PUMP WAVELENGTHS FOR AN UPCONVERSION-PUMPED Er:YAG GREEN-EMITTING LASER

O. TOMA, S. GEORGESCU
National Institute for Laser, Plasma and Radiation Physics, Solid-State Quantum Electronics Laboratory, 409 Atomistilor Street, 077125, Bucharest-Magurele, Romania
E-mail: octavian@pluto.infim.ro
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Mathematical modeling is used to study laser emission in an Er(0.5 at.%):YAG active medium on the transition $^4S_{3/2} \rightarrow ^4I_{15/2}$ for upconversion pumping. The emission regimes corresponding to two pump wavelengths (800 nm and 810 nm) are investigated. We find the optimum pump wavelength and optimum conditions for lowering of the continuous-wave emission threshold.

Key words: Upconversion laser, Erbium, YAG.

1. INTRODUCTION

Upconversion lasers are promising sources of coherent radiation in visible. Among the most used laser transitions is $^4S_{3/2} \rightarrow ^4I_{15/2}$ in erbium, that yields emission in green around 550 nm. Some problems, however, prevent the use of this laser transition in practical applications. Among them are the high emission threshold at room temperature and the self-pulsing behavior first observed in erbium-doped fluoride crystals [1, 2, 3]. Although this laser transition was intensely studied experimentally, there are still gaps in the understanding of these problems.

In this paper, we study both these problems in a widely used laser material, Er:YAG, for two different pumping mechanisms. This host crystal, although endowed with good chemical, thermal, and mechanical properties, was not yet systematically studied as a host for green upconversion-pumped laser emission.

Laser emission at 561 nm (transition $^4S_{3/2} \rightarrow ^4I_{15/2}$) has been obtained in Er:YAG for low dopant concentrations (0.5 at.%, 1 at.%) [4, 5, 6] for various pump wavelengths.

For direct pumping at 488 nm, the threshold of Er(1%):YAG was found lower than that corresponding to Er(1%):YLiF$_4$ [4], which is the most frequently


used material for this laser transition. This fact was attributed to lower re-absorption losses in Er:YAG.

For upconversion pumping at 810 nm, excited-state absorption (ESA) from the $^4I_{11/2}$ level was found responsible for the population of the upper laser level $^4S_{3/2}$ [5, 6]. The results obtained at this pump wavelength were inferior to those obtained at the same pump wavelength in Er:YLiF$_4$. The output energy was orders of magnitude lower than in Er:YLiF$_4$, and decreased after the first few shots to stabilize at a low value.

Following the study of an excitation spectrum of Er:YAG (pump wavelength 775 nm – 860 nm, corresponding to transition $^4I_{15/2} \rightarrow ^4I_{9/2}$, monitored on the transition $^4S_{3/2} \rightarrow ^4I_{15/2}$) [7], excitation at 800 nm was proposed as a pump wavelength for the green-emitting Er:YAG laser [8]. This wavelength corresponds to the greatest peak in the excitation spectrum, which is much greater than the peaks around 810 nm. Pumping at 800 nm was predicted to yield a lower laser threshold than that obtained at 810 nm.

As shown previously in Reference [8], an important role for the emission at 561 nm is played by the parasitic ESA $^4I_{13/2} \rightarrow {}^2H_{9/2}$ at the laser emission wavelength. This reabsorption loss not only increases the laser threshold, but can cause also the operation of the laser in a self-pulsing regime, as was first observed in Er-doped fluoride lasers on this transition [1, 2, 3]. Therefore, a comparison between various pump wavelengths must be based on the knowledge of the effect of various parameters (pump wavelength, pump intensity, resonator losses) on the operation regime of the Er:YAG laser. As we will show below, a change of only 10 nm in pump wavelength can change dramatically the dynamics of this upconversion laser.

Based on a rate-equation approach, we model the dynamical behavior of an Er(0.5 at.%):YAG laser emitting on the transition $^4S_{3/2} \rightarrow ^4I_{15/2}$ at room temperature. The active ion concentration was chosen low to minimize the effect of the energy-transfer upconversion (ETU) process that decreases the lifetime of the $^4S_{3/2}$ level at higher concentrations. The investigated pump wavelengths are 800 nm (transition $^4I_{15/2} \rightarrow ^4I_{9/2}$, followed by multiphonon relaxation to $^4I_{13/2}$ and ESA $^4I_{13/2} \rightarrow {}^2H_{9/2}$) and 810 nm (transition $^4I_{15/2} \rightarrow ^4I_{9/2}$, followed by multiphonon relaxation to $^4I_{11/2}$ and ESA $^4I_{11/2} \rightarrow {}^4F_{5/2}$). The dominant upconversion mechanisms for these two pump wavelengths were identified in [7].

2. MATHEMATICAL MODEL

Our model includes CW pumping at the two pump wavelengths mentioned above. Pumping is performed only by absorption processes, the contribution of
the ETU processes being negligible at this low Er$^{3+}$ concentration. The absorption processes that could contribute at the pumping process are represented in Fig. 1. Both pump wavelengths 800 nm and 810 nm correspond to ground-state absorption (GSA) process $^4I_{9/2} \rightarrow ^4I_{9/2}$. In Reference [7], for pumping in the $^4I_{9/2}$ level, three ESA processes that could populate the $^4S_{3/2}$ level were identified: [a] $^4I_{9/2} \rightarrow ^2H_{9/2}$, [b] $^4I_{13/2} \rightarrow ^2H_{11/2}$, and [c] $^4I_{11/2} \rightarrow ^4F_{5/2}$; for pumping wavelengths 800 nm and 810 nm, the dominant ESA processes were proved to be [b], respectively [c]. Therefore, process [a] will not be included in our model. The laser transition is $^4S_{3/2} \rightarrow ^4I_{5/2}$; another ESA process that must be taken into account is $^4I_{13/2} \rightarrow ^2H_{9/2}$, a parasitic absorption at the laser emission wavelength; the effect of this process on laser emission is not negligible, due to the high population of the $^4I_{13/2}$ level, which is the most long-lived level of Er$^{3+}$ in YAG. Due to the high phonon energy of YAG, we can consider the energy levels of Er$^{3+}$ as being successively connected by multiphonon transitions. Thus, we will consider that ions excited on short-lifetime levels above $^4S_{3/2}$ are instantly brought to $^4S_{3/2}$ by multiphonon transitions; $^4S_{3/2}$ will be considered the final level of all transitions ending on levels above it.

![Energy-level scheme of Er:YAG showing the processes considered in our model. Ground-state absorption processes at 800 nm and 810 nm are represented. The ESA processes [a], [b], [c] are various candidates for the second step of the upconversion pumping process. The ESA process of cross-section $\sigma_1$ is the parasitic ESA process. The laser transition $^4S_{3/2} \rightarrow ^4I_{5/2}$ is also shown.](image)
We have written the rate equations so as to include all pump processes taking place at both pump wavelengths; in the following sections we will particularize the values of the parameters for each pump wavelength:

\[
\begin{align*}
\frac{dN_0}{dt} &= \sigma_{em}(f_{51}N_5 - f_{08}N_0)\phi + \frac{N_1}{T_1}(\sigma_{01}\phi_1 + \sigma_{02}\phi_2)N_0 \\
\frac{dN_1}{dt} &= -\frac{N_1}{T_1} + \frac{N_2}{T_2} - \sigma_b\phi_1N_1 - \sigma_1N_1\phi \\
\frac{dN_2}{dt} &= -\frac{N_2}{T_2} + \frac{N_3}{T_3} - \sigma_c\phi_2N_2 \\
\frac{dN_3}{dt} &= -\frac{N_3}{T_3} + \frac{N_4}{T_4} + (\sigma_{01}\phi_1 + \sigma_{02}\phi_2)N_0 \\
\frac{dN_4}{dt} &= -\frac{N_4}{T_4} + \frac{N_5}{T_5} \\
\frac{dN_5}{dt} &= -\frac{N_5}{T_5} + \sigma_{em}(f_{51}N_5 - f_{08}N_0)\phi + \sigma_b\phi_1N_1 + \sigma_c\phi_2N_2 + \sigma_1N_1\phi \\
\frac{d\phi}{dt} &= N[\sigma_{em}(f_{51}N_5 - f_{08}N_0) - \rho - \sigma_1N_1]\phi + kN_5/T_5
\end{align*}
\]

where \(N_i\) are the populations of the six energy levels \(^4\text{I}_{15/2}, \quad ^4\text{I}_{13/2}, \quad ^4\text{I}_{11/2}, \quad ^4\text{I}_{9/2}, \quad ^4\text{I}_{9/2}\) and \(^4\text{S}_{3/2}\) (thermalized with \(^2\text{H}_{21/2}\), \(T_i\) - their lifetimes, while \(\phi\) is the laser photon flux inside the resonator. \(\sigma_{em}\) represents the stimulated emission cross-section of the laser transition, \(\sigma_b\) and \(\sigma_c\) are the cross-sections of the ESA processes [b], respectively [c] (presented in Fig. 1), and \(\sigma_1\) is the cross-section corresponding to the parasitic ESA process. \(\phi_i\) represent the pump photon flux respectively at 800 nm and 810 nm, while the corresponding GSA cross-sections are denoted by \(\sigma_0\). \(f_{51}\) and \(f_{08}\) are the Boltzmann factors that give the populations of the Stark levels 1 (lowest) of \(^4\text{S}_{3/2}\) and 8 (highest) of \(^4\text{I}_{15/2}\), the initial and final laser levels. \(v = c l_l/[(l' + (n - 1)l)], \quad c\) represents the speed of light in vacuum, \(n = 1.81\) is the refractive index of the laser medium, while \(l, l_p\) and \(l'\) are, respectively, the length of the active medium, its pumped length, and the length of the laser resonator. \(k\) is a factor taking into account the contribution of the spontaneous emission to the laser flux, while \(\rho\) represents the losses in the laser resonator. The values of the spectroscopic parameters are given in Table 1.

Uniform distribution of the pump radiation in the active medium has been assumed; for longitudinal pumping, this assumption is valid for an active medium length \(l\) much shorter than the inverse of the absorption coefficient of
the pump radiation (which is very low due to the low Er\(^{3+}\) concentration of the active medium).

As can be easily seen, the rate equations are not independent: the populations of the six energy levels taken into account are connected by an equation expressing the invariance of the total number of Er\(^{3+}\) ions:

\[
N_0 + N_1 + N_2 + N_3 + N_4 + N_5 = N_f
\]  

(2)

We will use the rate equations system Eqs. (1) in order to simplify its linearized form, which will be used in the stability analysis; however, when solving the stationary system or performing numerical integration, we will replace the first equation of the system Eqs. (1) with the invariance condition Eq. (2).

We model the behavior of an Er(0.5\%):YAG laser at room temperature with the following resonator geometry: \( l = l' = l_p \) (monolithic resonator). This choice eliminates the resonator geometry from the rate equations: \( v = c/n \). For longitudinal pumping, the length of the active medium can be chosen sufficiently small to allow a uniform longitudinal distribution of the pump power in the active medium for any of the pump wavelengths taken into account.

### 3. 800-nm PUMPING

In the case of upconversion pumping at 800 nm, \( \phi_2 = 0 \) and \( \phi_1 \neq 0 \). For the calculation of the steady-state solutions of Eqs. (1), we will neglect the factor \( k \)
that takes into account the spontaneous emission. This factor is important only for starting the laser oscillation, but it can be made arbitrarily small and does not influence the laser emission dynamics. We include it in the rate equations only when numerical integration is performed. With this assumption \((k = 0)\), the rate-equations system has three steady-state solutions: one of them corresponds to \(\phi = 0\), while for the other two the laser flux is not identically zero. The first solution corresponds to no laser emission, therefore we will not study here the behavior of this solution. The other two steady-state solutions of system (1) were analytically calculated in Reference [8]:

\[
\begin{align*}
\bar{N}_0 &= \frac{N_1 + \frac{\rho}{\sigma_1} - \left(\frac{\sigma_{em}}{\sigma_1} f_{51} + \frac{T_{25}}{T_5} \right) \bar{N}_5}{1 - \frac{\sigma_{em}}{\sigma_1} f_{08} + \sigma_0 T_{23} \phi_1} \\
\bar{N}_1 &= \frac{1}{\sigma_1} \left[ \sigma_{em} \left( f_{51} \bar{N}_5 - f_{08} \bar{N}_0 \right) - \rho \right] \\
\bar{N}_2 &= \sigma_0 \phi_1 T_2 \bar{N}_0 + \frac{T_2}{T_5} \bar{N}_5 \\
\bar{N}_3 &= \frac{T_2}{T_5} \bar{N}_2 \\
\bar{N}_4 &= \frac{T_4}{T_5} \bar{N}_5 \\
-\phi &= \left( \frac{1}{\rho} \frac{\sigma_{em}}{\sigma_1} \sigma_{ph} \phi_1 A_1 - \frac{1}{T_5} \right) \bar{N}_5 + \frac{\sigma_{em} \phi_1}{\sigma_1} \left( \frac{\sigma_{em}}{\rho} - B_1 - 1 \right)
\end{align*}
\]

where \(A_1\) and \(B_1\) are given by

\[
\begin{align*}
A_1 &= \frac{f_{51} \left( 1 + \sigma_0 T_{23} \phi_1 \right) + \frac{T_{25}}{T_5} f_{08}}{1 - \frac{\sigma_{em}}{\sigma_1} f_{08} + \sigma_0 T_{23} \phi_1} \\
B_1 &= \frac{-f_{08} \left( N_1 + \frac{\rho}{\sigma_1} \right)}{1 - \frac{\sigma_{em}}{\sigma_1} f_{08} + \sigma_0 T_{23} \phi_1}
\end{align*}
\]

\(\bar{N}_5\) is the solution of the following second-degree equation:

\[
\frac{\sigma_{em}}{\rho} A_1 \left( \frac{1}{T_5} - \frac{\sigma_{em}}{\sigma_1} \sigma_{ph} \phi_1 A_1 \right) \bar{N}_5^2 + \left[ \frac{\sigma_{em}}{\sigma_1} \left( \sigma_{ph} \phi_1 - \frac{1}{T_1} \right) - \frac{\sigma_0 \phi_1}{f_{08}} \right] A_1 -
\]
By $T_{ij}$ we will denote from now on the sum $\sum_{k=i}^{j} T_k$.

A stability analysis of these two solutions (using $\rho$ and $\phi_1$ as control parameters) reveals that one of them is always unstable; only the stable solution will be studied here. The results of the stability analysis of this solution are presented in Fig. 2. The parameter space is divided into three domains: (i) no laser emission, (ii) a domain of CW emission, and (iii) a domain of self-pulsing emission. The domain of self-pulsing emission is surrounded by the CW domain, as shown in the inset in Fig. 2.

Regarding the resonator losses $\rho$, there is a critical value that separates two domains in the parameter space. Under this value ($\rho_c = 9.54 \times 10^{-3}$ cm$^{-1}$), there are three bifurcation values of $\phi_1$, corresponding to: (i) a steady-state bifurcation that makes the steady-state solution stable, thus leading the system to a CW emission regime; (ii) a Hopf bifurcation that makes the steady-state solution unstable, thus leading to an emission regime in which the laser pulsates indefinitely; (iii) a second Hopf bifurcation that makes the steady-state solution

![Graph](image_url)
stable again: this leads to a second CW emission regime. For $\rho > \rho_c$, the two Hopf bifurcations disappear; there is only one steady-state bifurcation that leads from instability to stability of the steady-state solution and thus to CW emission of the laser.

The decreasing of resonator losses $\rho$ has as an effect the enlarging of the self-pulsing (SP) domain, and the narrowing of the thin CW emission domain under the SP zone. Thus, this CW emission domain is difficult to obtain experimentally, and the effective CW emission threshold corresponds to the second Hopf bifurcation (the upper limit of the SP domain). Therefore, for CW emission, there is an optimum value of $\rho$ ($= \rho_c$), that yields the minimum value of the CW effective threshold.

Because immediately over the laser threshold (corresponding to the steady-state bifurcation) the laser emits CW, steady-state rate equations could be used for the calculation of the laser threshold. Setting $\varphi = 0$ in Eqs. (1) and using the threshold condition (the gain $\sigma_{em} (f_{51}N_5 - f_{08}N_0)$ equals losses $\sigma_1 N_1 + \rho$), it was found [8] that for losses satisfying

$$\rho \leq \rho_{max} = \sigma_{em} f_{51} N_1 T_5 / T_{25}$$

the laser emission threshold is given by the following expression:

$$\phi_{1th} = \left( \xi + \frac{1}{\sigma_1 T_1} \frac{T_{13}}{T_5} \xi \right) + \sqrt{\Delta}$$

where $\xi = \rho / (\sigma_{em} N_1)$, $\zeta = \sigma_1 / (\sigma_{em} \sigma_p T_5)$ and

$$\Delta = \frac{1}{\sigma_1 T_1 T_5} \left( \frac{T_{13}^2}{\sigma_0 T_1} - 4T_{25} \right) \xi^2 + \frac{1}{\sigma_y T_1 T_5} \left( 2T_{13} \zeta - \frac{4f_{08} T_{25}}{\sigma_0 T_5} + \frac{4f_{51}}{\sigma_0} \right) \xi +$$

$$+ \zeta^2 + \frac{4f_{08} f_{51}}{\sigma_0 \sigma_p T_1 T_5}$$

If $\rho$ does not satisfy Eq. (6), Eq. (7) yields a negative value. That is, for values of resonator losses $\rho$ greater than a maximum value (expressed by Eq. (6): $\rho_{max} = 0.307$ cm$^{-1}$), the laser emission is impossible for all values of pump photon flux.

In order to estimate the effect of the parasitic ESA process on the laser emission threshold, we calculated $\phi_{1th}$ for $\rho = 0$

$$\phi_{1th} (\rho = 0) = \frac{1}{2f_{51}} \left[ \xi + \left( \zeta^2 + \frac{4f_{08} f_{51}}{\sigma_0 \sigma_p T_1 T_5} \right)^{1/2} \right]$$
and compared this value with the minimum pump photon flux that yields a population inversion (calculated for \( \rho = 0 \) and \( \sigma_1 = 0 \))

\[
\phi_{th}(\rho = 0; \sigma_1 = 0) = \left( \frac{f_{08}}{f_{51} \sigma_{01} \sigma_b T_S} \right)^{1/2}
\]

(10)

Eq. (9) represents the theoretical limit to which the emission threshold can be reduced by decreasing the resonator losses. For the Er:YAG material considered here, the calculated values are \( \phi_{th}(\rho = 0) = 1.62 \times 10^{18} \text{ cm}^{-2} \text{ms}^{-1} \) and \( \phi_{th}(\rho = 0; \sigma_1 = 0) = 2.24 \times 10^{17} \text{ cm}^{-2} \text{ms}^{-1} \). The value of \( \phi_{th}(\rho = 0) \) is much greater than \( \phi_{th}(\rho = 0; \sigma_1 = 0) \) because \( \zeta^2 \) is much greater than the second term under the square root in Eq. (9); i.e., the contribution of parasitic ESA to the laser threshold is much greater than the pump flux required for achieving the population inversion in this three-level laser.

4. 810-nm PUMPING

In the case of upconversion pumping at 810 nm, \( \phi_1 = 0, \phi_2 \neq 0 \). Assuming \( k = 0 \), the system Eqs. (1) in this case has also three steady-state solutions. One of them is the solution with \( \varphi = 0 \) and we will not study it here for the same reason as in the previous section. The other two steady-state solutions are given by:

\[
\vec{N}_0 = \frac{N_t + \frac{\rho}{\sigma_1} - \frac{\sigma_{em} f_{51} + \frac{T_2}{T_5 (1 + \sigma_c T_2 \phi_2)} + \frac{T_{35}}{T_5}}{1 - \frac{\sigma_{em} f_{08}}{\sigma_1} + \sigma_{02} \phi_2 \left[ \frac{T_2}{1 + \sigma_c T_2 \phi_2} + T_3 \right]}}{N_5}
\]

\[
\vec{N}_1 = \frac{1}{\sigma_1} \left[ \sigma_{em} (f_{51} \vec{N}_5 - f_{08} \vec{N}_0) - \rho \right]
\]

\[
\vec{N}_2 = \frac{T_3}{1 + \sigma_c T_2 \phi_2} \left( \frac{1}{T_5} \vec{N}_5 + \sigma_{02} \phi_2 \vec{N}_0 \right)
\]

\[
\vec{N}_3 = \frac{T_3}{T_2} (1 + \sigma_c T_2 \phi_2) \vec{N}_2
\]

\[
\vec{N}_4 = \frac{T_4}{T_5} \vec{N}_5
\]

\[
\varphi = \frac{\sigma_{02} \sigma_c T_2 \phi_2^2}{\rho (1 + \sigma_c T_2 \phi_2)} \vec{N}_0 - \frac{1}{\rho T_5 (1 + \sigma_c T_2 \phi_2)} \vec{N}_5
\]

where \( \vec{N}_5 \) is the solution of the following second-degree equation:
A stability analysis of these two solutions (with $\rho$ and $\phi_2$ as control parameters) reveals that, for all values of $\rho$, one of them is stable only on two small ranges of $\phi_2$ values; in one of these ranges the populations have complex values; in the second, $\phi_2$ is negative (i.e., no physical meaning). Therefore, we do not use this solution in our study. Only the third solution will be discussed.

For a given value of $\rho$, the stability analysis of this solution detects a single steady-state bifurcation, leading the steady-state solution from instability to stability. However, this bifurcation does not correspond to the CW laser threshold. At the bifurcation value of $\phi_2$, all the steady-state populations are complex, without a physical meaning. They become simultaneously real (they are all real linear functions of $N_5$) for a little greater value of $\phi_2$, which represents the CW threshold. This value of $\phi_2$ can be calculated as the greatest root of the discriminant of Eq. (12), regarding this discriminant as a polynomial in $\phi_2$. For values of $\phi_2$ in a range under the CW emission threshold, the laser emits in a self-saturating regime. This regime is illustrated in Fig. 3. First, the population of $^4S_{3/2}$ increases, increasing the population inversion between this level and $^4I_{15/2}$, which is depleted by the pump absorption. The population inversion reaches the threshold value and laser emission begins. In the meantime,
the population of $^4I_{13/2}$ slowly increases, this level having the longest lifetime of all Er:YAG levels and being populated by radiative and nonradiative processes from upper levels. This also increases the absorption coefficient of Er:YAG at the laser wavelength, due to process $^4I_{13/2} \rightarrow ^2H_{9/2}$. Finally, this parasitic ESA process becomes sufficiently strong to cease the laser oscillation. The threshold of this emission regime does not correspond to a bifurcation; it is not visible in a stability analysis, because the asymptotic behavior of the laser is the same in both cases: for $t \rightarrow \infty$, $\phi$ tends to a small value (given by the spontaneous emission), while the levels’ populations are distributed according to their lifetimes. This fact was put into evidence using numerical integration of the rate-equations system (including the spontaneous emission term $\kappa N_s/T_s$) by a fourth-order Runge-Kutta method. The threshold of this emission regime was calculated as the lowest value of $\phi_2$ for which the gain equals losses, thus producing a temporary amplification of the laser photon flux.

The results of our analysis are synthesized in Fig. 4. The parameter space of the rate-equations system Eqs. (1) is divided in three domains corresponding, respectively, to: no laser emission, self-saturating laser emission, and CW laser emission. As $\rho$ increases, the domain of self-saturated emission is enlarged. For low values of $\rho$ (less than $3 \times 10^{-3}$ cm$^{-1}$), the bifurcation value of $\phi_2$ and the greatest root of the discriminant of Eq. (12) are both lower than the calculated threshold of the self-saturated emission threshold. However, the numerical
integration of Eqs. (1) yielded the same sequence of the two emission regimes. This can be explained by the fact that the steady-state solution of Eqs. (1) becomes stable and real for a value of $\phi_2$ lower than the self-saturated emission threshold, but its attraction basin does not include the point $(N_p, 0, 0, 0, 0, 0, 0)$ in the phase space, which is the initial condition for the rate-equations system: unpumped crystal, $N_0 = N_i$, all the other populations and the laser photon flux zero. For this range of $\rho$ values, the CW laser threshold was calculated using numerical integration of Eqs. (1). This behavior of the laser system at low values of $\rho$ is illustrated in the inset in Fig. 4: the value of $\phi_2$ that corresponds to the transition complex - real of the steady-state solution was represented with dotted line, while the actual CW threshold and the threshold of the self-saturating emission regime were represented with continuous line.

The emission threshold of the Er:YAG laser pumped at 810 nm is greater than the emission threshold corresponding to 800-nm pumping.

5. CONCLUSIONS

Green laser emission in Er(0.5%):YAG at room temperature was studied using a rate-equations approach. Two pump wavelengths were investigated: 800 nm and 810 nm (upconversion pumping). Analytical steady-state solutions
for the rate equations were calculated and their stability investigated in order to determine the emission regimes of this laser for each pump wavelength.

For 800-nm pumping, the second step of the pump process and the parasitic ESA share the same initial level $^4I_{13/2}$, competing for its population. This makes possible the existence of a self-pulsing emission regime. The existence of this regime greatly increases the CW emission threshold at low values of the resonator losses. We found an optimum value of the resonator losses that yields the lowest CW emission threshold. We also calculated an analytical expression for the emission threshold and showed that the major contribution to its large value belongs to parasitic ESA.

For 810-nm pumping, the laser has two possible working regimes: a self-saturated emission regime and the CW emission regime. The existence of the self-saturated emission regime makes this wavelength more suitable for pulse pumping than for CW pumping: short pump pulses can be used to obtain laser emission with a threshold as low as the threshold of the self-saturated laser emission. The values of the emission and CW thresholds for 810-nm pumping are higher than the corresponding thresholds calculated for 800-nm pumping.

The lowest laser emission threshold was calculated at 800 nm. This fact can be explained by the depletion of the $^4I_{13/2}$ level by the second step of the pumping process (transition $^4I_{13/2} \rightarrow ^2H_{21/2}$), that decreases the losses by parasitic ESA $^4I_{13/2} \rightarrow ^2H_{9/2}$.

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