Minimization of spikes by pulse doubling pump in Q-CW operation of a Nd:YAG laser with flash lamp pumping

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Abstract. In this paper, we examine the factors minimizing the transient spikes in the evolution of a laser pulse. Our study is based on a mathematical model simulation of the laser implemented in Matlab Simulink. A model of the flash lamp excitation circuit is also included in the overall laser model. It allows us to show the correlation between the characteristics of the Q-CW laser pulse mode and the various physical parameters of the oscillator. The model proposed is applicable to the case of a single- or multiple-mesh pulse-forming network (PFN) of the flash lamp excitation current. The spikes in the laser pulse are substantially reduced by using the pulse doubling pump (PDP) technique. The simulations results give a clean laser pulse in a single mesh and in five meshes.

Keywords: Solid-state laser, PFN, rate equations, Q-CW mode, pulse doubling pump, spikes.

1. Introduction
The problem of suppressing spikes has been studied since the invention of the laser [1]. Numerous articles in the literature have been devoted to the evolution and structure of these spikes [2-6]. A number of techniques have been used to suppress the inherent spiking behavior due to the relaxation of the oscillations in pulse-pumped solid state lasers. H. Thomas et al. studied the suppression of spikes by means of the second harmonic generation technique [7]. P. Randall et al. used the technique of frequency doubling [8], and J. Wu et al. chose a driving circuit with pre-excitation [9]. The Q-CW mode of operation of the Nd:YAG laser was developed for use in some applications (medical, materials science), where long and smooth laser pulses are required [10-12].

In the model of our Nd:YAG laser oscillator (figure 1), based on the rate equation, we also considered the excitation circuit, thus simulating the overall operation of the system. Our simulator, based on the implementation of the mathematical model in Matlab Simulink, allows us to show the correlation between the characteristics of the Q-CW laser pulse mode and the various physical parameters of the oscillator. This enables us to find how we should adjust our excitation parameters to obtain smooth pulses. It was shown in [9] that a suitable choice of the initial excitation circuit with pre-excitation minimizes the initial spikes energy in case of a pulsed TE CO2 laser. We show that this principle is valid for flash-lamp optically-pumped lasers by using dual excitation pulses. The excitation pulses are controlled by an insulated-gate bipolar transistor (IGBT) circuit. In our model, we used a flash lamp as a pumping source because it has several advantages over the other pumping sources, such as laser diode, power LED and solar radiation. The pumping is homogeneous [14], the quality of the laser beam is good.
at low repetition rates [14] and the cost is lower. In addition, one can consider the flash lamp as a quasi-solar source [15].

![Figure 1](image-url)

**Figure 1.** (a) Schematic of Nd:YAG; (b) multi-mesh excitation circuit of a flash lamp.

2. **Laser oscillator model**

We start with the laser rate equations as given by Koechner [14]:

\[
\frac{dn}{dt} = -\zeta n \Phi \sigma_{21} c - \frac{n + n_{tot} (\zeta - 1)}{\tau_f} + W_p (n_{tot} - n) \tag{1}
\]

\[
\frac{d\Phi}{dt} = \frac{ac \Phi \sigma_{21} n - \Phi}{\tau_C} + S, \tag{2}
\]

where \(n\) is the population inversion, \(\Phi\), the photon density, \(S\), the spontaneous emission rate, \(W_p\), the pumping rate, \(c\), the speed of light, \(a\), the ratio between the lengths of the rod and the laser cavity. The losses in the resonator are estimated using the equation [14]:

\[
\gamma = -\log R_1 + b. \tag{3}
\]

The pumping cavity is represented by its transfer coefficient \(\eta_p\) [14]

\[
P_e = \eta_p P_\lambda, \tag{4}
\]

where \(P_\lambda\) is the useful pump radiation emitted by the source and \(P_e\) is the fraction of the radiation emitted by the source and transferred into the laser material. The pumping rate \(W_p\) is related to the electrical excitation power \(P_{in}\) by the total transfer coefficient [14].

\[
W_p = \eta_{tot} P_{in} \tag{5}
\]

The PFN circuit delivers current pulses of a specific shape to the flash lamp. Ordinarily, multiple-mesh networks are used [16]. In our case, we determine \(P_{in}\) from the excitation circuit equations:

\[
\begin{align*}
V_{C1} &= \frac{m}{C} \int (i_2 - i_F) dt, \\
V_{C2} &= \frac{m}{C} \int (i_3 - i_2) dt, \ldots, \\
V_{CM} &= \frac{m}{C} \int (i_{(m-1)} - i_{(m-1)} - i_{(m-1)}) dt \\
i_F &= \frac{m}{L} \int (V_{C1} - V_{RL1} - V_F - V_{RSL}) dt, \\
i_2 &= \frac{m}{L} \int (V_{C2} - V_{C1} - V_{RL2}) dt, \ldots, \\
i_m &= \frac{m}{L} \int (V_{CM} - V_{C(m-1)} - V_{RLm}) dt
\end{align*} \tag{6}
\]

where \(C\) is the storage capacitance, \(L\), the coil inductance, \(m\), the number of meshes, \(V_{CM}\), the potential difference across the capacitor, \(i_F\), the current through the flash lamp, \(V_F\), the potential difference across the flash lamp, \(V_{RLm}\), the potential difference across the active resistance of coil \(R_{Lm}\), \(V_{RSL}\), the potential difference across the resistance of switch \(R_s\). The current-voltage characteristics of the flash is given by:

\[
V_F = \pm K_0 \sqrt{|i_F|}, \tag{7}
\]

where \(K_0\) is the characteristic impedance of the lash lamp.

Thus, \(P_{in}\) given by:
$P_{in} = V_F \cdot i_F$  

(8)

The IGBT is modeled by a controllable switch.

3. Laser simulator

To implement the mathematical model in Simulink, we performed a normalization of the equations. The population inversion and the photon density are normalized with respect to the inversion threshold $n_{S0}$:

$$n_{S0} = \frac{1}{a \sigma_{21} c \tau_C}$$  

(9)

The time is normalized with respect to $\tau_C$:

$$\tau_C = \frac{2L_C}{c \gamma}$$  

(10)

The resistances, voltages, currents are normalized as follows:

$$R_{ij} = \frac{R_i}{Z}; \quad V_{ij} = \frac{V_i}{V_0}; \quad i_{ij} = \frac{i_j}{V_0} ; \quad j = 1, 2, ..., m,$$

(11)

where $Z$ is the characteristic impedance of the circuit, and $V_0$ is the initial voltage.

The following diagram shows the different parts of the laser.

**Figure 2.** Laser simulator.

4. Simulation results

The parameters used in the simulation are given in the table 1:
Table 1. Parameters used in the simulation.

| Parameters                                | Symbol | Values                                                                 |
|-------------------------------------------|--------|------------------------------------------------------------------------|
| Reduction factor                          | ζ      | 1 (four-level laser)                                                  |
| Cavity losses (absorption, scattering, diffusion) | b      | 0.1                                                                   |
| Cavity length                             | L_C    | 0.60 m                                                                |
| Laser rod length                          | L_b    | 0.065 m                                                               |
| Fluorescence lifetime                     | τ_f    | 230 µs                                                                |
| Stimulated emission cross section         | σ_{21} | 6×10^{-23} m^2                                                        |
| Total population density                  | n_{tot}| 1.38×10^{26} atomes/m^3                                              |
| Mirror reflectivity                       | R_1    | 90%                                                                   |
| Resonator losses                          | γ      | 0.20                                                                  |
| Characteristic time of the cavity         | τ_c    | 1.95 ns                                                               |
| Inversion threshold                       | n_{S0} | 0.30×10^{21} atomes/m^3                                              |
| Total population density normalized       | n_{totN}| 4.84×10^{4}                                                           |
| Fluorescence lifetime normalized          | τ_{fN}| 5.24×10^{3}                                                           |

4.1. Temporal evolution of the spikes

The relaxation of the oscillations is discussed in [2-5]. In our work, we illustrate the temporal evolution of the laser pulse and of the population inversion. Figure 3 (a) shows the variation of the population inversion \( n \) and the photon density \( Φ \) as a function of time. Figure 3 (b) shows the same signals as in (a) in an expanded scale.

![Figure 3](image1)

**Figure 3.** (a) Evolution of \( Φ \) and \( n \). (b) Evolution of \( Φ \) and \( n \) in an expanded scale.

Figures 4 (a), 4 (b) and 4 (c) present \( Φ_{\text{max}} \) as a function of \( Φ_{\text{min}} \), \( n_{\text{max}} \) as a function of \( Φ_{\text{min}} \), and \( Φ_{\text{max}} \) as a function of \( n_{\text{min}} \), respectively. One can conclude that the amplitude of the spikes is reduced when the minimum flux is high, which is also the case of the spikes dependence on the population inversion.

**Hypothesis:** Figure 4 (c) shows that the spikes are all small when the minimum inversion is high (but remaining ≤\( n_{S0} \)). This suggests that \( n \) can reach a maximum initial value below \( n_{S0} \) by means of pre-excitation. We, therefore, adopt a double-pulse excitation system.
Figure 4. Evolution of $\Phi_{\text{max}}$ and $n_{\text{max}}$ as a function of $\Phi_{\text{min}}$ (a), (b); Evolution of $\Phi_{\text{max}}$ as a function of $n_{\text{min}}$ (c).

4.2. Spikes minimization by PDP
The principle of spikes minimization by PDP in the cases of single and five meshes is shown in figure 5. The signals shown by a dashed line correspond to excitation by a single pulse; the signals presented by a continuous blue line correspond to a double pulse excitation.

Referring to figure 1, the control signal of the IGBT at $t = 0$ is set at On position, which initiates a discharge of the PFN circuit through the flash lamp. The population inversion increases with the current to a value $n_0$ (limit) for time $t = t_0$ (limit) just before the threshold is reached. At this moment, we interrupt the control signal (Off value) during a time interval $\Delta t$ before returning control to the On position. The discharge current then determines the evolution of $n$ from its threshold value, which gives rise to the pulse of $\Phi$ after a period of development with minimal spikes.

Figure 5. Minimization of spikes by double pulse. (a) single mesh, (b) five meshes. dashed line – classical excitation; blue line – double-pulse excitation.

Multiple-mesh networks, or pulse forming networks (PFN), are used to generate pump pulses with a rectangular shape [16].

5. Conclusion
A numerical model is developed describing a solid-state laser pumped by a flash lamp. The model can simulate all laser modes (relaxation, continuous, Q-switched (passive or active), burst, etc.). It allows the acquisition of pertinent results concerning the basic parameters, such as pulse waveform, pulse repetition rate, pulse duration, average power. Using our numerical model, we present a way of minimizing the spikes, namely, the pulse doubling pump (PDP) technique, whereby the initial photon density is first brought to a value sufficiently high to prevent the spikes from reaching high values. We
present simulation results of a clean laser pulse in the case of a single-mesh and five-mesh pulse forming networks.

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