Nonconventional Technologies Review
Romania, March, 2012

THEORETICAL ANALYSIS OF A PASSIVELY Q-SWITCHED ERBIUM DOPED FIBER LASER

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ABSTRACT: In this paper preliminary results obtained in numerical simulation of various aspects regarding passively Q-switched high power Er^{3+} fiber lasers are presented. The developed numerical analysis has the aim of a better understanding of high power fiber laser pointing to their possible applications in sensing and telecommunications. The numerical simulations are performed for passive Q-switches cells made of Co^{2+} and U^{2+} (uranyl) doped in different crystalline and phosphate glass hosts. The difference between the initial conditions for the first output laser pulse and the rest of the output pulses train is investigated and its significance has to be underlined.
KEY WORDS: passive optical Q-switching, numerical simulation, rate equations, Er^{3+} fiber laser, Co^{2+} passive Q-switch cell, U^{2+} passive Q-switch cell.

1. INTRODUCTION

Fiber lasers operated in passive Q-switching regime became, in the last fifteen years, quantum oscillators of increasing interest for a wider range of applications. This paper is presenting results obtained in numerical simulation of CW diode pumped erbium doped fiber laser oscillators, operated in passive optical Q-switching regimes using several possible Q-switch cells made of bulk crystals doped with rare earth ions.

Since recently, single mode optic fibers, mostly of them having the core doped with erbium ions Er^{3+} as laser active centers were operated as amplifiers used extensively in telecommunications for long range signal transmission and for various other applications. Such doped optic fibers are pumped with laser diodes which are usually operated as signal sources. Fiber amplifiers have the necessary conditions to be easily transformed into oscillators, pumped with adequate laser diodes and operated in free-running regime. For properly design optoelectronic devices of this type, a numerical simulation procedure is useful. Numerical simulation results referring to passive optical Q-switching of Er^{3+} doped fiber optic lasers are presented in Section III. These numerical simulations are performed aiming to obtain an improved design methodology of this class of laser oscillators.

As in the case of solid state lasers, the next step in evolution of such devices is to operate them in Q-switching regime. Erbium doped optic fiber lasers operated in Q-switching regime have found various applications in various fields such as communications, reflectometry, distributed fiber optical sensing and so on. Like solid state lasers, there are two methods, active and passive, to enforce a laser to generate giant pulses. Actively Q-switched fiber lasers are well known, wide spread and intensively investigated. However, all actively Q-switched lasers contain bulk elements, which make their design rather complicate and costly. That is why attention of researchers is recently attracted to develop passively Q-switched erbium fiber lasers with a saturable absorption cell, physically a crystal; even un-pumped, un-excited erbium doped optic fiber inside the cavity. Such lasers have a set of conclusive advantages comparing the actively Q-switched ones: they have smaller size, simplicity of the design, and principal opportunity of performance as all-fiber devices. Because of few existing atomic scale entities with spectral saturable absorption characteristics, there are only reduced number approaches to realize the passive Q-switch mode of operation in a fiber optic erbium lasers: laser with distributed back-scattering [1], laser with a gallium liquefying mirror, laser with a saturable absorber semiconductor structure functioning as a mirror (SESAM) [2-3]. In Section III an all-solid-state erbium fiber optic laser operated under CW pumping in passive optical Q-switch operation using a Co^{2+}:ZnSe, Co^{2+}:Phosphate Glass, uranyl (UO_2^{2+}) doped various hosts is investigated.

2. THEORY

A schematic representation of the investigated passively optical Q-switched Er^{3+} doped optic fiber laser oscillator, in a such general form as can be considered correct, can be observed in figure 1. The most common case, the case of a single mode optic fiber having the core doped with Erbium ions (Er^{3+}) as the laser active centers is investigated [4].

The active medium of the investigated laser oscillator consists of an Er^{3+} doped optic fiber, which can be considered as an EDFA – Erbium Doped Fiber Amplifier [15]. Pumping of an EDFA is performed using a laser diode, the single technology reported in literature. In the presented theoretical analysis the pumping wavelength plays an important role. EDFA pumping is mostly performed by using two wave-lengths: 980 nm or 1480 nm. A preliminary analysis of EDFA pumping can be made on considering the Boltzmann population ratio, β, defined as:

$$\beta = \frac{N_3}{N_2} = e^{-\left(\frac{\Delta E}{kT}\right)} \qquad (1)$$

where N_2 is the population density of the upper laser level, N_3 is the population density of the pumping band, ΔE is the energy difference between these two Er^{3+} electronic levels, k is the Boltzmann coefficient and T is the temperature of the active medium. In considering equation (1), several parameters are useful to be defined: N is the Er^{3+} concentration, N_1 is the population density of the lower laser level.

For performing a proper analysis of "pros" and "cons" between these two pumping wavelengths several criteria can be considered:

A - Boltzmann population ratio – β_{1480} = 0.38 while $\beta_{980} \sim 0$. This means an advantage for 980 nm pump wavelength.

B - The comparison can be done by using the relation

$$\left(\frac{N_2 - N_1}{N}\right)_{\max} = \frac{1-\beta}{1+\beta} \tag{2}$$

The net result is that, at the same pumping power, maximum gain for 1480 nm is 0.45 of that obtained by using 980 nm.

C - The amplified spontaneous emission (ASE) noise is proportional to n_{spon} defined as:

$$n_{spon} = \frac{N_2}{N_2 - N_1} \tag{3}$$

For a continuous wave (cw) pumping with a laser diode emitting at a wave-length of 980 nm or 1480 nm, in the stationary case (d/dt =0), the system of coupled rate equations (1), (2) and (3) reduces to an algebraic one which can be easy solved. After some algebraic calculus, several important parameters which characterize the Er3+ doped optic fiber can be defined. The "β" factor is defined in the condition of a low value of lifetime τ_{32} value, of ~ ps range, which corresponds to a fast $E_3 \rightarrow E_2$ transition of phonon emission.

Among the parameters characterizing the Er^{3+} doped optic fiber amplifier and, implicitly, as a cw emitting laser is the relative population inversion (ΔN/N) defined as:

$$\frac{\Delta N}{N} = \frac{N_2 - N_1}{N} = \frac{(1-\beta)W_P\tau_{21} - 1}{(1+\beta)W_P\tau_{21} + 2W_S\tau_{21} + 1} \tag{4}$$

The maximum value of the relative population inversion is defined as:

$$\frac{\Delta N_{\max}}{N} = \frac{(1-\beta)W_P\tau_{21} - 1}{(1+\beta)W_P\tau_{21} + 1} \tag{5}$$

Using the maximum value of the relative population inversion in equation (4), a relation using the saturation value of signal transition probability is defined as:

$$\frac{\Delta N}{N} = \frac{\Delta N_{\max}}{N} \frac{1}{1 + \frac{W_S}{W_S^{Sat}}} \tag{6}$$

The saturation value of signal transition probability is defined as, τ_{21} being the lifetime of transition $E_2 \rightarrow E_1$:

$$W_S^{Sat} = \frac{1}{\tau_{21}}\left(1 + \frac{1+\beta}{1-\beta}\frac{W_P}{W_P^{th}}\right) \tag{7}$$

The threshold value of the pumping transition probability is defined as:

$$W_P^{th} = \frac{1}{(1-\beta)\tau_{21}} \tag{8}$$

The above defined parameters are used for analyzing the operation of continuous wave emitting Er^{3+} optic fiber lasers.

The starting point of the numerical investigation of model is a system of differential coupled laser rate equations [5-15]. This system of differential coupled laser rate equations is valid for a quasi-three level active medium (Er^{3+} ions doped optic fiber) and a generalized two-level saturable absorber Co^{2+} or U^{2+} doped in ZnSe, $MgAl_2O_4$ (spinel) or other crystalline or glass hosts, denoted as Saturable Absorber (SA) in the followings.

The operation of the investigated laser system can be defined using a system of three coupled differential equations [5-22]:

$$\frac{d\phi}{dt} = \frac{\phi}{\tau_r}(2\sigma_g l_g N_g - 2\sigma_a l_a N_a + \ln(R_1 \cdot R_2) - L) + S \tag{4}$$

$$\frac{dN_g}{dt} = -c\sigma_g l_g \phi N_g - \frac{N_g}{\tau_g} + R_p \tag{5}$$

$$\frac{dN_a}{dt} = -c\sigma_a l_a \phi N_a + \frac{N_{ao} - N_a}{\tau_a} \tag{6}$$

In equations (4-6) the following parameters of the investigated laser system are introduced:

ϕ - the photon density;

N_g - the population inversion density;

N_a - the instantaneous population density of the SA ground absorbing state;

N_{a0} - the total population density of the SA;

l_g - the length of the gain medium;

l_a - the length of the SA;

c - the speed of light;

R_p - the pumping rate of the active medium;

R_1 - the reflectivity of the rear, high reflectance laser mirror;

R_2 - the reflectivity of the output coupler;

L - the round trip dissipative optical loss;

σ_g - the stimulated emission cross sectional area of the gain medium;

σ_a - the ground state absorption cross section of the SA;

τ_r - the round trip transit time in the laser resonator;

τ_g - the lifetime of the upper laser level of the gain medium;

τ_a - the lifetime of the SA excited state.

The round trip transit time of the laser resonator, parameter which appears in equation (2) is defined as:

$$\tau_r = \frac{2l_r}{c} \tag{7}$$

where l_r is the optical resonator length. The pumping rate density into the upper laser level rate, R_p [$Wcm^{-3}s^{-1}$], appearing in equation (2) is approximated in the specific case of investigated laser configuration as [5-22]:

$$R_p \approx \frac{P_p}{h\nu A_g l_g} \tag{8}$$

where P_p is the pumping power, A_g is the area of the Er^{3+} doped optic fiber active medium core area and $h\nu$ is the energy of a laser photon. This approximation is considered as analyzing the Er^{3+} doped optic fiber active medium 980 nm emitting pumping laser diode. The basic observation concluded by performing this analysis consists in the fact that the Er^{3+} doped optic fiber can be considered as uniformly pumped, i.e., a uniform, constant R_p value is attained at pumping energy values of interest. As can be noticed in figure 1, the 980 nm pumping diode laser is coupled at one end facet of the optic fiber. As a net result, the Er^{3+} doped optic fiber is uniformly illuminated with pumping radiation from one end.

For defining output Q-switched laser pulse energy, E_{out}, peak power, P_{out}, and FWHM pulse width, τ_{out} the following relations can be used [5-8]:

$$E_{out} = \frac{-h\nu A_g l_g}{\tau_r} \ln(R_2) \int_0^{\infty} \phi(t) dt \tag{9}$$

$$P_{out} = \frac{-h\nu A_g l_g}{\tau_r} \ln(R_2) \phi_{\max} \tag{10}$$

$$\tau_{out} \approx \frac{E_{out}}{P_{out}} \tag{11}$$

In equations (6-8) A_g is the active area of the beam in the laser medium, $h\nu$ is the laser photon energy and $\phi_{\max}$ is the maximum photon density in the laser cavity [5-7].

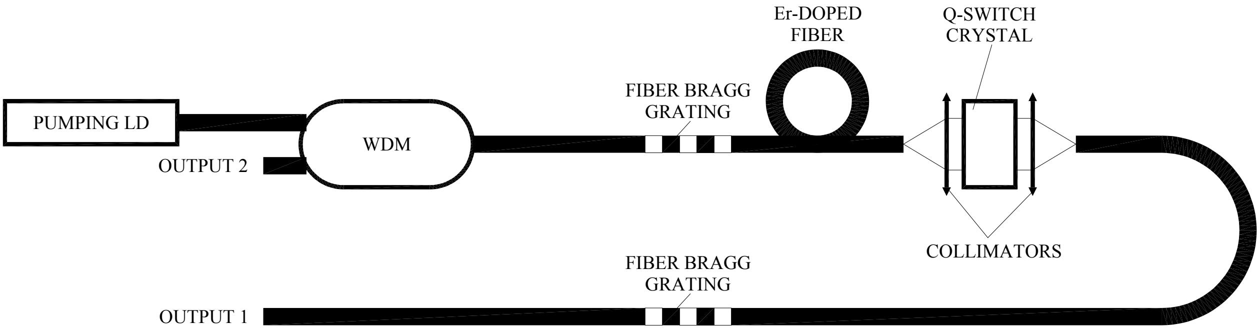

Figure 1. Schematic representation of the investigated passively Q-switched Er^{3+} doped fiber laser. PUMPING LD - the 980 nm pumping laser diode, WDM - wavelength demultiplexer, FIBER BRAG GRATING - two Bragg optical fibers used as laser mirrors, one with 90% reflectivity, the second with 98% reflectivity, Er-DOPED FIBER - the laser active medium; Q-SWITCH CRYSTAL - the passive optical Q-switching cell; COLLIMATORS - two collimation lens.

An important issue to be considered when designing a CW or quasi-CW pumped laser operated in passive Q-switching regime is the time necessary to build up the first Q-switched laser pulse from starting the pump of the gain medium, T_1, correlated with the pulse repetition frequency f_r. T_1 is defined as [5-7]:

$$T_1 = \tau_g [\ln(R_p \tau_g) - \ln(R_p \tau_g - N_{gi0})] \tag{12}$$

N_{gi0} in equation (9) denotes the initial value of the population inversion in the active medium before the start of the first passive optical Q-switching process. In this equation it can be noticed that T_1 is different from the time interval between two successive laser pulses, the pulse repetition frequency f_r, because the population inversion density starts from different values for the first pulse and for the following ones. Because it is of a very low intensity value in comparison with Q-switched laser pulses, fluorescence emission of the active medium can be neglected, can be considered as having a minor contribution at the first passive optical Q-switch threshold condition, N_{gi0} can be defined as [14,15,22]:

$$N_{gi0} = \frac{2\sigma_a l_a N_{a0} - \ln(R_1 \cdot R_2) + L}{2\sigma_g l_g} \tag{13}$$

After emission of the first laser pulse, a residual population inversion remains in the active medium, N_{gfin}. This residual value of population inversion has to be considered in defining the population inversion density immediately before an output pulse, which is given by:

$$N_{gi} = N_{cw} - (N_{cw} - N_{gfin}) \exp(-T_2 / \tau_g) \tag{14}$$

N_{gfin} can be defined as a function of the first laser pulse output energy and initial value of population inversion as [5-7,14,15,22]:

$$N_{gfin} = \frac{-E_{out}}{h\nu A_g l_g \ln(R_2)} - N_{gi0} \tag{15}$$

N_{cw} is the population inversion density for the same system if continuously pumped and is defined as [5-7]:

$$N_{cw} = R_p \tau_g \tag{16}$$

The time interval between two successive laser pulses, practically the pulse repetition frequency, T_2, is defined as:

$$T_2 = \tau_g [\ln(R_p \tau_g - N_{gfin}) - \ln(R_p \tau_g - N_{gi})] \tag{17}$$

Equations (11-13) can lead, as a logical consequence, to the condition necessary to be fulfilled in order to obtain a single output passively Q-switched laser pulse per pump pulse of a time length τ_p can be defined as [5-7]:

$$T_1 < \tau_p < T_1 + T_2 \tag{18}$$

An additional condition has to be added to the system of simple mathematical relations on which a method of high energy passively Q-switched Er^{3+} doped optic fiber laser analysis is based. This additional condition expresses simply the fact that the SA centers are preferable to be in the passive Q-switch cell ground energy level in order to accurately define N_{gfin} using equation (12). Basically, the fluorescence lifetime of the excited energy levels of SA centers has to be much shorter than T_2.

As a concluding remark of Section 2, regarding a numerical simulation/analysis method, procedure dedicated to design of a high energy passively Q-switched the Er^{3+} doped optic fiber laser, the followings can be noticed:

- Numerical integration of coupled rate equations (4-6), when using initial condition of the population inversion density defined as in equation (14), can give information about the output laser pulse time shape (FWHM time width), energy and the value of residual population inversion density remaining in the active medium after the laser pulse emission.

- The previously mentioned value of residual population inversion density can be used for solving equations (14) and (16) in order to define the initial condition of the population inversion density for generation of second and the following laser pulses, implying the possibility to define with increased accuracy the output laser pulses train time shape.

3. NUMERICAL SIMULATION RESULTS

In performing the numerical simulations using the method defined in Section 2, some of the parameters of the investigated Er^{3+} doped optic fiber laser were kept constant at varying types of passive Q-switch cells. In order to be define specific details, the constant parameters of the investigated laser system are: reflection coefficients of the two coupled Bragg fiber output mirrors are R_1 = 90 % and R_2 = 95 %; the length of the Er^{3+} doped optic fiber active medium is l_g = 1500 cm; the fluorescence lifetime of the Er^{3+} ions upper energy level is τ_g = 10 ms; the emission cross section of Er^{3+} ions is $\sigma_g = 0.7\cdot10^{-20}$ cm^2; the Er^{3+} ions doped optic fiber core diameter is Φ_g = 6.5 µm. The emission spot in the active medium and in the passive Q-switch cell is considered as Φ_g. The CW pumping power was considered as variable, numerical simulations being performed at different CW pumping power levels. The numerical simulation results presented in the followings are obtained considering the pumping power as 125 mW.

In table 1, the parameters of the investigated passive optical Q-switches are summarized. For all the five investigated passive optical Q-switching cells, based on the use as saturable absorber centers of Co^{2+} ions doped in ZnSe, $MgAl_2O_4$ (spinel) or $MgAl_2O_4$ nano-crystallites embedded in phosphate glass matrix or U^{2+} ions doped in CaF_2 or phosphate glass the length is considered to be l_a = 50 µm [23]. In table 1 [24], as can be noticed, the value of the saturable absorber centers, N_{a0}, varies slightly depending on the absorption cross-section, σ_a, just for imposing the same initial, small signal value of passive Q-switching cell (T_{in} = 0.90). Besides the observed differences between the values of σ_a for Co^{2+} and U^{2+} ions, being larger for Cobalt ions with about an order of magnitude, another difference of major importance consist into the fluorescence lifetime of the first excited energy level of the investigated passive Q-switch cells, τ_a.

It is to notice that for Co^{2+}:ZnSe the value of this parameters is three orders of magnitude larger in comparison with values encountered for the other four investigated Q-switch cell.

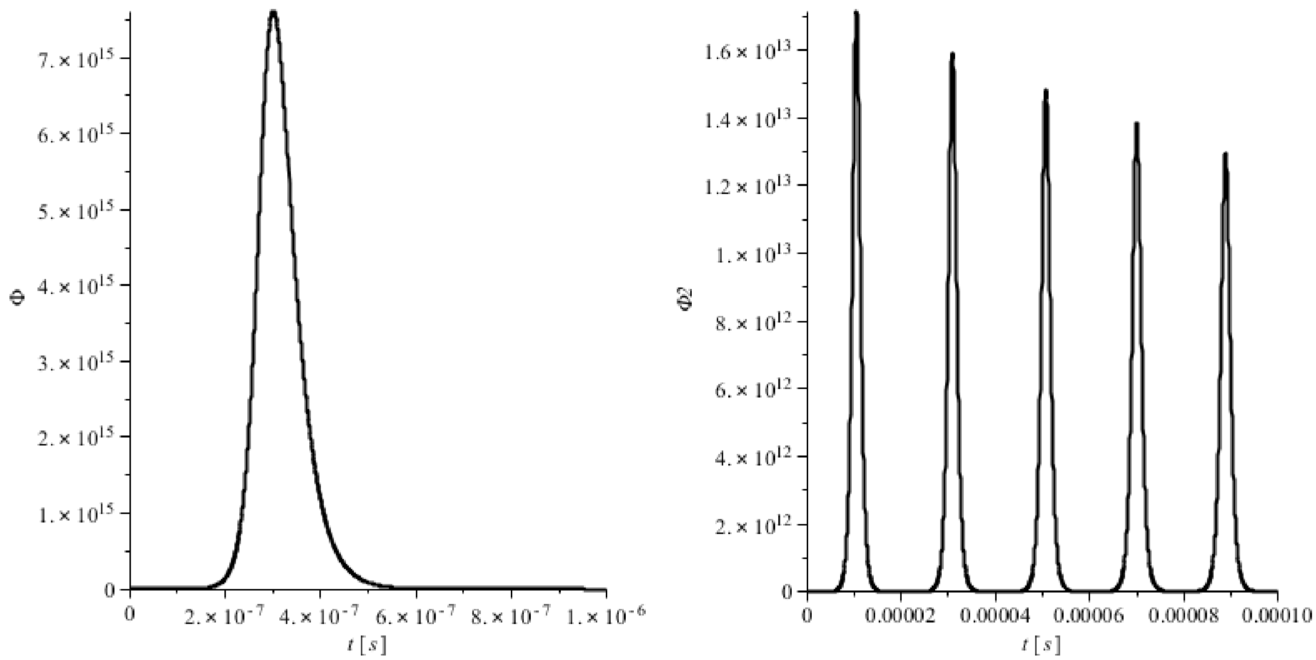

Figure 2. The first output laser pulse time shape (left) and the first part of the train of output laser pulses time shape (right) numerical simulated using Co^{2+}:ZnSe crystal as the Q-switch cell.

Table 1. Summary of investigated Q-Switch cells parameters.

Q-Switch	σ_a [cm^2]	τ_a [s]	N_{a0}[cm^{-3}]	n
Co^{2+}:ZnSe	$5.31\cdot10^{-19}$	$2.9\cdot10^{-4}$	$5.914\cdot10^{19}$	2.45551
Co^{2+}:$MgAl_2O_4$(nanocrystals)	$3.85\cdot10^{-19}$	$6.0\cdot10^{-7}$	$9.053\cdot10^{19}$	2.16416
Co^{2+}:$MgAl_2O_4$	$3.51\cdot10^{-19}$	$1.8\cdot10^{-7}$	$1.152\cdot10^{20}$	1.69416
U^{2+}:CaF_2	$7.05\cdot10^{-20}$	$2.0\cdot10^{-7}$	$6.139\cdot10^{20}$	1.42601
U^{2+}:Phosphate Glass	$5.56\cdot10^{-20}$	$1.0\cdot10^{-7}$	$7.622\cdot10^{20}$	1.51647

In table 2, the numerical simulated laser output parameters obtained for the investigated Q-switch cells are summarized. By analyzing this summary of results, it can be noticed the role played by the parameter τ_a, mainly regarding the energy and FWHM time width of the first output laser pulse, τ_{p0}. It can be observed that the smallest value of τ_{p0}, less than 88 ns, is evaluated for Co^{2+}:ZnSe, the passive optical Q-switch cell having the longest fluorescence lifetime of the saturable absorber centers first excited energy level, while for the other investigated absorbers, τ_{p0} increases up to 97 ns (for U^{2+}:CaF_2). Also, by analyzing the data summarized in table 2, it can be noticed that smallest first output laser pulse energy, E_{out0}, is observed for U^{2+}:CaF_2, being about two thirds of the maximum value obtained for Co^{2+}:ZnSe. The value of output laser pulses repetition frequency varies slowly from 49.054 kHz (Co^{2+}:ZnSe) up to 49.273 kHz (Co^{2+}:$MgAl_2O_4$).

Table 2. Summary of numerical simulated laser output parameters.

Q-Switch	τ_{p0} [ns]	E_{out0} [nJ]	τ_{p1} [µs]	E_{out1} [nJ]	f_{out} [kHz]
Co^{2+}:ZnSe	87.6	48.19	1.924	2.39	49.054
Co^{2+}:$MgAl_2O_4$(nanocrystals)	89.4	42.51	1.934	2.17	49.112
Co^{2+}:$MgAl_2O_4$	93.9	34.89	1.950	1.89	49.273
U^{2+}:CaF_2	97.0	31.52	1.957	1.77	49.221
U^{2+}:Phosphate Glass	95.3	32.52	1.955	1.80	49.236

In figures 2-6, the numerical simulated first output laser pulse time shape and the first part of the train of output laser pulses time shape are presented in the case of the five types of studied passive optical Q-switch cells (as presented in Table 2).

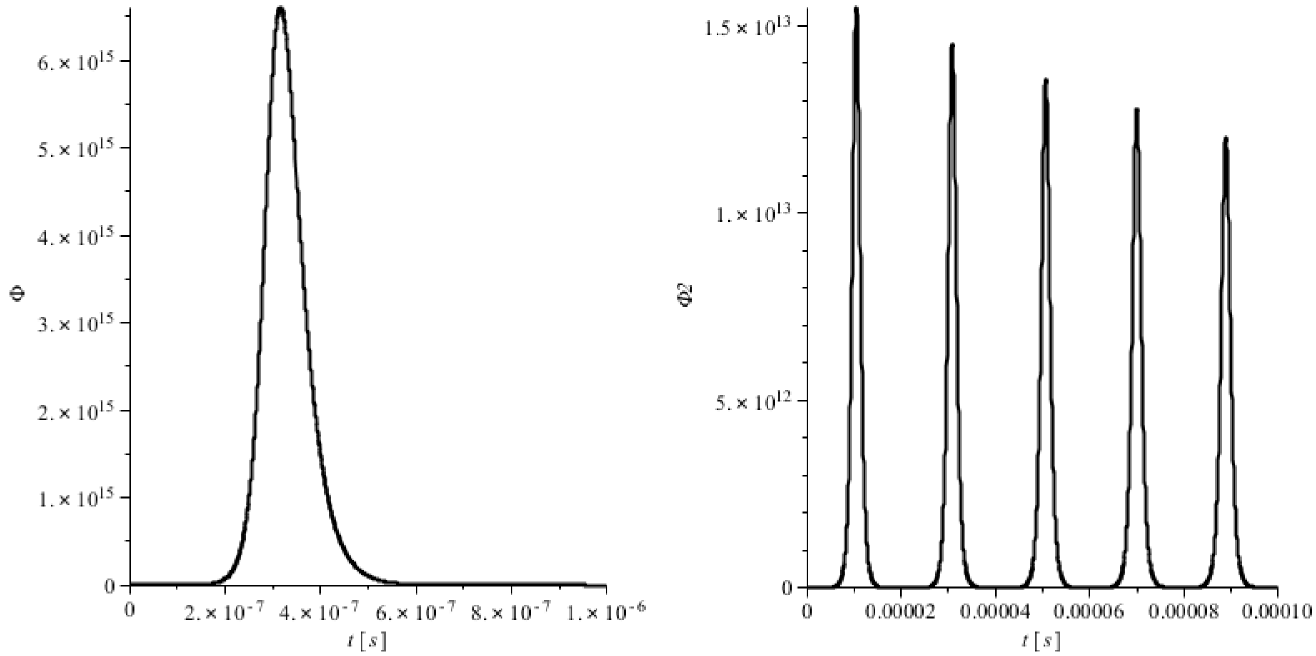

Figure 3. The first output laser pulse time shape (left) and the first part of the train of output laser pulses time shape (right) numerical simulated using Co^{2+}:$MgAl_2O_4$(nanocrystals) crystal as the Q-switch cell.

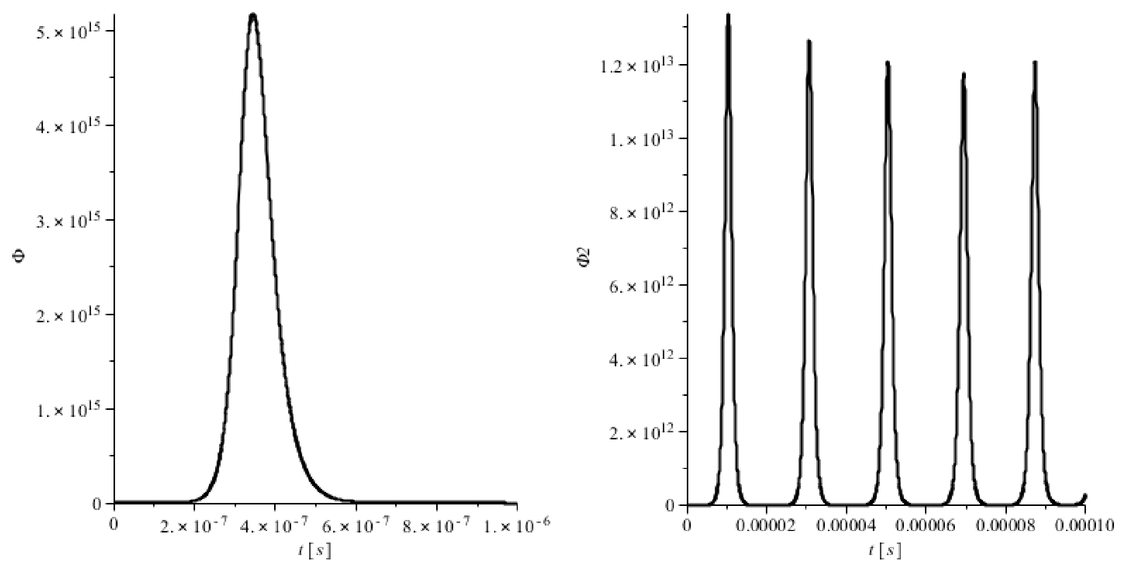

Figure 4. The first output laser pulse time shape (left) and the first part of the train of output laser pulses time shape (right) numerical simulated using Co^{2+}:$MgAl_2O_4$ crystal as the Q-switch cell.

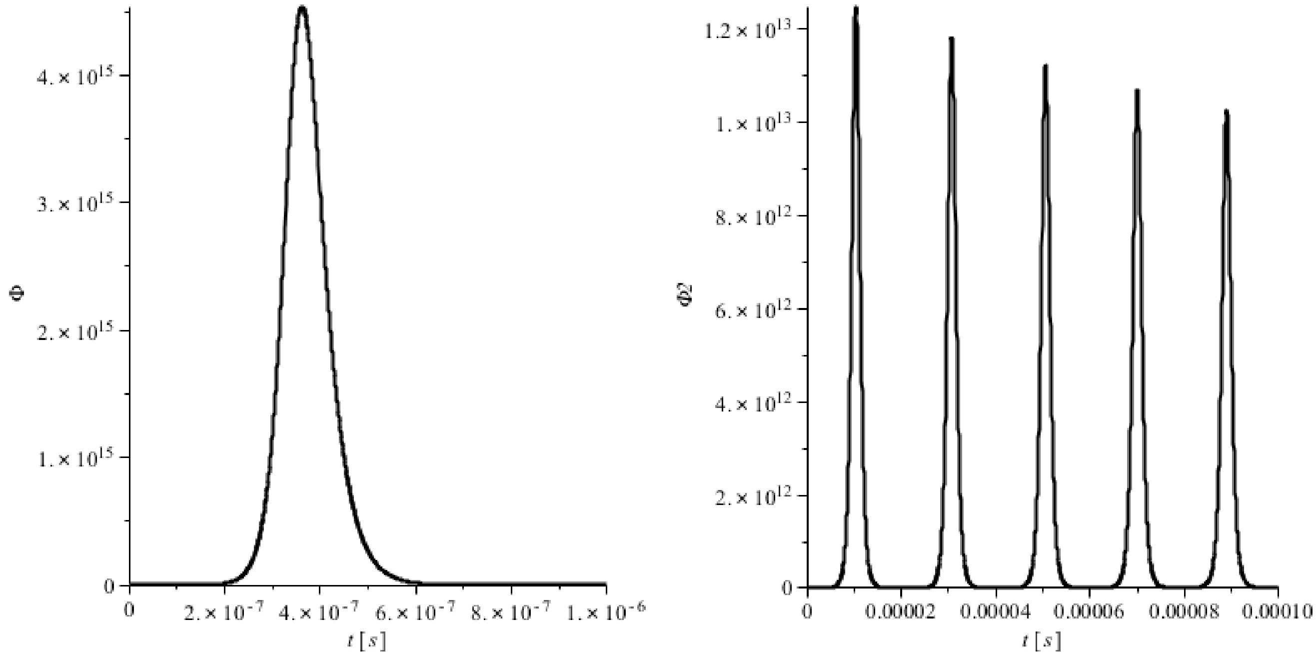

Figure 5. The first output laser pulse time shape (left) and the first part of the train of output laser pulses time shape (right) numerical simulated using U^{2+}:CaF_2 crystal as the Q-switch cell.

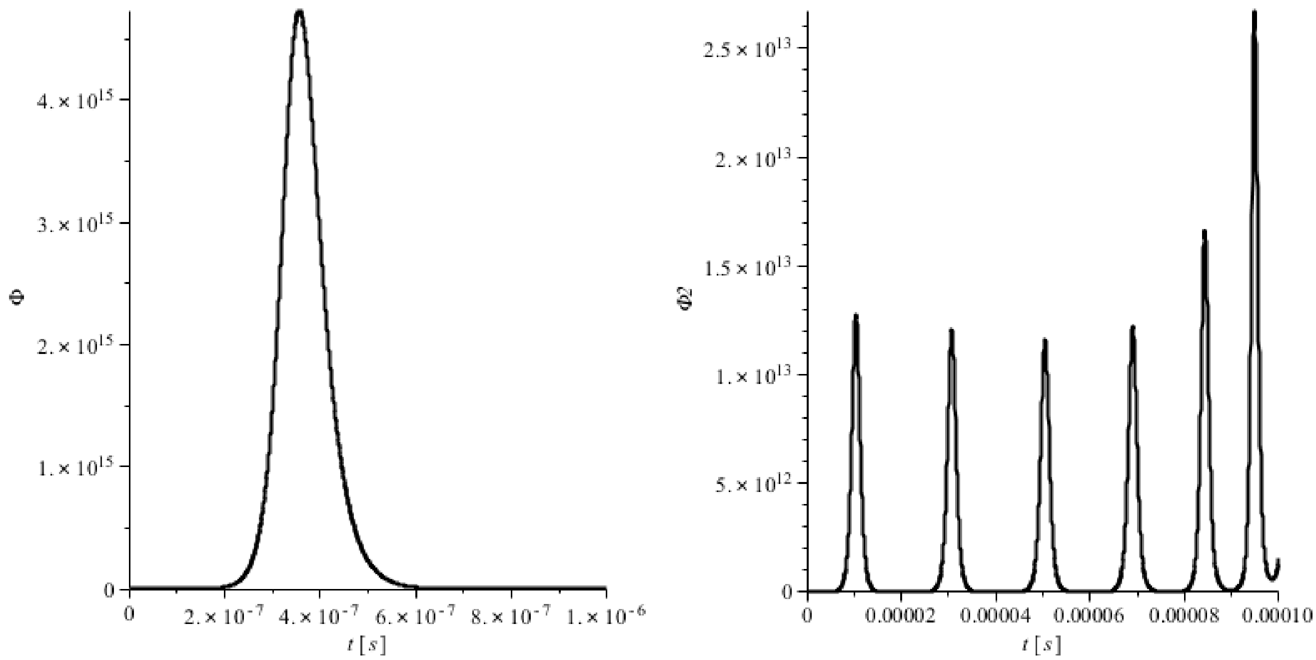

Figure 6. The first output laser pulse time shape (left) and the first part of the train of output laser pulses time shape (right) numerical simulated using U^{2+}:Phosphate Glass crystal as the Q-switch cell.

Regarding the train of the pulses that follows the first pulse we can outline some trends. The pulse width grows as the first pulse does but its variation is minor (from 1.924 µs up to a maximum of 1. 955 µs). The energy E_{out1} decreases, like E_{out0}, from a maximum of 2.39 nJ down to a minimum of 1.77 nJ.

The tendency of decreasing amplitude of laser pulses can be observed, with the mention that only the first part of the numerical simulated train of output laser pulses is represented because of a possible interest into individual laser pulse time shapes. Anyway, no significant modifications of laser pulse time shape was observe for longer simulation times. For longer simulation times, a stabilization of laser pulses amplitude is observed.

4. CONCLUSIONS

As our simulation outlined, best results can be obtained using Co^{2+}:ZnSe crystal as Q-switch because of its properties: a large absorption cross-section σ_a ($5.31\cdot10^{-19}$ cm^2 and a high refractive index n (2.45551). The energy per pulse is obviously the highest among all studied variants. The influence of these parameters (absorption cross-section and refractive index) is unimportant for the repetition frequency of the pulses since it varies with only 0.4%.

The presented numerical simulation results are perfectible and will be further developed for improved designing purposes by comparison with experimental results. It has to be underlined the difference observed between the first output laser pulse and the rest of laser pulses of the output train of laser oscillation.

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