) Q-switched laser action for these absorbers. It has been found that the output peak power in Q-switched laser operation mode is much larger for both the absorbers than in free running regime. Further, the results of Q-switched output power obtained with these absorbers have been compared and it has been found that pulse width in case of Black YAG crystal is larger in comparison to that obtained with BDN dye, thereby providing a better way of overcoming spiking phenomenon generally occurring in solid state lasers.

[Keywords: Saturable absorbers, Q-switching, Q-switched laser modulators, Bleaching effects, Laser modulators]
IPC Code: HOIS 5/00

1 Introduction

Nd:YAG laser comes under the category of rare earth ion doped solid state lasers. Nd is the most useful rare earth ion that can be doped in a variety of host lattices. Out of the various host materials the most commonly used are YAG or glass to get pulsed as well as continuous laser action. Flash lamp pumped pulsed Nd:YAG laser has been used successfully for several years in many scientific areas. Nanosecond lasers have the applications in resonance induced spectroscopy, CARS, LIDAR and in surface damaging investigations whereas the picosecond lasers are used for time domain spectroscopy, satellite ranging and many more applications where high peak power or short pulses are required. The thermalisation effects on Q-switched laser properties have also been studied by Degan et al.

In a pulsed solid state laser the time dependence of the optical pumping leads to the undesirable phenomenon of 'spiking' (mode hopping) in laser output power. The output power may be increased by Q-switching, which is achieved by exciting the laser medium so that a population inversion occurs by delaying the application of the feedback from the axial mirrors. This can be achieved by either mechanically or by acousto-optic or electro-optic shutters or by using opaque dye solution (saturable absorbers). In order to have effective Q-switching it is required that:

(i) The pumping rate must be faster than spontaneous decay rate of upper laser level to have sufficiently large population in the upper level.

(ii) Q-switch must switch rapidly in comparison to the build up of laser oscillation to have high peak power. In practice Q-switch should operate in a time less than one nanosecond.

Out of the passive and active ways of Q-switching mentioned above in the present work, former has been done using Black YAG crystal and BDN dye. This method relies on the action of so called saturable absorbers (mainly dye solutions), whose absorption decreases with increasing irradiance. The effect becomes prominent with the increase in absorption of photons by these absorbers in the ground state, thereby reducing the overall factor of absorption. At this stage the absorber behaves as a transparent medium as the light becomes more intense. This increase in transparency is known as bleaching effect or saturation of dye.

The Black YAG crystal used in the present work is a crystal of Yttrium aluminium garnet doped with Cr ions (Cr**YAG). It has been found that chromium impurities are present in garnet crystal in the Cr** state. When the crystal is simultaneously doped with metal ions having valence +2 such as Mg²⁺ and Ca²⁺, then this kind of doping preserves the charge balance in the crystal and their chemical composition is given by stoichiometric formula:

\[ (Y_{3x}^{3+}Mg_{x}^{2+}) (Al_{1x}^{3+}Cr_{x+}^{3+}Cr^{4+})O_{12} \]

Crystals are grown by Czochralski method and are of black color and completely opaque. Black YAG has the spectral characteristics such as absorption located in the 0.8 to 1.2 μm range, luminescence in 1.1 to 1.7 μm range and...
Cr\(^{3+}\) ions can be used as passive Q-switch modulator for 0.9 to 1.1 \(\mu m\) range where crystal exhibits bleaching effect\(^{6,10}\).

BDN dye on the other hand is a transparent plastic material impregnated with (Bisymmetric) Bis Dimethyl amino dithio benzyl Nickel molecule (Fig. 1). It can be used for giant pulses up to 1 to 3 MW before the damage occurs\(^{11}\).

2 Experimental Details
2.1 Electrical and optical measurements

Selection of gain medium—In the present study a Nd:YAG crystal has been taken which is free from internal strains and dislocations thereby providing low threshold energy requirement. The optical work connected with the crystal has been done that includes size and shape of the crystal, surface finishing, grinding, polishing and coating of the end faces. Doping of the Neodymium ions in the YAG crystal has been restricted between 1.0 to 1.5\% (atomic percent) in order to shorten the fluorescent lifetime and broadening of line width\(^{6}\). The beam divergence and threshold value requirements have been minimized by setting surface finish of the order of \(-\lambda/10\) of Na light and parallelism of end faces of 10\(\) s of an arc respectively.

Excitation mechanism—Nd:YAG is a four level laser system where excitation of the upper laser level is provided by using a Xe flash lamp as it can be simmered more easily with low current and there is sufficient overlapping of Xe lamp emission lines with absorption lines of Nd:YAG. The lamp with arc length of 45 mm and of bore diameter 4 mm is used. The gas pressure is kept at 450 torr. The power supply of Xe lamp consists of a pulse forming network, trigger network and a charging unit.

The pulse-forming network consists of a 60 \(\mu F\), 1KV low inductance, high storage capacitor and 27\(\mu H\) air core inductor. The equations most commonly used for design of single section flash circuit are given by\(^{12}\):

\[ E_{\text{store}} = \left(\frac{1}{2}\right) (CV)^2 \]  

energy stored in the capacitor \(\ldots(1)\)

\[ T_r = \left(\frac{LC}{2}\right)^{1/2} \]  

pulse rise time \(\ldots(2)\)

where \(V_o\) is the charging voltage and \(C\) is kept fixed at 60 \(\mu F\).

The trigger circuit initiates the discharge of stored energy into the flash lamp by creating an ionised spark.

![Fig.1—Molecular structure of BDN dye.](image1)

![Fig.2—Absorption and emission spectra of Nd:YAG (______) and Xe flash lamp (______)](image2)
steamer between the two electrodes. The function of a charging unit is to charge the energy storage capacitor to a selected voltage. This capacitor-charging source usually consists of a transformer followed by a rectifier bridge, a switching element in the primary of the transformer, a current limiting element, a voltage sensor and the control electronics.

*Feedback configuration* - The resonator cavity used in the present work is a plane-parallel stable resonator configuration \(0 = G \leq G_c = 1\) where \(G_c = 1 - L/R_p\), \(G_s = 1 - L/R_s\) and \(R_p\) and \(R_s\) are radii of curvature of two mirrors. For \(R_p = R_s = \infty\), \(G_c = G_s = 1\). The pair of mirrors used as resonators in this case are the corner cube prism and partially coated one end of the laser rod itself. The cavity used is of closed-coupled configuration with a silver-coated perfect cylindrical reflector.

*Procedure* - The specifications used for the Nd:YAG rod can be summarized as:

- **Length**: 50 mm
- **Diameter**: 5 mm
- **End configuration**: plano-plano
- **Surface finish**: \(\sim 0.10\)
- **Perpendicularity** (end of rod axis): \(<5\text{ min of arc}\)
- **Parallelism of end faces**: 10 arc sec
- **Shape**: Right circular cylinder with flat ends
- **Doping of Nd\(^{3+}\) ions**: 1.12% by atom
- **Coating of end faces of laser rod**: One end has anti reflection coating of 1.064\(\mu\)m and other is partially coated.

The rod with the above specifications is fitted into the cavity (closed coupled configuration) with the help of plastic rings. The excitation is done by using Xe flash lamp mentioned above. The passive Q-switch element consisting of a plastic sheet is placed inside the optical resonator, preferably between the laser medium and the rear mirror. After optical excitation it initially absorbs the laser rod fluorescence emission to the degree that the rear reflector is optically isolated from the remainder laser cavity hence introducing optical losses with the cavity. This prevents premature emission and allows energy to be stored in the laser material through population inversion until the Q-switching element is bleached and becomes transparent. Oscillations build up in cavity and the available stored energy is discharged in a single high power pulse (giant pulse). The output energy of the laser pulse is measured by using an energy-meter having a silicon pin photo diode with a diffuser as a detector. The pulse width is measured at full width at half maximum (FWHM) using 100 MHz storage oscilloscope.

**Fig.3** - Oscilloscope tracing of output pulses (a) without Q-switching element (b) with Q-switching element

### 3 Results and Discussion

**Fig. 3** depicts the qualitative behavior of the output laser pulse with and without Q-switching element. The observations were recorded at free running regime and for Q-switching lasing action with both the absorbers separately (Table 1). In all the observations, capacitance value is kept constant at 60 \(\mu\)F, whereas charging voltage is varied up to the requirement of lasing threshold. The energy stored in the capacitor in each case is calculated using Eq. (1). The output energy \(E_o\) and the pulse width are measured using a photodiode and a 100 MHz storage oscilloscope respectively. The pulse separation in case of double pulse generation is also recorded. Finally, the output power is calculated from the known data of output energy and pulse width using the relation

**Peak Power** = \(E_o/\tau\).

The threshold power requirement is verified by focussing the output pulse on a photographic film and the observations were taken when a spot is found burnt on the photographic film.
The output energy in case of free running mode is much less in comparison to that of Q-switched laser. No single/double pulse generation takes place without Q-switching element, only multiple spikes are observed; however, with the Q-switching element, single and double pulse generation takes place depending upon the charging voltage. Pulse width in case of Nd:YAG laser Q-switched with Black YAG is 10 nsec, whereas with BDN dye, it is 8 nsec. Although the cavity parameters for the two cases are exactly identical, the difference in pulse width is owing to the fact that laser is functioning in the pulse reflection mode in which pulse width depends on response time of the Q-switching element. This property of Black YAG makes it superior to be used as Q-switch element as well as for passive mode locking. It is also used in construction of Nd:YAG pulsed laser for laser range finders and laser systems generating giant pulses with high repetition rate. The BDN dye on the other hand is suitable in the applications of plastic Q-switches in certain low repetition rate military and scientific systems.

The peak power obtained is of the order of MW, and is approximately 10% higher than that of a free running mode. The results are in good agreement with those reported by Fedin et al. as they have obtained 4 MW peak power in case of passive Q-switched with LiF:F₂ crystal, Nd:YAG laser.

### 4 Conclusions

Black YAG crystal and BDN dye have been studied as the passive Q-switching modulators and in this following conclusions can be drawn:

1. No pulse generation takes place in absence of Q-switched element, whereas single/double pulses are observed with Q-switching element depending upon the charging voltage.
2. Output energy in case of free running mode is much smaller than that of Q-switched laser.
3. Pulse widths of the order of 8 nsec and 10 nsec are obtained with BDN dye and Black YAG crystal, respectively.
4. High peak power is obtained in both the cases.

### Acknowledgements

The work has been carried out at Instruments Research and Development Establishment (IRDE), Dehradun (India). Authors are thankful to the referees for their helpful suggestions.

### References


<table>
<thead>
<tr>
<th>Mode of operation</th>
<th>Charging voltage (V)</th>
<th>E_{in} (J)</th>
<th>E_{out} (mJ)</th>
<th>Pulse generation</th>
<th>Pulse width (μs)</th>
<th>Pulse separation (μs)</th>
<th>Peak power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Without Q-switch element</td>
<td>480</td>
<td>6.91</td>
<td>2.0</td>
<td>No single pulse</td>
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<tr>
<td>(B) With Q-switch element</td>
<td></td>
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<td>(a) BDN dye</td>
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<tr>
<td>(i) 678</td>
<td>13.79</td>
<td>12.5</td>
<td>Single pulse</td>
<td>8</td>
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<td>1.56</td>
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<td>17.78</td>
<td>26.0</td>
<td>Double pulse</td>
<td>8</td>
<td>30</td>
<td>3.25</td>
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<td>(b) Black YAG crystal</td>
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<td>4.2</td>
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Table 1—Observations at free running regime and for Q-switching lasing action with both the absorbers.