A STUDY OF SOLID STATE LASER PASSIVE OPTICAL Q-SWITCHING OPERATION REGIME (Part 1)

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Abstract

This paper is the first of a four series treating, theoretically with experimental comparison, the issue of solid state laser passive optical Q-switching regime. In this first paper the technique of solid state lasers passive optical Q-switching is numerically investigated considering the case of longitudinally and transversally uniform photon, population inversion and absorption centres densities. The coupled differential equations defining photon, population inversion and absorption centres densities are numerically solved being the basis of passively optical Q-switched laser functional simulation. The numerical simulations are performed using the several software packages, mostly SCILAB programs. The developed SCILAB programs can be used for a large range of saturable absorption centre and active media parameters, mainly the initial (low signal) optical transmittance of the passive optical Q-switch. The developed FORTRAN and SCILAB programs can be applied for passively Q-switched solid state lasers of several types emitting at several NIR wavelengths, in domain $1 \div 2 \ \mu m$. For validating the numerical simulation results are compared with The results of the numerical simulation are compared with experimentally obtained ones, in the case of a $LiF:F_2^-$ passively Q-switched Nd:YAG. A good agreement between the two kinds of results is observed.

Keywords: solid state laser, passive optical Q-switching, nonlinear absorption, second harmonic radiation, Scilab

1. Introduction

This paper treats an important feature of solid state laser engineering: determining the fundamental mode parameters of the laser cavity under real pumping and Q-switching condition. It is one of the oldest and still vital problems in laser physics. This feature is important regarding the various possible medical, industrial and military applications. Since mid - sixties various approaches were tried regarding computer numerical simulation of Q-switched solid state lasers operated using different techniques.

In this paper the passive optical Q-switching of solid-state lasers is investigated by numerically solving a system of coupled differential equations considering the case of spatially uniform photon, population inversion and absorption centre densities inside a laser resonator. The system of coupled differential equations defines the time variation of population inversion and absorption centre densities inside a laser resonator. The numerical simulation is performed mainly using FORTRAN and SCILAB developed programs and compared with results obtained using several other software packages.

The main purpose of performed activities consists into the development of laser functional simulation techniques which can be used for various solid state laser active media and saturable absorbers. The functional simulation techniques are dedicated to functional simulation of both main types of solid state lasers: with fixed output wavelength, such as Nd:YAG, Nd:Glass (phosphate or silicate) coupled with chromium ions doped crystals or colour centres passive optical Q-switches and with tuneable output

wavelength, such as passively optical Q-switched $Cr:BeAl_2O_4$ lasers. The developed functional numerical simulation techniques are also applicable for solid state lasers continuous or pulsed flash lamp or diode pumped operated in passive optical Q-switching regime. The developed SCILAB program can be used for a large range of saturable absorber centre parameters, mainly the initial (low signal) optical transmittance.

Two forms, two versions of the system of coupled differential equations were considered:
- The "natural form", meaning that all coefficients appearing in the differential equations are defined with more or less experimental accuracy for a given laser resonator under investigation;
- The "normalized form", meaning that all numerical coefficients and unknown functions are normalised to a constant parameter of the studied laser resonator.

The above mentioned versions of the coupled differential equations system were used considering the possible software and hardware problems appearing in numerically solving these differential equations. These problems are related to the binary representation of numbers inside the electronic calculator used for the main purpose of the presented paper. The conclusions regarding these aspects are also mentioned.

2. Theory

In Figure 1 the schematic of a passively Q-switched solid state laser setup is presented. In practice, depending upon the specific laser active medium and pumping technique, there are little

differences between such laser configurations. Related to this experimental setup one problem to be solved consists in defining a system of coupled differential equations describing laser parameters of interest time evolution.

The laser parameters of interest are:

$n(t)$ - photon density;

$N_g(t)$ - laser active medium population inversion density;

$N_a(t)$ – passive Q-switch saturable absorber ground-state population density.

A number of approximations are made regarding this system of differential equations, among which the most important consists in considering the laser parameter as spatially uniform inside laser resonator, having no longitudinal or radial variations versus optical axis.
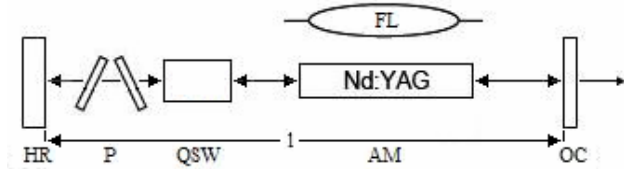

Fig.1- Schematic of a passively Q-switched solid state laser setup.

HR - High Reflectivity Mirror (~100%); P – Polarizer (two quartz plates placed at Brewster angle); QSW - Q-Switch crystal; AM - Nd:YAG Laser Active Medium; FL – Pumping Flash Lamp; OC - Output Coupler (Mirror)

In Figure 2 a second important feature of the presented attempt of laser functional simulation model is presented, namely the energy-level diagram applicable for the laser active medium and for the passive optical Q-switch. For both laser components a modified 4-energy level diagram with the possibility of excited-state absorption was used for describing their functions.
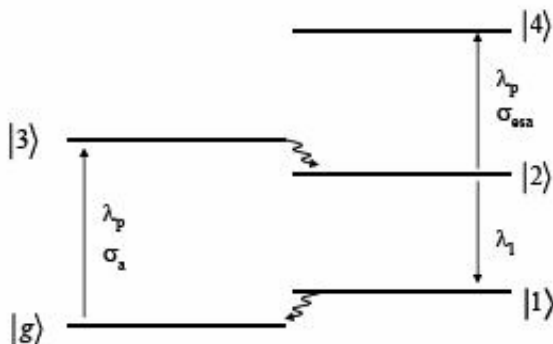

Figure 2 – The diagram of energy levels used for the active medium and saturable absorber.

$|g\rangle$- ground-state energy level; $|1\rangle$- first state energy level; $|2\rangle$- second state energy level; $|3\rangle$- upper energy level; $|3\rangle$- higher energy level; σ_a - ground-state absorption cross section; σ_{esa} - excited-state absorption cross section.

The following rate equations were used as the "natural form", in order to model a solid-state laser passively Q-switched by a saturable absorber centre system having excited state absorption [3]:

$$\frac{dn}{dt} = K_g N_g n - K_a N_a n - \beta K_a (N_{a0} - N_a)n - \gamma_c n \quad (1)$$

$$\frac{dN_g}{dt} = R_p - \gamma_g N_g - \gamma K_g N_g n \quad (2)$$

$$\frac{dN_a}{dt} = \gamma_a (N_{a0} - N_a) - K_a N_a n \quad (3)$$

In Equations (1), (2) and (3), besides the above defined time varying laser parameters, several other material and resonator constants and parameters are additionally introduced, namely:

- K_g is the coupling coefficient for laser photons and active centres, defined as

$$K_g = 2 \cdot \sigma_g / \tau_r \cdot A_g \quad (4)$$

(σ_g - laser emission cross section; A_g - the effective laser beam area in the active medium; τ_r - cavity round –trip transit time);

- K_a is the coupling coefficient for laser photons and passive saturable absorber centres, defined as

$$K_a = 2 \cdot \sigma_a / \tau_r \cdot A_a \quad (5)$$

(σ_a - saturable absorber ground-state cross section; A_a - the effective laser beam area in the saturable absorber);

- R_p is the pumping rate of the active medium;

- γ_c is the effective laser cavity decay time;

- γ_g is the effective decay rate of the upper laser level;

- γ is a coefficient depending on active medium ener-gy-level diagram (2 for three energy-level case, 1 in the four level case);

- γ_a is the effective saturable-absorber relaxation rate coefficient, ;

- β is the ratio of excited state absorption cross section to ground state absorption cross section, defined as:

$$\beta = \sigma_{esa} / \sigma_a \quad (6).$$

The system of differential equations (1), (2) and (3), are numerically solved in order to define the behaviour of a specific Q-switched laser system. However, important characteristics of a passively optical Q-switched laser system can be found from

analyzing these three coupled rate equations. In some specific cases, e.g. use of high contrast passive optical Q-switches, numerical simulation results obtained by solving approximations of the studied differential equations can be observed and compared with those obtained by solving the differential equation system. The results of this comparison are good enough, denoting an acceptable agreement between the observed results.

It has to be emphasized that the developed numerical simulation method can be used to describe solid state lasers operated in Q-switching regime of other types than the Nd:YAG one used for validation by comparison and for other pumping technologies (cw and diode).

The most important verification of the numerical simulation results consist in comparison with experimentally data observed for investigated laser emit-ters by the authors or published in literature. In this aspect, the attention was focused on two main laser output parameters: light pulse half measure time width (FWHM) and its energy.

The results of the numerical simulation are in good agreement with experimental data, mainly regarding laser pulse half measure time width (FWHM).

3. Results

The results of the computer analysis are presented in Figures 3, 4 and 5. In Figure 3 the computer simulated laser photon density time evolution is presented. Its half amplitude time width is in good agreement with the experimentally observed value of ~5 ns, which is presented in Fig.7. The simulated laser pulse time shape is symmetric and in agreement with theoretical predictions [1]. In Figure 4 the time variation of computer simulated population inversion density in the active medium is shown.

In Figure 5 the computer simulation of absorption center density in the passive optical Q-switch crystal time variation is presented.

The system of differential equations (1), (2) and (3) is numerically solved using the SCILAB specialized solvers. Basically, this solver is based on a Runge-Kutta-Fehlberg algorithm [1 – 4]. It's most important feature consists into an efficient balance between the software tolerance and the need of using a variable time step of integration.

An important problem to be solved in order to perform a numerical simulation as correct as possible consists in using a fine time step during the Q-switching start, when laser intensity is abruptly

growing, while a larger value of this parameter is needed on the tail of the laser pulse.

Use of a very fine time step means to overload the computing system, to overload its memory capacity. The solution to this problem seems to be concerning the ability of the software package and computing system to efficiently binary represent the numbers with different rate of change on a given number of bits.
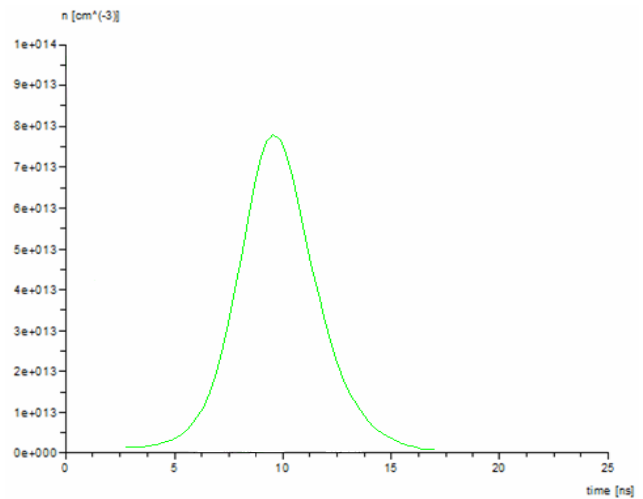

Fig. 3 - The computer simulated laser photon density. Its half amplitude time width is in good agreement the experimentally observed value of ~5 ns. The simulated laser pulse time shape is too abrupt, being different in comparison with the experimentally observed one, of ~ 1ns. Laser emission wavelength $\lambda_L = 1.06 \ \mu m$ $[R_p = 4.50*10^{21} \ s^{-1}]$
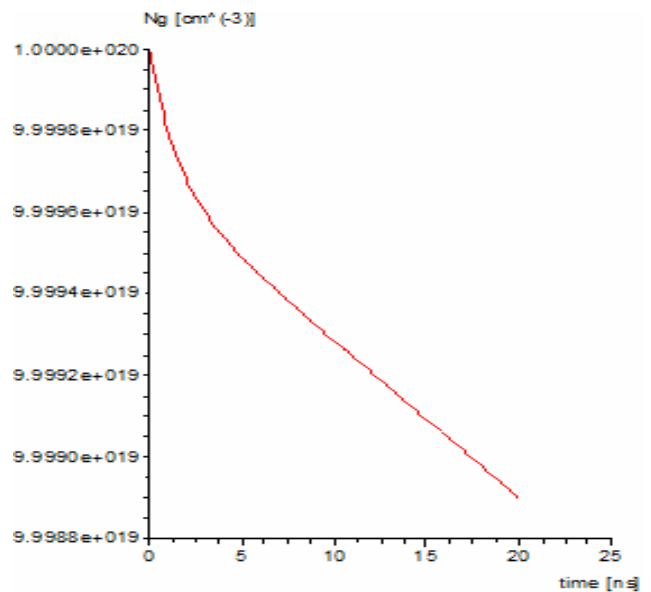

Fig. 4 - The computer simulated population inversion density in the active medium during laser pulse emission.
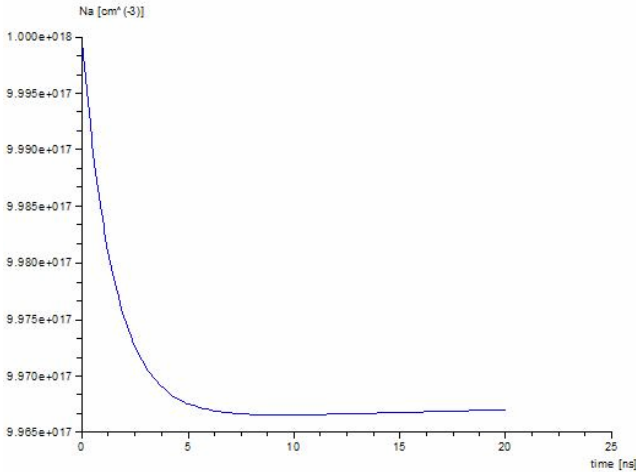
Fig. 5 - The computer simulated time variation of absorption centers population density in the passive optical Q-switch crystal.

In Fig.6 the experimentally observed variations of laser output energy (in free running and Q-switched regimes) vs. pumping energy are presented. The experiments were performed on the experimental setup presented in Fig.1 and using a LiF:F_2^- Q-Switch crystal (denoted as sample C0074). Sample C0074 was obtained by successive 7MeV high energy electrons and Co^{60} γ ir-radiations of Φ9×76 mm LiF crystals grown by Czochralski method. The laser output energy was measured using a Quantronix 504B energy meter and monitorized with a ROL 71 photodiode operated in photoconductive regime. The observed value of single pulse laser output energy was of ~235 mJ.
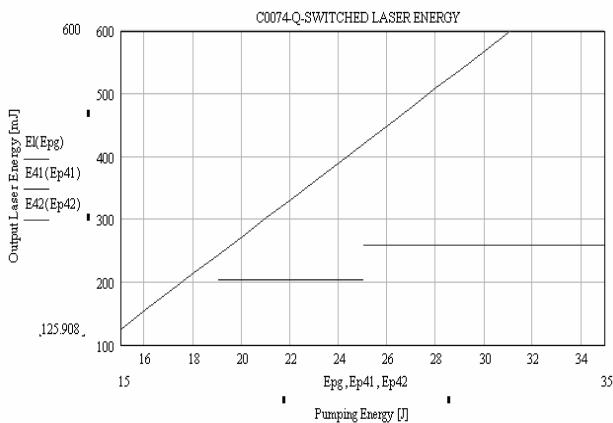

Figure 6. - The experimentally observed variations of laser output energy (in free running and Q-switched regimes) versus pumping energy.

In Figure 7 the experimentally observed laser pulse time shape is presented. The laser pulse time shape was measured using an ITT F4014 vacuum photodiode mounted on a Tektronix 519

oscilloscope. The response time of this measuring system was estimated as ~ 1 ns. The laser pulse time shape was measured using an ITT F4014 vacuum photodiode mounted on a Tektronix 519 oscilloscope (1GHz bandwidth).
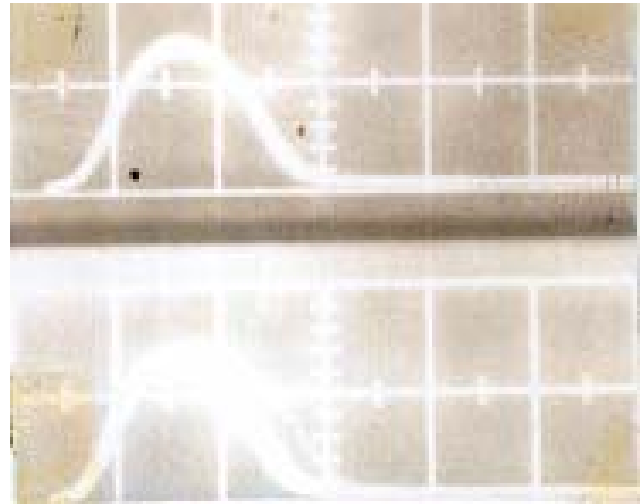

Figure 7 - The experimentally observed laser pulse time shape. The oscilloscope time per division is of 5 ns. The first laser pulse time shape was obtained for a singular laser shot. The second was obtained for five successive laser shots superposed on the same photo snapshot.

4. Conclusions

A set of programs dedicated to computer simulation of passively Q-switched solid state lasers is presented. It is validated by comparison with experimentally obtained data.

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