

Q-SWITCHED LASER

FIELD OF THE INVENTION

- 5 This invention relates to lasers and, more particularly, to Q-switched lasers.

BACKGROUND OF THE INVENTION

Q-switching is widely used in lasers to generate short pulses with high peak
10 powers, which are desirable in laser applications such as micro-machining and
lidar systems. Q-switching can be realised either actively or passively in solid state
lasers. Active Q-switch elements include an acoustic-optical (AO) modulator or an
electrical-optical (EO) modulator. Passive Q-switching elements include saturable
absorbers like $F_2^-:LiF$, $Cr^{4+}:YAG$, $GaAs$, and $InGaAsP$. Passive Q-switching
15 elements are usually inserted into the laser cavity either at the Brewster angle or
with antireflection coating to reduce insertion loss.

One known conventional Q-switched pulse laser is shown in Fig. 1. The Q-
switched laser has a laser medium 11, a pump cavity 12 and a resonator, which
20 includes a total reflection rear mirror 13 and an output coupler 14 placed one
either side of laser medium 11. A single Q-switching element 31 (active or
passive) is provided between laser medium 11 and output coupler 14. Such lasers
compromise between the pulse width and the pulse energy. Large pulse energy
and narrow pulse width are difficult to achieve simultaneously in low to average
25 power lasers such as a diode end-pumped $Nd^{3+}:YVO_4$ laser.

Active Q-switching elements are generally unable to produce laser pulses less
than 10 nanoseconds. Passive Q-switching with a saturable absorber produces
short pulses of picosecond duration without having to use mode-locking.
30 However, passively Q-switched lasers have a limited range of applications for
several reasons. Firstly, passively Q-switched lasers can only generate short

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pulses in very short cavities (such as microchip lasers). This is because a short cavity provides efficient laser during the pulse build up, the pulse width being linearly proportional to the cavity length. Additionally, the pulse repetition rate of a passively Q-switched laser is not controllable. It is generally in the range of a few
5 hundred kilohertz and dependent on the saturation characteristics of the passive Q-switching element and the pulse intensity in the laser cavity. The uncontrollable high repetition rate usually results in a small pulse energy, in the range of 10^{-6} joules.

10 SUMMARY OF THE INVENTION

An object of the present invention is to provide a Q-switched laser having improved pulse energy and narrower pulse width.

15 The present invention provides a Q-switched laser including a pump cavity, a laser medium in said pump cavity for generating laser light, an active Q-switching element for controlling Q-switching oscillation of laser light in said laser according to a selected modulation rate, and a passive Q-switching element for Q-switching oscillation of laser light in said laser according to selected saturation
20 characteristics of said passive Q-switching element.

In accordance with the present invention, it has been found that a Q-switched laser which simultaneously employs an active Q-switching and a passive Q-switching element can generate laser pulses with a relatively shortened duration, enhanced peak power and variable repetition rate. In effect, the combination of
25 an active Q-switching and a passive Q-switching element causes "mixed" or "double" Q-switching. Thus, a "double" Q-switched laser can be used to produce compressed laser pulses. The active Q-switching element is used to control the pulse repetition rate and ensures that the population inversion is fully saturated in
30 the laser medium. The role of the passive Q-switching element is to generate the short laser pulses by increasing the power-loss coefficient maximum.

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Preferably, the active Q-switching element is located between the laser medium and the passive Q-switching element. It is preferred that both the active Q-switching element and the passive Q-switching element are located between the
5 laser medium and an output coupler of the laser.

In a preferred form of the invention the passive Q-switching element also preferably acts as the output coupler. The passive Q-switching element can be a saturable absorber. Preferably, the passive Q-switching element is uncoated.
10 The saturable absorber can be selected from one of LiF, F_2^-LiF , GaAs, GaAs wafer, SF_6 , InGaAsP, InGaAsP wafer or $Cr^{4+}:YAG$.

The active Q-switching element is preferably an acoustic-optical modulator or an electric-optical modulator.
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The Q-switched laser includes any suitable pump source for pumping light into the laser medium. The pump source can either end-pump or side-pump the laser medium. The pump source can be a laser diode, a laser diode array, an optic fibre coupled laser diode array or a flash lamp.
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It is preferred that the Q-switched laser has means for cooling the laser medium. The cooling means can, for example, be a thermoelectric cooler.

The laser medium preferably has a doped portion. It is preferred that the doped
25 portion is doped with at least one rare earth ion. The laser medium can be a laser crystal or a composite laser crystal. The rare earth ion can be one of Nd, Er, Ho, Tm, Pr, Cr and Ti.

The combination of an active and a passive Q-switching element advantageously
30 shortens the laser pulses and enhances the pulse energy (usually from about 10^{-6}

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joules to 10^{-3} joules). The peak power of the doubly Q-switched laser is also increased significantly (usually from about 37.5 kW to 120 kW).

It has also been found that saturable absorbers, such as GaAs wafers or Cr^{4+} :YAG absorbers, can act as both the passive Q-switching element and the output coupler in solid state lasers. This has several advantages by enabling a simpler configuration for the laser and a short cavity length. In particular, the saturable absorbers do not need coating to reduce insertion loss. The surface reflection of the saturable absorber in fact provides the resonator with both the necessary feedback for the laser action and the Fabry-Perot oscillation to enhance saturable absorption characteristics.

The abovementioned improvements can be explained with the well-known formula for the pulse width of passive Q-switching:

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$$\tau_p = 1.76 \frac{2T_R}{\Delta R}, \quad (1)$$

where τ_p is the pulse width;

T_R is the cavity round-trip time; and

20 ΔR is the maximum modulation depth with respect to the intensity.

For a fixed cavity length, the above equation clearly indicates that ΔR has to be as large as possible for short pulses. In a purely passively Q-switched laser, the maximum modulation depth is given by $\Delta R = 1 - \exp(-\Delta q)$ where Δq is the maximum change in the power-loss coefficient of the passive Q-switching element.

In the present invention with mixed Q-switching by simultaneously using active and passive Q-switching elements, the maximum value of the power-loss coefficient is increased significantly due to the insertion of the active Q-switching element. This means that no laser oscillation can occur at all in the cavity during

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its low Q-state. When the active Q-switching element is in its high Q-state, the power loss is then low, being dependent only on the absorption characteristics of the passive Q-switching element, and the minimum loss is then the same as that in passive Q-switching. Therefore the value of ΔR is increased significantly, and in turn the pulse width in the simultaneous Q-switching of the active and passive Q-switching elements is shortened according to Eq. (1).

The increase in pulse energy can be explained by referring to the expression for the total energy in a Q-switched pulse:

$$E = \frac{V h \nu \ln(1/R)}{\gamma \varepsilon} (n_i - n_f), \quad (2)$$

where E is the total energy;

V and γ are the cavity constants;

ε is the linear power-loss coefficient;

$h \nu$ is the photon energy;

R is the reflectivity of the coupler;

n_i is the initial inversion population; and

n_f is the final inversion population.

When the passive Q-switching element is used as the output coupler, all the parameters except n_i in Eq. (2) are the same in both passive Q-switching and in the present invention where double or mixed Q-switching occurs. However, the initial inversion population n_i is quite larger in the present invention, resulting in an important difference between these two cases.

In passive Q-switching, once the gain exceeds the loss in the cavity, the laser pulse starts to build up slowly. This brings about the depletion of the upper population and leads to a reduction in the absorption of the passive Q-switching element, in turn speeding up pulse build up. The initial inversion population, therefore, is very dependent on the saturable absorption characteristics and the

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pump power levels as well. In low continuous wave (CW) pumping, this initial value (and thus the pulse energy) is usually small as observed in most passively Q-switched lasers.

- 5 In the mixed or double Q-switching that occurs in the present invention, the active Q-switching element ensures that the initial population inversion is independent of the passive Q-switching element and always equal to the saturated level. This leads to a much higher pulse energy.

10 BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the present invention will now be described, by way of example only, with reference to the drawings, of which:

- 15 Fig. 1 is a schematic diagram illustrating one known conventional Q-switched solid state laser;

Fig. 2 is a schematic diagram illustrating a Q-switched solid state laser according to a first preferred embodiment of the present invention;

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Fig. 3 is a schematic diagram illustrating a Q-switched solid state laser according to a second preferred embodiment of the present invention;

Fig. 4 is a schematic diagram illustrating an experimental setup of the Q-switched
25 laser of Fig. 3; and

Fig. 5 illustrates a temporal evolution curve of a laser pulse from the Q-switched solid state laser of Fig. 3.

30 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

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Fig. 2 shows a Q-switched solid state laser according to a first embodiment of the present invention. The laser has a laser medium 11, a pump cavity 12 and a resonator, which includes a total reflection rear mirror 13 and an output coupler 14 placed one either side of laser medium 11.

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A pump source (not shown) is used for generating pumping light used to pump the laser medium 11. The pump source may be put inside or outside the pump cavity 12, depending on the type of pump source used. If the pump source is a flash lamp, it is usually put inside the pump cavity 12. If the pump source is a laser diode, a laser diode array or an optic fibre coupled laser diode array, the pump source is located outside pump cavity 12. The laser medium 11 can be either end-pumped or side-pumped.

15 An active Q-switching element 15 is located between laser medium 11 and output coupler 14 for controlling Q-switching oscillation by abruptly changing a loss of resonant laser light passing through. The active Q-switching element is an AO modulator 15.

20 A passive Q switching element 16 is placed between AO modulator 15 and the output coupler 14. The passive Q-switching element is a saturable absorber 16. Examples of a saturable absorber 16 are LiF, $F_2:LiF$, GaAs, GaAs wafer, SF_6 , InGaAsP, InGaAsP wafer or $Cr^{4+}:YAG$.

25 The laser medium 11 can have an undoped portion and doped portion, the doped portion being doped with at least one rare earth ion. Rare earth ions include Nd, Er, Ho, Tm, Tr, Pr, Cr and Ti.

30 Examples of suitable laser crystals include YAG ($Y_3Al_5O_{12}$), $YAlO_3$, Al_2O_3 , YLF ($LiYF_4$), GSGG ($Gd_3Sc_3Al_3O_{12}$), GSAG ($Gd_3Sc_3Al_3O_{12}$), GGG ($Gd_3Ga_5O_{12}$), YVO_4 , glass, LaF_3 , $BeAl_2O_4$ or BaY_2F_8 . Alternatively, the laser medium can be a compound laser crystal, such as YAG ($Y_3Al_5O_{12}$), YLF ($LiYF_4$) and YVO_4 .

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In this preferred embodiment, the laser medium 11 is a laser crystal doped with one rare earth ion. Both sides of the laser crystal 11 are deposited with anti-reflection layer at the laser wavelength.

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The first preferred embodiment is different in construction from the conventional Q-switched laser as shown in Fig. 1. Namely, in the preferred embodiment in Fig. 2, an active Q-switching element (the AO modulator 15) and a passive Q-switching element (the saturable absorber 16) are employed simultaneously. In contrast, the conventional Q-switched laser only uses a single Q-switching element 31 (either active or passive) in Fig. 1.

Fig. 3 illustrates a second embodiment of the present invention. The same reference numerals have been used to refer to integers corresponding to integers in the first embodiment of Fig. 2.

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The main difference between the first and second embodiments is that output coupler 14 in the first embodiment has been removed in the second embodiment. The saturable absorber 17 acts as both the passive Q-switching element and the output coupler. In this case, the end surfaces of the saturable absorber 17 are not coated with an anti-reflection coating. Nor is saturable absorber 17 positioned at the Brewster angle. Instead, the surface reflection of saturable absorber 17 in fact provides the resonator with both the necessary feedback for the laser action and the Fabry-Perot oscillation to enhance its saturable absorption characteristics. The combination of output coupling and passive Q-switching in saturable absorber 17 makes it possible to realise highly compact, lasers with a short pulse width and high peak power.

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Fig. 4 is a schematic diagram of an experimental setup using the second embodiment. The laser medium 11 is a $\text{Nd}^{3+}:\text{YVO}_4$ laser crystal with a dimension of $3 \times 3 \times 5 \text{ mm}^3$ and is doped with 0.5% Nd^{3+} . Laser crystal 11 is coated on both

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ends to replace the rear reflection mirror 13 and reduce insertion loss. The coating on the crystal end 23 facing the lenses is dichroic with high reflection at 1064nm and high transmission at 808nm, and the other end 25 is high-transmission coated at 1064nm.

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Laser crystal 11 is end-pumped with a laser diode array 20 that is coupled with an optical fibre cable 21. The maximum output power from the fibre cable 21 is 30W at 808nm and the temperature is set at 25° C. The pump beam from the fibre cable 21 is reshaped with a set of collimating and focusing lenses 22, which
10 reduce the beam waist size by about 1.8 times to < 0.45mm. The effective pump beam size incident on the laser crystal 11 is adjusted by moving lenses 22 along the optical axis to ensure that the laser operates in the fundamental mode.

The active Q-switching element 15 is an AO modulator.

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The passive Q-switching element 17 is a saturable absorber, being a commercially available bulk GaAs wafer with both surfaces mirror-polished. The GaAs wafer is un-doped and has an un-saturable absorption coefficient of 1.2 cm^{-1} measured with an UV-3901 spectrometer. Two samples of GaAs wafers were tested in
20 experiments having thicknesses of 0.625 mm and 0.5 mm, respectively. Although no significant conclusion can be drawn regarding the effects of the wafer thickness on the laser performance, it was found that the GaAs wafer with 0.5mm thickness gave better results.

25 A thermal electric cooler (TEC) 41 cools laser crystal 11 to reduce thermal effects. Thermal dissipation is well managed by wrapping laser crystal 11 tightly with thermally conductive films and inserting it into a matched rectangular hole in a much bigger heat sink, which is cooled effectively by the TEC 41. The temperature of both the diode array 20 and the heat sink is set at 20° C.

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Two typical pulse profiles emitting from the Q-switched laser of Fig. 4 are shown in Fig. 5 for different repetition rates of (a) 1 kHz and (b) 30 kHz, respectively. The effective cavity length is about 110 mm, the shortest that could be obtained due to the insertion of the AO modulator 15. The pump power was 20W. The pulse width measured was 4.2ns at 1kHz. The pulse width may be slightly reduced by decreasing the repetition rate or increasing the pump power. The shortest pulse width obtained was 3.72ns at 10Hz at the same pump power level of 20W. The pulse width increases linearly with the repetition rate, as shown in Fig. 5. In particular, in Fig. 5(b), the pulse width was 26.6ns at 30kHz.

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For comparison, separate experiments were performed on the individual Q-switching elements in the cavity each time, either the AO modulator 15 or the GaAs wafer 17.

- 15 In the case of the active Q-switching element AO modulator 15, the cavity length was 130 mm, slightly longer due to the use of a lens holder for a separate output coupler. The coupler was a flat-flat glass mirror with coating for 15% transmission at 1064 nm, optimised for the above cavity specifications and pump power. A flat surface was chosen for the coupler because the GaAs wafer had flat surfaces.
- 20 The pulse width from this AO Q-switched laser was around 20 ns at 1 kHz with an average power of 0.75 W. For a repetition rate of more than 10 kHz, the pulse width was usually larger than 100 ns with average powers over 3W.

- 25 In the case of the passive Q-switching element GaAs wafer 17, the cavity could have been shortened down to less than 50mm, which meant the pulse width could have been as short as 10 ns. At the set cavity length of 110mm, the pulses were usually long, about 400 ns, and had a repetition rate of around several hundred kHz.

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The maximum peak power observed for both cases was 37.5 kW, which occurred in the configuration using a purely active Q-switching element, the AO modulator 15.

- 5 It is noted that the average power in the mixed Q-switching was lower than that for the purely active Q-switching element, the AO modulator 15. This is because the GaAs wafer, acting as the output coupler, had a transmission of about 38%, which was higher than the optimum value of 15%.
- 10 Alternative configurations of the laser medium 11 can be constructed by persons skilled in the art. For example, rear mirror in Fig. 2 can be replaced by depositing a high reflection layer on the side of laser medium 11 facing rear mirror 13.

In conclusion, the mixed or doubly Q-switched solid state laser using an active Q-switching element and a passive Q-switching element simultaneously generated laser pulses with high energy, short duration and variable repetition rate. Furthermore, the combination of the output coupler and the passive Q-switching element in the one component advantageously compresses the pulse duration and allows for a simpler structure to be used to construct solid state lasers with mixed or double Q-switching.

It is understood that various modifications, alterations, variations and additions to the construction and arrangement of the embodiment described herein are considered as falling within the ambit and scope of the present invention.

The claims defining the invention are as follows:-

1. A Q-switched laser including a pump cavity, a laser medium in said pump
5 cavity for generating laser light, an active Q-switching element for
controlling Q-switching oscillation of laser light in said laser according to a
selected modulation rate, and a passive Q-switching element for Q-
switching oscillation of laser light in said laser according to selected
saturation characteristics of said passive Q-switching element.
- 10 2. The Q-switched laser according to claim 1, wherein the active Q-switching
element is located between the laser medium and the passive Q-switching
element.
3. The Q-switched laser according to claim 1 or claim 2 wherein both the
active Q-switching element and the passive Q-switching element are
15 located between the laser medium and an output coupler of the laser.
4. The Q-switched laser according to claim 1 or claim 2, wherein the passive
Q-switching element acts as an output coupler of the laser.
5. The Q-switched laser according to any one of claims 1-4, wherein the
passive Q-switching element is a saturable absorber.
- 20 6. The Q-switched laser according to claim 5, wherein the saturable absorber
is uncoated.
7. The Q-switched laser according to any one of claims 1-6, wherein the active
Q-switching element is an acoustic-optical modulator or an electrical-optic
modulator.
- 25 8. The Q-switched laser according to any one of claims 1-7, wherein the Q-
switched laser has a pump source for pumping light into the laser medium.

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9. The Q-switched laser according to claim 8, wherein the pump source side-pumps or end-pumps the laser medium.
10. The Q-switched laser according to claim 8 or claim 9, wherein the pump source is a laser diode, a laser diode array, an optic fibre coupled laser diode array or a flash lamp.
11. The Q-switched laser according to any one of claims 1-10, wherein the laser medium has a doped portion.
12. The Q-switched laser according to claim 11, wherein the doped portion is doped with at least one rare earth ion.
- 10 13. The Q-switched laser according to claim 12, wherein the rare earth ion is selected from one of Nd, Er, Ho, Tm, Pr, Cr and Ti.
14. The Q-switched laser according to any one of claims 1-13, wherein the laser medium is a laser crystal.
- 15 15. The Q-switched laser according to claims 14, wherein the laser crystal is selected from one of YAG ($\text{Y}_3\text{Al}_5\text{O}_{12}$), YAlO_3 , Al_2O_3 , YLF (LiYF_4), GSGG ($\text{Gd}_3\text{Sc}_3\text{Al}_3\text{O}_{12}$), GSAG ($\text{Gd}_3\text{Sc}_3\text{Al}_3\text{O}_{12}$), GGG ($\text{Gd}_3\text{Ga}_5\text{O}_{12}$), YVO_4 , glass, LaF_3 , BeAl_2O_4 or BaY_2F_8 .
16. The Q-switched laser according to any one of claims 1-15, wherein the laser medium is a composite laser crystal.
- 20 17. The Q-switched laser according to claim 16, wherein the composite laser crystal is a composite crystal of YAG ($\text{Y}_3\text{Al}_5\text{O}_{12}$), YLF (LiYF_4), or YVO_4 .