Laser Modeling In Q-switch Regime

Ivana Veselinovic[1], Milesa Sreckovic[2] and Biljana Veselinovic[3]

***Abstract* – A method which is often used to increase laser oscillator power and for obtaining short pulses consists of Q-switching (Q-spoiling method). The technique allows the production of laser pulses with extremely high (gigawatt) peak power. Some ways of laser cavity dumping by loss modulation (Q-switching) are analyzed in this paper. The chosen approach is performed used by numerical modeling.**

***Keywords* – Q-switching, Q-spooling, Laser cavity, Loss modulation.**

I. Introduction

We will analyze a mode of laser operation extensively employed for the generation of high pulse power which is known as Q-switching in this paper. The laser system should be designated to produce the adequate optical Q switch of the resonant cavity. The quality factor Q can be treated on various points of view. Generally speaking Q factor is defined as the ratio of the energy stored in the cavity to the energy loss per cycle.

In the technique of Q-switching, optical pumping energy is stored in the amplifying (active) medium while the Q factor is lowered to prevent the onset of laser emission. Although the energy stored and the gain in the active medium are high, the cavity losses are also high, lasing action is not possible. When a high Q is restored, the stored energy is suddenly released in the form of a very short pulse. Because of the high gain created by the stored energy in the active material, the excess excitation is discharged in an extremely short time. The peak power of the resulting pulse exceeds that obtainable from an ordinary long pulse by several orders of magnitude. Without Q modulation the dynamical lasing regime is in μs scale, (i.e. in free generation regime the spikes would be expressive). The theory of Q-switch regime is covered in numerous references [1-6], [9]. Some of them are based on five general laser equations. The principal facts are that the obtained pulses could be described by:

-triangle shape

- three characteristics zones.

Triangle shape for Q-switch pulse progress is presented in the Fig 1a.

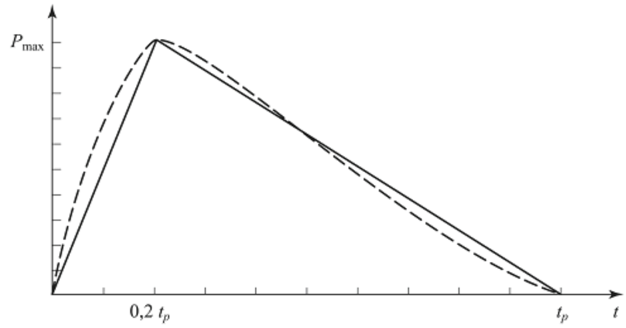

Fig. 1a. Triangle shape for Q-switch pulse progress

Three characteristic zones of pulse progress are shown in the Fig. 1b:

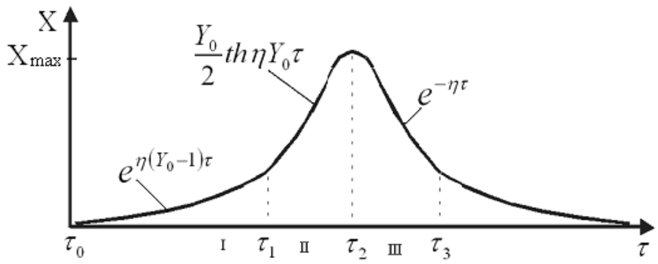

Fig. 1b. Three characteristics zones for Q-switch pulse progress

The most popular time cycle for Q-switching is shown in the Fig. 1c.

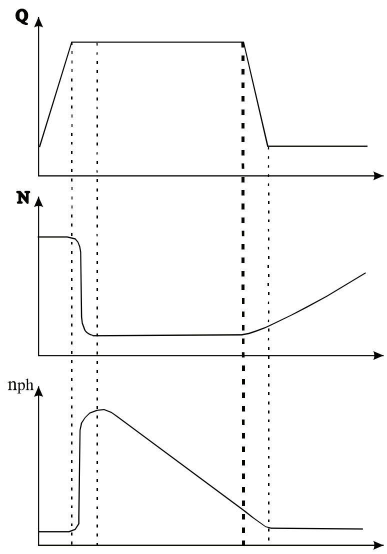

Fig. 1c. The most popular Q-switching cycle

[1]Ivana Veselinović, 11000 Beograd, Serbia, E-mail: ivancica1301@yahoo.com

[2]Milesa Srećković, Belgrade University, Dept. Electric Engineering, Bulevar Kralja Aleksandra 73, 11001, Belgrade, Serbia, Email: Milesa@Tesla.rcub.bg.ac.yu

[3]Biljana Veselinović, Vinča Institute of Nuclear Sciences, Laboratory of computer sciences, P.O. Box 522, 11001, Belgrade, Serbia, Email:bilja@vin.bg.ac.yu

Output power may be written as:

$$P = \frac{h\nu n_f}{\tau_c}, \quad (1)$$

General approach to max output power may be evaluated as:

$$P = n_{f\,\max}\frac{h\nu}{\tau_c} = \begin{cases} \frac{N_0}{2}\frac{h\nu}{t_c}, 3-level-system \\ N_0\frac{h\nu}{\tau_c}, 4-level-system \end{cases} \quad (2)$$

where N_0 is linked to inversion population.

II. Laser Cavity Dumping by Loss Modulation

Further, a method enabling to exceed the threshold carrier density in a laser will be described here. The method allows $n_{d0} \rangle\rangle n_{threshold}$. Because of that, during an initial period, the cavity losses α_c are artificially increased to maintain cold cavity conditions. The density [1] of electrons which occupy level $|2\rangle$ is given by Eq. 3:

$$n_2(t) = R\tau_2\left(1 - e^{-t/\tau_2}\right). \quad (3)$$

The T_a is made enough large so that the most of available states $|2\rangle$ become occupied ($T_a \approx n/R$, where n is the total density of emission centres). The reflectivity of the exit mirror can be considerably reduced by means of a Pockels cell. As a result, the quality factor Q of the cavity can be modulated or Q-switched. The inversion population density $n_i \approx n$ (i for initial) in level $|2\rangle$ at the end of the first low-Q cycle is very large in comparison to the clamped inversion density $n_{threshold}$ during laser emission (Fig. 2).

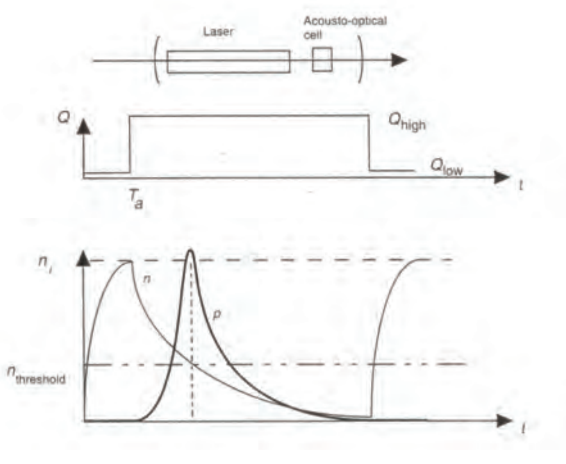

Fig. 2. Principle of laser cavity dumping by loss modulation (Q-switching)

In Fig. 2, between 0 and T_a, significant cavity losses are presented as a means of decreasing the Q factor of the cavity. That is achieved by using, acoustooptic, electrooptic and magnetooptic modulators or by mechanical modulation techniques.

While the Q of the cavity is artificially maintained at a value Q_{low}, the inversion population is build up to a value n_i exceeding the value of $n_{threshold}$ for the high-Q cavity. The Q-factor of the cavity is than restored to its original value of Q_{high}. The additional energy which is stored during the low-Q charging phase is released into a single giant pulse.

The same is true for the energy stored by the occupied states. The cavity is switched to a high-Q value, by restoring the high reflectivity of the mirrors, for example. Simplifying elementary equations for EM field [1], the energy stored in the cavity is released as:

$$\frac{d}{dt}Y = (X - 1)Y, \quad (4\text{ a})$$

$$\frac{d}{dt}X \approx -XY. \quad (4\text{ b})$$

To simplify, we will suppose that the lifetime of level $|2\rangle$ remains very large in comparison with the photon lifetime. The Eq. 4 may be written as:

$$\frac{d}{dt}Y = (X - 1)Y, \quad (5\text{ a})$$

$$\frac{d}{dt}X \approx u(X_0 - X) - XY. \quad (5\text{ b})$$

Dividing (5 a) with (5 b), we obtain:

$$\frac{dY}{dX} \approx \frac{1}{X} - 1, \quad (6)$$

which may be integrated and written as:

$$p = n_{threshold}\ln\frac{n_d}{n_i} - (n_d - n_i). \quad (7)$$

The photon density is at a maximum when $dp/dt = 0$ in Eq. 5, i.e. when $n = n_{threshold}$:

$$p_{\max} = n_i\left(1 + \frac{n_{threshold}}{n_i}\ln\frac{n_{threshold}}{n_i} - \frac{n_{threshold}}{n_i}\right) \approx n_i, \quad (8)$$

when $n_{threshold} \langle\langle n_i$. That is often the case. We will now calculate the increase in maximum power of the laser relative to its stationary operation. The number of photons available in the cavity (p_{cw} where CW refers to continuous wave) without Q-switching, may be written as:

$$p \approx p_{sat} \frac{n_{d0}}{n_{threshold}} = \frac{\tau_c}{\tau_{sat}} n_{d0} \approx \frac{\tau_c}{\tau_2} n_{d0} = R_2 \tau_c, \quad (9\text{ b})$$

or $p_{cw} = R\tau_c$, where τ_c is the photon lifetime in the high-Q cavity and R is the pump rate. The maximum photon density (p_{QS}) achieved by Q-switching is given by Eq. 8 or

$$p_{QS} = n_i = RT_a, \quad (9)$$

where $n_i \approx n$ is the total density of the emission centres. The time T_a is fairly close to the lifetime τ_2. Than, the ratio of the CW exit power to the Q-switch power is (Fig.3.):

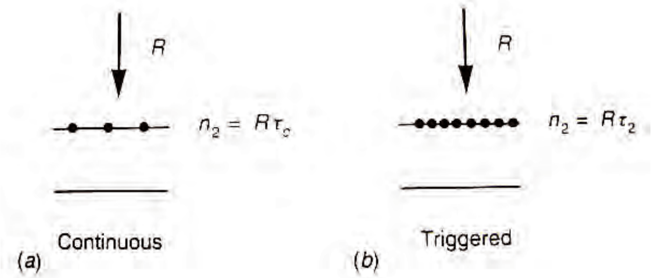

Fig. 3. Simplified comparison of the CW output power to the Q-switch power: (a) continuous (CW) mode, (b) Q-switched mode

In a laser operating in a continuous (CW) mode (a), the maximum density of electrons in the excited state is given by the threshold density value which is determined by photon lifetime in the cavity τ_c. In Q-switched mode (b), the maximum electron density is determined by carrier lifetime in the excited state τ_2, and can be considerably larger than τ_c.

$$\frac{P_{QS}}{P_{CW}} = \frac{n_i}{n_{threshold}} \approx \frac{\tau_2}{\tau_c} \rangle\rangle 1. \quad (10)$$

The lifetime τ_2 is generally of the order of 1 ms and τ_c is generally of the order of 1 ns. Because of that, we can conclude that the ratio given in Eq. 10 may become considerable. The peak output power of the pulse is precisely given by the product of half the internal photon density (we divide by two as only those photons moving in the direction of the exit mirror are to be considered) with and the transmittance T_s of the output mirror the cross-sectional area A of the laser cavity:

$$P_{QS} = h\upsilon \frac{c}{2} T_s A n_i. \quad (11)$$

The length of the laser pulse may be calculated by numerically integrating the non-linear differential Eq. (5).

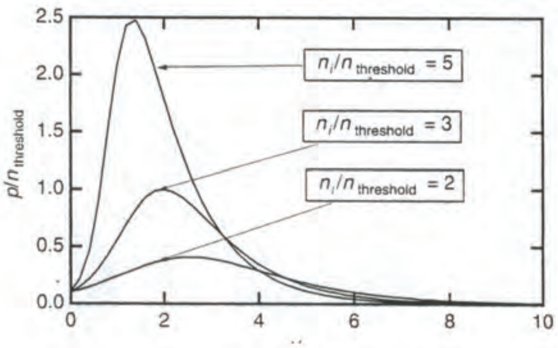

Fig. 4. $p/n_{threshold}$ in function t/τ_c in Q-switched laser mode for various values of $n_i/n_{threshold}$ above threshold

III. Results of program P1

Analyzing references [1-9] we will present a program which allows to obtain dynamic behavior of a Q-switched laser, written for MATHEMATICA.

As the Eq. 5 has a zero photon density as an initial condition (Y(0) = 0), it enforce as acceptable solutions the time-independent inversion population X(T) = X(0) and zero photon density Y(T) = 0. As shown in Fig. 4, we have had to put artificial initial conditions (Y(0) = 0.1) to simulate the effect of Q-switching. This points up the physical necessity of spontaneous emission in triggering laser oscillations. The program P1 allows calculation of the temporal response of a laser to modulated cavity loss. It is written assuming that X(0) = 4.

P1. Mathematica program which allows to obtain Q-switched laser dynamics

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eq1 = y'[t] == y[t] (x[t] - 1);
eq2 = x'[t] == -x[t] y[t];
sol = NDSolve[{eq1, eq2, x[0] == 4, y[0] == 0.1},
   {x[t], y[t]}, {t, 0., 10}];
plot23 = Plot[Evaluate[y[t] /. sol],
   {t, 0, 10}, PlotStyle → {RGBColor[0, 1, 1]},
   DisplayFunction → Identity];
Show[plot23, DisplayFunction → $DisplayFunction]
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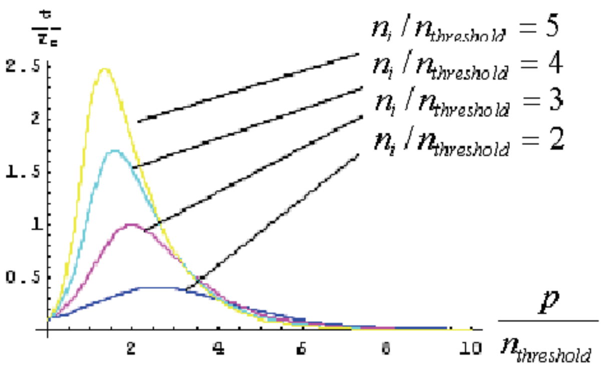

Fig. 5. Results of program P1

IV. Analysis of Results

Fig. 5. gives four examples from which we conclude that the typical pulse lengths are of the order of a few photon lifetimes (a few τ_c), i.e. tens of nanoseconds for laser cavities [1] measuring a few centimeters in length. Loss modulation in the cavity can be achieved without external application of electrical pulses to an optical shutter, for instance. Beside mentioned electrooptics and mechanical ways, this can be achieved by placing a saturable absorber in the laser cavity, too. The introduction of such a passive element will result in spontaneous Q-switching of the cavity. At the beginning of the cycle, the absorbing characteristics of the material lower the Q factor of the cavity. During that time electrical energy is stored in the cavity by increasing the electron density in the excited level. When the medium saturates, the cavity losses are reduced and stimulated emission proceeds to liberate the stored energy in the carriers into the form of an optical pulse with high-power (giant pulse).

V. Conclusion

Some methods for pulse shortening by Q-switch methods are analyzed in this paper. Laser cavity dumping by loss modulation (Q-switching) was chosen for analyze in this paper. A program which allows to obtain dynamic behavior of a Q-switched laser has been written for MATHEMATICA. The results from reference are agreed with other references, and for given domains program works. We analyzed various approaches to Q - switch regime, qualitative description and variation of Lamb theory.

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