Energy recycling versus lifetime quenching in erbium-doped 3- μ m fiber lasers

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In recent years, there have been enormous research efforts to improve the performance of lasers emitting at 3 μ m mainly because of their potential applications in laser surgery. Due to the high absorption of 3- μ m radiation in water, high-quality cutting or ablation is demonstrated in biological tissue using erbium-doped solid-state lasers. We have recently demonstrated a CW output power of 1.7 W at 2.7 μ m with a slope efficiency of 17% from an $\text{Er}^{3+}/\text{Pr}^{3+}$ codoped ZBLAN fiber [1].

In this paper, we investigate whether energy recycling by energy-transfer upconversion (ETU) from the $^4I_{11/2}$ lower laser level with its inherent enhancement of the slope efficiency [2] by a factor of 2 can operate this fiber laser more efficiently than lifetime quenching of the lower laser level by the Pr^{3+} codopant (see Fig. 1). In order to answer this question, we determined spectroscopically the parameters W_1 and W_2 of ETU from the $^4I_{11/2}$ lower and $^4I_{13/2}$ upper laser levels, respectively (see Fig. 2), as well as cross relaxation from the $^4S_{3/2}/^4F_{7/2}$ levels and energy transfer from the Er^{3+} laser levels to the Pr^{3+} codopant in ZBLAN bulk samples. We find that ETU from the lower laser level is typically a factor-of-three larger than ETU from the upper laser level (Fig. 2). These values are more favorable than the corresponding values in $\text{Er}^{3+}:\text{LiYF}_4$. We use these values to calculate the performance of Er^{3+} and $\text{Er}^{3+}/\text{Pr}^{3+}$ doped ZBLAN fiber lasers for the commonly chosen dopant concentrations. The calculation uses the fiber parameters of [1] and includes pumping at 790 nm with 12 W of power launched into the double-clad fiber.

For the $\text{Er}^{3+}/\text{Pr}^{3+}$ codoped system, we find good agreement of the calculated results with the experimental data of [1]. Our results show that ETU in Er^{3+} :ZBLAN is sufficiently strong to deplete the lower laser level and recycle the energy to the upper laser level, thereby enhancing the slope efficiency from 14 to 22% for a dopant concentration of 4 mol.% (see Fig. 3), which allows for almost complete pump-power absorption in a 10-m long fiber. Pumping at 980 nm may further enhance the slope efficiency to approximately 30% ZBLAN double-clad fibers with the investigated dopant concentrations are commercially available with low losses. Experimentally, output powers of approximately 5 W can be expected at 2.7 μ m.

Fig. 1. Partial energy-level diagram of the 2.7- μ m Er^{3+} and $\text{Er}^{3+}/\text{Pr}^{3+}$ doped ZBLAN fiber lasers.

Fig. 2. Measured ETU parameters W_1 , W_2 from the Er^{3+} lower and upper laser levels.

Fig. 3. Calculated slope efficiencies for Er^{3+} and $\text{Er}^{3+}/\text{Pr}^{3+}$ doped ZBLAN fibers versus Er^{3+} conc.

References

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Luminescence and Laser Action of Nd^{3+} doped double chloride crystal

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The low-energy phonon spectrum of chloride crystals allows rare-earth ions to serve as favorable luminescent centers for laser action in the IR spectral region, whereas the luminescence of fluoride and oxide crystals is quenched by fast multiphonon relaxation. We have searched for a crystalline chloride matrix suitable for diode-pumped lasers.

The knowledge of radiative probabilities of the transitions in rare-earth ions is useful for prediction of possible practical applications, and for this reason we studied the optical spectra of double chloride $\text{KPr}_2\text{Cl}_5\text{-Nd}^{3+}$ crystals. The crystals were grown, for the first time, using the Bridgman technique. We deduced the distribution coefficient of K_{Nd} 0.86 for $\text{KPr}_2\text{Cl}_5\text{-Nd}^{3+}$. The neodymium concentration in the sample was determined by x-ray spectral analysis with the electron-probing micro-analyzer Camebax. The absorption and luminescence spectra were recorded, intensity parameters were determined by the Judd-Ofelt method, radiative and non-radiative transition probabilities were calculated, and concentration quenching was considered.

The maximum absorption cross-section near 589 nm was found to be $\sigma_a(\lambda) = 1.5 \cdot 10^{-19} \text{ cm}^2$, while the absorption band near 810 nm coinciding with emission band of laser diodes is $\sigma_a(\lambda) = 6.5 \cdot 10^{-20} \text{ cm}^2$. The intensity parameters have been obtained by the Judd-Ofelt method. For $\text{KPr}_2\text{Cl}_5\text{-Nd}^{3+}$ we obtained the following values: $\Omega_2 = 10.98 \cdot 10^{-20}$, $\Omega_4 = 8.01 \cdot 10^{-20}$, and $\Omega_6 = 6.19 \cdot 10^{-20} \text{ cm}^2$. The probabilities of radiative transitions were calculated using these values of intensity parameters. The estimates of multiphonon non-radiative transition rates were provided and it was concluded that $\text{KPr}_2\text{Cl}_5\text{-Nd}^{3+}$ crystals experience considerable quenching for excited levels separated by the energy gap of $A_{\text{LF}} = 1000 \text{ cm}^{-1}$. These conclusions are in good agreement with the results the luminescence spectra. The intense luminescent bands in visible and near IR spectral regions (at 606, 760, 890, 1060 nm) were identified with the transitions to the ground state and the bands around 600, 660 and 690 nm are associated with transitions between excited states. Under UV excitation the most intense transitions in UV and VIS originate from $^3D_{3/2}$ level.

The combination of high intensity of luminescent transitions and long life time of neodymium radiative levels (up to 200 μ s for $^4F_{3/2}$ level) permit us to conclude that the $\text{KPr}_2\text{Cl}_5\text{-Nd}^{3+}$ crystals may be considered as a new luminescent material promising for laser and telecommunication applications. We have thus far demonstrated laser action at 1.06 μ m achieving a slope efficiency of 7 %, using a 5.5 mm crystal and pumping at 882 nm with a Cr:LiSAF laser.

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