Research of Laser Mechanism of High Power Double-Cladding DBR Fiber Laser

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Abstract. A mathematical model of double-cladding DBR Er\textsuperscript{3+}-Yb\textsuperscript{3+} codoped fiber laser is established based on rate-equation theory, taking into account the energy transfer between Er\textsuperscript{3+} and Yb\textsuperscript{3+}. The population of upper level of Er\textsuperscript{3+} & Yb\textsuperscript{3+} and the output power and laser gain are analyzed and their factors influenced by pump power, fiber length, scatter loss and mirror reflectivity. The results calculated can directly be used in design and applications of fiber laser.

1. Introduction

Recently the research of double-cladding fiber laser is hotspot in photo-electricity and laser. For its structural particularity double-cladding fiber laser has following characteristics:

- Adopting facet pumping, the evolution of upper level population along the fiber is asymmetric.
- Pump laser may not be single mode, and has very high gain and transform efficiency.
- Scattering losses in the signal and the pump bands are not nonnegligible.

Therefore, in order to analyze the laser mechanism of Er\textsuperscript{3+}/Yb\textsuperscript{3+} codoped double-cladding DBR fiber laser, the influence of variety parameter must be took into account.

In this paper, An mathematical model of double-cladding DBR Er\textsuperscript{3+}/Yb\textsuperscript{3+} codoped fiber laser is established based on rate-equation theory, taking into account the energy transfer between Er\textsuperscript{3+} and Yb\textsuperscript{3+}. The population of upper level of Er\textsuperscript{3+} and Yb\textsuperscript{3+}, the output power and laser gain are analyzed and their factors influenced by pump power, pumping configuration, fiber length, scatter loss and mirror reflectivity.

2. Theoretical model

Double-cladding DBR Er\textsuperscript{3+}/Yb\textsuperscript{3+} codoped fiber laser is researched according to Er\textsuperscript{3+}/Yb\textsuperscript{3+} rate-equations. The configuration of DBR fiber laser is shown as Figure 1. Energy level diagram for Er\textsuperscript{3+}/Yb\textsuperscript{3+} -codoped system is shown as Figure 2. Where, $N_{Er}$ and $N_{Yb}$ are Er\textsuperscript{3+} and Yb\textsuperscript{3+} concentration. Assumption they are uniformly distributed on the cross section along fiber core.

According to Figure 2, considering Er\textsuperscript{3+} and Yb\textsuperscript{3+} energy transfer, Er\textsuperscript{3+} homogenous upconversion, amplified spontaneous emission and scattering losses in the signal and the pump bands, $r_{43}$ is very small, the excited state $I_{9/2}$ decays almost instantaneously into the $I_{11/2}$ state, thus implying $N_4 \geq 0$.
Where, in the equation (1)-(3), \( C_2 \) is \( \text{Er}^{3+} \) homogenous upconversion coefficient, and \( R_{61} \) and \( R_{35} \) are the forward and backward energy transfer coefficient, respectively. The \( \tau_{ij} \) and \( \sigma_{ij} \) denote the relaxation lifetimes and the wavelength-dependent emission or absorption cross sections between levels \( i \) and \( j \), respectively. Assume that \( \alpha(\lambda) \) is constant between signal wavelength and pump wavelength. In the equation(4)-(5), \( P_0(\lambda) \) denote the contribution of spontaneous emission into the propagating laser mode, \( P_0(\lambda) = \frac{2}{3} \frac{hc}{\lambda} \). \( W_{13} \) and \( W_{56} \) are the pump absorption rates by \( \text{Er}^{3+} \) and \( \text{Yb}^{3+} \) in the ground state.\( W_{65} \) is the pump emission rate by excited \( \text{Yb}^{3+} \). Reckon them referencing literature [2].

The calculations of equations (1)-(6) are complex. In actual calculations assumptions are made to simplify them.

- Neglect up homogenous upconversion coefficient, i.e., \( C_2 \leq 0 \). \( \tau_{32} \) of \( I_{11/2} \) is very short which result to \( N_3 \) is very small compared with \( N_{\text{Er}}(z) \), \( N_1(z) \) and \( N_2(z) \). Thus assume \( N_3 \leq 0 \). i.e., \( N_3 \leq N_1 + N_2 \).

- In the DBR laser, the ASE of signal laser and pump laser may be deemed that signal laser is very strong for narrow signal band and mirror feedback.

\[
\begin{align*}
\frac{dP_{\text{Er}}(z, \lambda)}{dz} &= \{ \Gamma(\lambda) \{ \sigma_{21}(\lambda) N_2(z) - \sigma_{12}(\lambda) N_1(z) \} - \alpha(\lambda) \} \cdot P_{\text{Er}}(z, \lambda) \\
&+ \Gamma(\lambda) P_0(\lambda) \sigma_{21}(\lambda) N_2(z) \\
\frac{dP_{\text{Yb}}(z, \lambda)}{dz} &= \{ \Gamma(\lambda) \{ \sigma_{56}(\lambda) + \sigma_{56}(\lambda) \} N_6(z) - \sigma_{56}(\lambda) N_3(z) - \sigma_{13}(\lambda) N_1(z) \} - \alpha(\lambda) \\
&\cdot P_{\text{Yb}}(z, \lambda) + \Gamma(\lambda) P_0(\lambda) \sigma_{56}(\lambda) N_6(z)
\end{align*}
\]

Where:

\[
\begin{align*}
\pm \frac{1}{P_{\text{Er}}(z)} \frac{dP_{\text{Er}}(z)}{dz} &= g_s(z) - \alpha(\lambda) \\
\frac{dP_{\text{Yb}}(z)}{dz} &= \{ \Gamma(\lambda) \{ \sigma_{56}(\lambda) \} N_6(z) - \sigma_{56}(\lambda) N_3(z) - \sigma_{13}(\lambda) N_1(z) \}
\end{align*}
\]

In condition of above assumptions, (4) may be simplified as:

\[
\pm \frac{1}{P_{\text{Er}}(z)} \frac{dP_{\text{Er}}(z)}{dz} = g_s(z) - \alpha(\lambda)
\]

Where:

\[
g_s(z) = \Gamma(\lambda) \{ \sigma_{21}(\lambda) + \sigma_{12}(\lambda) N_2(z) - \sigma_{12}(\lambda) N_{\text{Er}} \}
\]
It may be considered as signal gain of per unit length when \( \lambda = \bar{\lambda}_c \).

Taking into account the boundary condition, we have:

\[
P_{E_r}(0, \lambda) = R_3(\lambda)P_{E_r}(0, \lambda)
\]

\[
P_{E_r}(L, \lambda) = R_5(\lambda)P_{E_r}(L, \lambda)
\]

(10)

3. Simulation result and discussion

For the above equations, they may be solved with MATLAB. Figure 3 shows \( E_{r}^{3+} \) upper level population \( N_2 \), \( Yb^{3+} \) upper level population \( N_6 \), the gain and signal power distribution along fiber length in the two-ends pumping. The conclusions of one-end pumping are the same.

As shown in Figure 3 (a) (c), \( E_{r}^{3+} \) upper level population \( N_2 \) hardly change with pump power. On the contrary, when pump power increases the population decreases. The change of gain is same. This denotes that output signal power change linearly with input pump power and it is gain saturation effect for the population and gain decrease in a certain degree. Figure 3 (b) shows that \( Yb^{3+} \) upper level population \( N_6 \) increases with pump power linearly. Here the increase speed of \( N_6 \) is greater than the transform speed from \( Yb^{3+} \) to \( E_{r}^{3+} \), so the bottleneck effect comes into making many \( N_6 \) particles drop into the pump ASE bands.

![Figure 3](image)

**Figure 3.** Evolution of variety parameter along the fiber with pump power.

Figure 4 shows Evolution of various parameter along the fiber with pump configuration. As Figure 4 (a) and (b) shown, there is much difference in \( E_{r}^{3+} / Yb^{3+} \) upper level population. In two-end pump, the population is almost symmetrically distributed on the fiber centre. However on one-end pump, it forms monotony downtrend, and the laser gain is same. However, (d) shows that the laser output power of the two-end pump is much higher than that of the one-end pump.

Figure 5 shows Evolution of various parameters along the fiber with different scatter losses on two-end pump. The scatter losses have two different values \( 1 \times 10^{-2} \) and \( 3.2 \times 10^{-3} \) m\(^{-1}\). From (a), (b), (c) and (d) the scatter losses have hardly influence on every parameter. There is the same conclusion on one-end pump.

Figure 6 shows evolution of various parameters along the fiber with reflectivity \( R_1 = 0.04 \) [3]. On two-end pump other parameters have not any change except output power. Whereas on one-end pump the gain has stood out approach pump input \( (z=0) \), so there is the least output power at the break point. As
(a), (b) and (d) shown, the population of $Er^{3+}$ upper level is the maximum. As Figure 6 (e) shown, the population of $Yb^{3+}$ has no change.

![Graph](image1)

![Graph](image2)

**Figure 4.** Evolution of variety parameter along the fiber with pump configuration.

![Graph](image3)

![Graph](image4)

**Figure 5.** Evolution of variety parameter along the fiber with scatter loss.

4. Conclusion

- Evolution of upper level population along the fiber is asymmetrical. Pump power and pump configuration largely affect $Yb^{3+}$ upper level population, but none on other parameters. However $Er^{3+}$ upper level population is affected by pump configuration and mirror reflectivity. All figures show that patterns of laser gain are same with that of $Er^{3+}$ upper level population.
- Laser output power is proportional linearly with pump power.
Two-end pump may be as well adopted. From above analysis the change of all parameters almost affect two-end pump.

(a) gain                        (b) output power(one-end pump)       (c) output power (two-end pump)

(d) $\text{Er}^{3+}$ upper level population                                        (e) $\text{NYb}^{3+}$ upper level population

Figure 6. Evolution of variety parameter along the fiber with (R1=0.04).

| Parameter | Value | Notes               |
|-----------|-------|---------------------|
| $\lambda$ | 1600nm|                     |
| $\tau_{21}$ | 10.8×10^{-3} sec |                 |
| $\tau_{32}$ | 0.1×10^{-6} sec |                 |
| $\tau_{65}$ | 1.5×10^{-3} sec |                 |
| $\sigma_{2d}(\lambda),\sigma_{55}(\lambda)$ | data from[2] |          |
| $\sigma_{13}(\lambda)$ | data from[2] |          |
| $R_{31}, R_{55}$ | data from[2] |          |
| $C_2$ | 3×10^{-24} m^3 sec^{-1} | |
| $A_{ave}$ | 9×10^{-11} m^2 |          |
| $\eta$ | 1.46 |                     |
| NA | |                     |
| $a(\lambda_2)$ | 6.5×10^{-3} m^{-1} |          |
| $a(\lambda_3)$ | 3.2×10^{-3} m^{-1} |          |
| $\Gamma(\lambda)$ | data from[2] |          |
| $\Gamma_{\lambda}(\rho=920nm)$ | 0.002 |          |
| L | 5m |                     |
| $R_{2}(\lambda_2)$ | 0.98 |          |
| $R_{3}(\lambda_3)$ | 0.04 |          |
| $N_{Er}$ | 4×10^{25} m^{-3} |          |
| $N_{Yb}$ | 6×10^{25} m^{-3} |          |

Table 1. Parameters used in the numerical calculation.

References
[1] Eldad Yahel, Amos Hardy et al 2003 Modeling High-Power $\text{Er}^{3+}$-$\text{Yb}^{3+}$ Codoped Fiber Lasers Journal of lightwave technology 21 2044-52
[2] Kunzhong Lu Ph.D. 2001 Rare-earth doped high power fiber lasers and amplifiers (University of Connecticut)
[3] Nam Seong KIM, Toshihiro Hamad et al 2000 Numerical analysis of output performance of Nd-doped double-clad fiber lasers Proceedeing of SPIE 3889 583-589