Simulation of medical Q-switch flash-pumped Er:YAG laser

WANG -Yan-lin, HUANG-Chuyun*, YAO-Yucheng and Zou Xiaolin
Physics school, Hubei University of Technology, Wuhan, China 430068
Wangyanlin0@126.com chuyunh@163.com yyuch@soho.com zouxiaol@126.com

Abstract: Er: YAG laser, the wavelength is 2940nm, can be absorbed strongly by water. The absorption coefficient is as high as 13000 cm\(^{-1}\). As the water strong absorption, Erbium laser can bring shallow penetration depth and smaller surrounding tissue injury in most soft tissue and hard tissue. At the same time, the interaction between 2940nm radiation and biological tissue saturated with water is equivalent to instantaneous heating within limited volume, thus resulting in the phenomenon of micro-explosion to remove organization. Different parameters can be set up to cut enamel, dentin, caries and soft tissue. For the development and optimization of laser system, it is a practical choice to use laser modeling to predict the influence of various parameters for laser performance. Aim at the status of low Erbium laser output power, flash-pumped Er: YAG laser performance was simulated to obtain optical output in theory, the rate equation model was obtained and used to predict the change of population densities in various manifolds and use the technology of Q-switch the simulate laser output for different design parameters and results showed that Er: YAG laser output energy can achieve the maximum average output power of 9.8W under the given parameters. The model can be used to find the potential laser systems that meet application requirements.

Keyword: Er:YAG laser; rate equation; Q-switch

1. INTRODUCTION
The wavelength of Er(50at.%):YAG laser radiation(\(\lambda=2.940\mu m\)) matches a pronounced absorption band of water. So the small penetration depth of the radiation (little more than 1\(\mu m\) in water) and the high intensity of the Er:YAG laser pulses promote effective ablation of soft and hard human tissues (the latter group is of special interest for dentistry) with minimum inevitable destruction of the area closed to the treated location. However the output power of Erbium laser is low, so aim at this flash-pumped Er: YAG laser performance was simulated to obtain optical output in theory and we also used Q-switch technology to short pulses[1], all of this based on the rate equation. The result show that Er: YAG laser output energy can achieve the maximum average output power of 9.8W under the given parameters.

2. CRYSTAL CHARACTER
Zhavikov E V have firstly reported the output of 2.94\(\mu m\) Er(30at.%):YAG in 1967; Li-Mengyu , in 1987, have also obtained the 2.94\(\mu m\) laser output by use Er(50at.%):YAG.

In 1990, Li-Yuanqi use optical crystal with 2mm deep gain fluorescence emission spectrum of Er\(^{3+}\), show in Fig 1 and Fig 2 [2].
3. SPECIAL APPLICATION

The interaction between body and laser, whether through photochemical effect makes organizing molecular fracture, or by thermal effects to tissue vaporization cells, all of this require cell to fully absorb the laser energy. In biological cells and tissues, the water content of more than 70% usually (some up to 90%)\[2\], due to the laser wavelength of 2.94 \( \mu m \) is consistent with the vibration frequency of water molecules, it was very strong in the water absorption, absorption coefficient to \( \mu_a=13000 \text{ cm}^{-1} \), can use less energy to achieve greater the effect. The superiority is unmatched by other wavelengths, using it can be very precise cutting and soft tissue surgery. In addition, the interaction of water saturated tissue and 2.94\( \mu m \) laser focus, equivalent to a limited volume of transient heating, increased pressure within the volume, with the substance (eg blood) from the incision emission, the phenomenon does not produce blood clotting. This feature determines the Er: YAG lasers in the medical field wide application. Figure 3 shows the absorption spectra of water molecules and the commonly used CO\(^2\), Nd: YAG, Er: YAG laser output wavelength of the location, can be seen, for laser energy is absorbed by tissue, select the output wavelength of 2.94 \( \mu m \) of Er: YAG laser is the most ideal outcome\[3\].

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**Figure 1.** Absorption spectrum of Er\(^{3+}\)

**Figure 2.** \(^{4}I_{11/2}\) to \(^{4}I_{15/2}\) fluorescence spectrum in Er:Y\(_3\)Al\(_5\)O\(_{12}\)
4. RATE EQUATION FOUNDATION

Two pumping channels are effectively present in Er:YAG lasers. The so-called direct-pumping channel consists of the Er$^{3+}$ ground-state absorption with transition to states $^{4}I_{11/2}$, $^{4}I_{9/2}$ and $^{4}F_{9/2}$ and a nonradiative relaxation of the latter two to the upper laser level $^{4}I_{11/2}$. The indirect-pumping channel, on the other hand, starts with a shorter-wavelength excitation to states $^{4}S_{3/2}$, $^{2}H_{11/2}$ and $^{4}F_{7/2}$, and a nonradiative relaxation of the later two to the high-lying metastable level $^{4}S_{3/2}$. Through inter-ionic cross relaxation of this level, both the upper and the lower laser level ($^{4}I_{13/2}$) are excited to the same extent[4].

Despite a shorter lifetime of the emitting level as compared with the terminal one, efficient long-pulse or even CW 2.94 µm emission was obtained at room temperature in concentrated erbium systems[5]. Excited state absorption (ESA) from the terminal laser level and/or energy transfer processes as a cooperative upconversion inside the system of Er$^{3+}$ ions were invoked to explain the success of the 2.94 µm erbium laser. The presence of efficient laser emission in concentrated systems favors the cooperative upconversion model. According to this model, the driving mechanism for 2.94 µm erbium lasers is the upconversion process ($^{4}I_{11/2} \rightarrow ^{4}I_{15/2}$) + ($^{4}I_{13/2} \rightarrow ^{4}I_{9/2}$) followed by the rapid multiphonon transition to $^{4}I_{11/2}$. This mechanism depopulates the terminal laser level and repopulates the initial one. In order to understand the peculiarities and the possibilities of the 2.94 µm Er lasers working in the Q-switch regime, we constructed and used rate equatio erbium systems is given in (1).
Here, in addition to differential equations for the populations $N_2$ and $N_3$ of the lower ($^4I_{13/2}$) and the upper ($^4I_{11/2}$) laser level, this model accounts explicitly for the population $N_4$ of the state $^4S_{3/2}$, and $\phi$ is the photos desity, while the relaxations of other electronic states are assumed to be instantaneous.

The energy transfer processes are represented in (1) by $\omega_1$, the rate of upconversion from $^4I_{13/2}$, $\omega_2$, the rate of upconversion from $^4I_{11/2}$ and $\omega_0$ and the rate of the cross relaxation from $^4S_{3/2}$ and $\sigma$, $\beta$ are the Boltzmann population coefficients for the Stark sublevels involved in the laser transition. $c$ is the speed of light. The parameter $l$ and $L$ are crystal length and optical length in cavity, the connection of them can expressed as this:

$$L = L_0 + (n_r - 1)l$$

in this formulary; $L_0$ is the length of cavity; $n_r$ is the refractive index of the crystal.

The total loss per round trip $\rho$ is expressed as [5]:

$$\rho = -\ln\frac{R_1 R_2 T_Q^2}{2l} + \rho_0$$

where $R_1, R_2$ are the reflectivity of the total (rear) and partial (coupling) laser mirrors, $T_Q$ is the one-way optical transmission of the Q-switch, and $\rho_0$ is the total passive loss.

The Q-switch operation is simulated in (1) by changing the optical transmission of the Q-switch. This can be done by assuming various temporal dependencies of transmission, we found that the change of the -switch transmission can be quite realistically represented by the expression:

$$T_Q(t) = T_Q^{low} + (T_Q^{low} - T_Q^{high}) \cdot [(\cos(\frac{2\pi}{\tau_Q}(t - t_1)))^m - 1]$$

where $T_Q^{low}$ and $T_Q^{high}$ are, respectively, the values of the transmission in the closed and open state of the Q-switch and $t_1$ is the Q-switching moment. With two parameters, $\tau_Q$ and $m$ (where $m$ is an even integer), we can simulate various fronts and duration of the transmission interval of the Q-switch.

### 5. SIMULATION

Firstly, we simulated the Q-switch transmission (2) under those parameters:

$$T_Q^{low} = 0.3, \quad T_Q^{high} = 0.95, \quad \tau = 16 \mu s$$

$$m = 12, \quad t_Q = 1.5 \mu s$$
The picture we obtained (as up given parameter) as figure 5:

![Graph showing Q-switch transmission](image)

**Figure 5.** Simulate Q-switch transmission

Then we simulated the rate equation, we chose suitably parameter as follows:

- \( \sigma = 2.6 \times 10^{-24} \text{ m}^3 \)
- \( \omega_{22} = 3.7 \times 10^{-21} \text{ m}^3 \text{s}^{-1} \)
- \( \omega_{11} = 1.3 \times 10^{-21} \text{ m}^3 \text{s}^{-1} \)
- \( \omega_{d0} = 1.06 \times 10^{-21} \text{ m}^3 \text{s}^{-1} \)
- \( h = 6.626 \times 10^{-34} \)
- \( c = 3.0 \times 10^8 \text{ m} \text{s}^{-1} \)
- \( n_e = 1.838 \)
- \( R_1 = 0.6 \)
- \( R_2 = 0.4 \)
- \( \tau_3 = 0.1 \times 10^{-3} \text{ s} \)
- \( \tau_2 = 2.0 \times 10^{-3} \text{ s} \)
- \( \tau_4 = 1.6 \times 10^{-5} \text{ s} \)
- \( T_{out} = 0.80 \)
- \( T = 1 \)

Then we made use of matlab to simulate and result have showed as follows:
Figure 6. Simulate Q-switch rate equation

Long pulse Q-switch laser is similar to CW laser, so the output power can be expressed by [7]:

\[ P_{\text{out}} = \phi \sigma \frac{c^2}{\lambda} \]

based on the simulation, the output power about 10W.

6. CONCLUSION

We have simulated the Q-switch flash-pumped Er:YAG laser and calculated the output power about 10W in theory, this model based on rate equation can afford some suggestions to manufacture and application of Er:YAG, but what we done just in theory so it existence error. Actually a lot of parameters affect the output of the laser, such as bulk of model, total efficiency of pump in different condition. So what we did in this article, compare to practice, is just a guid for the law.

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