Saturation of the 2.71 $\mu$m laser output in erbium-doped ZBLAN fibers

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Abstract

The saturation of the 2.71 $\mu$m laser output power has been investigated in an erbium doped ZBLAN single-mode fiber with an Er$^{3+}$ concentration of 5000 ppm mol. The bleaching of the ground state, the absorption coefficient at the pump wavelength and the fluorescence intensities over a wide wavelength range have been measured simultaneously during laser emission. In a computer simulation the rate equation system of the Er$^{3+}$ system in ZBLAN fibers has been analyzed. The saturation of the 2.71 $\mu$m laser output is explained by simultaneous lasing at 850 nm.

1. Introduction

The great advantages of single-mode fiber lasers are based on their geometry. The guiding structure guarantees an optimal overlap between low order pump modes and the laser mode such that single-mode emission is achieved even at high pump powers. Fibers can be cut to lengths allowing an optimal adjustment to pump light absorption. Due to the small core area, high pump intensities are available even at low pump powers which allows low laser thresholds. The large surface area to volume ratio leads to good heat dissipation. The generation and transport of laser emission takes place in the same medium and, together with diode pumping, a very compact all-solid-state laser device can be obtained. The single-mode structure of the fiber, however, requires single-mode pump sources. From single-mode laser diodes only limited pump power is available. To surpass this limit, double-clad fibers can be used. These fibers allow the use of high power multimode laser diodes as pump sources to generate single transverse mode laser output. With double-clad single-mode fibers output powers of 1 to 5 W have been obtained [1–4]. A further increase of the output power can be expected by using the side pumped geometry [5]. The side pumping opens the possibility to considerably increase the pump power by repetitive pumping. The limits are then given by the damage threshold of the fiber [6] and by saturation effects of the laser system [7].

Our goal is to develop a high power all-solid-state erbium single transverse mode fiber laser at 2.71 $\mu$m for medical applications such as cutting of tissue [8]. Saturation of the laser output may occur due to bleaching of the ground state. An additional saturation effect, however, seems to limit the output power to even lower values [9]. This additional saturation effect has not yet been experimentally investigated in erbium doped ZBLAN fibers.

In the present paper we report on investigations of the saturation in an erbium doped ZBLAN single-mode fiber laser. The bleaching of the ground state, the absorption coefficient at the pump wavelength at 791 nm and the fluorescence intensities over a wide wave-
length range have been measured simultaneously during laser emission at 2.71 µm. The rate equation system of the Er$^{3+}$ in ZBLAN single-mode fiber is analyzed in a computer simulation.

2. Experimental arrangements

The saturation of the 2.71 µm laser output power was investigated in an erbium doped ZBLAN single-mode fiber with an Er$^{3+}$ concentration of 5000 ppm mol. ($8 \times 10^{19}$ cm$^{-3}$). The fiber length was 82 cm and the core diameter 6.5 µm. To simulate high power diode pumping, a titanium sapphire laser (Spectra Physics 3900) was used operating at 791 nm in TEM$_{00}$ mode. The pump power could be adjusted between 25 mW and 1.2 W using a variable beam splitter. The pump beam was focused with a microscope objective (Olympus 20×) into the fiber. No external mirrors were used for the laser resonator. The 2.71 µm resonator was formed using only the Fresnel reflections at the two cleaved fiber ends. This was in order to raise the threshold to higher pump powers so that processes occurring below threshold could clearly be determined. The laser light at the fiber end was filtered using a long wavelength pass filter (Corion RL-2000) and measured with a thermo-electric detector (Sensor Physics 210-S).

In a first experiment the bleaching of the ground state was investigated by measuring the transmission of probe light through the fiber with and without excitation of the erbium ions in the fiber at different pump powers. The experimental setup is shown in Fig. 1. The 791 nm pump light from the titanium sapphire laser was guided by a dichroic mirror, $R > 99\%$ at $\lambda = 791$ nm, and focused with a microscope objective (Olympus 20×) into the fiber. The pump power could be blocked with a mechanical shutter. The probe light from the halide lamp (Riluma, 400 W), modulated by a chopper, was focused into the other end of the fiber with a microscope objective (Olympus 20×). The transmitted probe light was collimated with the microscope objective for the pump beam, passed through the dichroic mirror, $T = 90\%$ at $\lambda = 510$ nm, through a monochromator set at 510 nm and onto a photo diode (Laser Components OSD-5T). The probe light at 510 nm was chosen because at this wavelength only ground-state absorption (GSA) occurs [10]. The signal was analyzed with a lock-in amplifier (Stanford Res. SR 530) in connection with a PC. By comparison of the transmission of the probe light at 510 nm with and without excitation of the erbium ions the population of the ground state could be determined. In a previous experiment the ground-state absorption coefficient at 510 nm was determined to be 0.02 cm$^{-1}$ for a ground-state population of $8 \times 10^{19}$ cm$^{-3}$.

In a second experiment the absorption coefficient at the pump wavelength was determined by measuring the transmission of the pump beam as a function of the pump power at the fiber end using a thermo-electric detector (Sensor Physics) and an interference filter for 791 nm.

In a third experiment the fluorescence intensities over a wide wavelength range were measured as a function of pump power. The fluorescence light from the fiber end was collimated by a lens and divided using two beam splitters in series. The divided fluorescence light was detected simultaneously by a multichannel spectrum analyzer (Tracor Northern TN-1710) and two grating monochromators (Jobin Yvon H20, 300 lines/mm) in connection with a photo diode (Laser Components OSD-5T) and a PbS detector (Ealing 28-7870) and two lock-in amplifiers (Stanford Res. SR 530).

3. Results

The experimental data from the measurements of the laser output at 2.71 µm, the bleaching of the ground state, the absorption coefficient at 791 nm and the fluorescence intensities are summarized in Fig. 2.

Fig. 2a shows the laser output at 2.71 µm as a function of launched pump power at 791 nm. The threshold was 144 mW and the slope efficiency in the unsaturated
saturation occurs above 480 mW. The fluorescence intensity at 850 nm strongly increases above a threshold of 480 mW.

4. Rate equations

In a computer simulation the behavior of the 791 nm pumped 2.71 µm ZBLAN:Er$^{3+}$ single-mode fiber laser is analyzed. The results of the computer simulation lead to a deeper understanding of the population mechanisms and laser properties of the Er$^{3+}$ system in ZBLAN single-mode fibers. Despite the inhomogeneous broadening of the absorption and emission lines many spectroscopic data of erbium in ZBLAN glass are comparable to the corresponding data in LiYF$_4$, so the energy of the Stark levels, the degeneracy of the multiplets and branching ratios have been adopted from that system [11]. Experimentally determined parameters of Er$^{3+}$ in ZBLAN glass such as the lifetimes and the stimulated emission cross section are taken from [12]. Unknown parameters such as the excited-state absorption cross sections for erbium in ZBLAN glass were estimated and determined to lead to the best fit between experimental data and the computer simulation.

The rate equation system considers all excited levels up to level $^4$F$_{3/2}$ (Fig. 3). Levels $^2$H$_{11/2}$ and $^4$S$_{3/2}$ as well levels $^4$F$_{3/2}$ and $^4$F$_{5/2}$ are thermally coupled to each others, therefore they are combined to one level, respectively. The levels are labeled in the energetic order of the Er$^{3+}$ level system, starting with $i=0$ for the ground state $^4$I$_{15/2}$. The rate equation system further takes into consideration the lifetimes $\tau_i$ (Fig. 3), branching ratios $\beta_{ij}$ on the transitions $i \rightarrow j$, ground-state absorption $R_0$, ground-state bleaching, excited-state absorption $R_{ij}$ from level $^4$I$_{13/2}$ and $R_{i2}$ from level $^4$I$_{11/2}$, stimulated emission rates s$E$ at 2.71 µm ($^4$I$_{11/2} \rightarrow ^4$I$_{13/2}$) and at 850 nm ($^4$S$_{3/2} \rightarrow ^4$I$_{13/2}$), possible stimulated emission at 1560 nm ($^4$I$_{13/2} \rightarrow ^4$I$_{15/2}$), 970 nm ($^4$I$_{11/2} \rightarrow ^4$I$_{15/2}$) and 546 nm ($^4$S$_{3/2} \rightarrow ^4$I$_{15/2}$), the radiative fraction $\gamma_{ij}$ on the laser transitions, Boltzmann populations $b$ and degeneracies $g_{ij}$ of the assumed Stark laser levels $j$ of level $i$, core sections $\sigma_{ij}$ on the transitions $i \rightarrow j$, fiber length $l$, optical fiber length $l_{opt}$, core radius $r_{core}$, transmittances $T$ at the fiber ends, fiber losses $L$, the fraction $P_i/P$ of the spontaneous emission emitted into the laser mode, pump wavelength $\lambda_p$,
Fig. 3. Er\textsuperscript{3+} level scheme with GSA (R\textsubscript{03}), ESA (R\textsubscript{15}, R\textsubscript{27}) and stimulated emission at 2.71 μm (stE\textsubscript{21}) and at 850 nm (stE\textsubscript{51}).

Launched pump power \( P_{in} \), Planck’s constant \( h \) and the velocity of light \( c \). Interionic processes such as upconversion and cross relaxation are not included in the simulation, because the Er\textsuperscript{3+} concentration in the fiber is rather low.

The rate equations for the population densities \( N\textsubscript{i} \), the photon densities \( \phi\textsubscript{ij} \) and the stimulated emission rates \( stE\textsubscript{ij} \) are given by

\[
dN\textsubscript{7}/dt = + R\textsubscript{27}N\textsubscript{2} - \tau\textsubscript{7}^{-1}N\textsubscript{7} , \quad (1)
\]

\[
dN\textsubscript{6}/dt = - \tau\textsubscript{6}^{-1}N\textsubscript{6} + \beta\textsubscript{16} \tau\textsubscript{1}^{-1}N\textsubscript{7} , \quad (2)
\]

\[
dN\textsubscript{5}/dt = + R\textsubscript{15}N\textsubscript{1} - \tau\textsubscript{5}^{-1}N\textsubscript{5} + \sum_{i=6,7} (\beta\textsubscript{15} \tau\textsubscript{i}^{-1}N\textsubscript{i}) - stE\textsubscript{51} - stE\textsubscript{50} , \quad (3)
\]

\[
dN\textsubscript{4}/dt = - \tau\textsubscript{4}^{-1}N\textsubscript{4} + \sum_{i=5,7} (\beta\textsubscript{14} \tau\textsubscript{i}^{-1}N\textsubscript{i}) , \quad (4)
\]

\[
dN\textsubscript{3}/dt = + R\textsubscript{03}N\textsubscript{0} - \tau\textsubscript{3}^{-1}N\textsubscript{3} + \sum_{i=4,7} (\beta\textsubscript{13} \tau\textsubscript{i}^{-1}N\textsubscript{i}) , \quad (5)
\]

\[
dN\textsubscript{2}/dt = - R\textsubscript{27}N\textsubscript{2} - \tau\textsubscript{2}^{-1}N\textsubscript{2} + \sum_{i=3,7} (\beta\textsubscript{12} \tau\textsubscript{i}^{-1}N\textsubscript{i}) - stE\textsubscript{21} - stE\textsubscript{20} , \quad (6)
\]

\[
dN\textsubscript{i}/dt = - R\textsubscript{03}N\textsubscript{0} + \sum_{i=1,7} (\beta\textsubscript{0i} \tau\textsubscript{i}^{-1}N\textsubscript{i}) + stE\textsubscript{10} + stE\textsubscript{51} - stE\textsubscript{10} , \quad (7)
\]

\[
dN\textsubscript{0}/dt = - R\textsubscript{03}N\textsubscript{0} + \sum_{i=1,7} (\beta\textsubscript{0i} \tau\textsubscript{i}^{-1}N\textsubscript{i}) + stE\textsubscript{10} + stE\textsubscript{20} + stE\textsubscript{50} , \quad (8)
\]

\[
d\phi\textsubscript{ij}/dt = (\lambda_{ij}/P_{in}) \left[ (P_{i}/P) \frac{\gamma_{ij} \beta_{ij} \tau_{i}^{-1}N_{i}}{1 - l_{opt}} \right] + stE\textsubscript{ij} \quad (9)
\]

\[
stE\textsubscript{ij} = (b_{t}N_{t} - (g_{i}/g_{f})b_{t}N_{j}) \sigma_{ij} c \theta_{ij} . \quad (10)
\]

The equation for the pump rate including excited-state absorption and bleaching of the ground state is

\[
R_{g} = [\sigma_{p}(\sigma_{03}N_{0} + \sigma_{15}N_{1} + \sigma_{27}N_{2})] \\
\times [\lambda_{p} \frac{(h c l \tau_{core}^{2})}{\hbar}] \\
\times [1 - \exp(- (\sigma_{03}N_{0} + \sigma_{15}N_{1} + \sigma_{27}N_{2})l)] P_{in} . \quad (11)
\]

The rate equation system is solved in a Runge–Kutta calculation of 4th order.

5. Discussion

A possible reason for the saturation of the laser output power is the bleaching of the ground state due to accumulation of population in excited states. Beside the absorption from the ground state there are also transitions to the ground state. When both processes are in equilibrium the ground-state population takes a constant value. This occurs above a launched pump power of 230 mW, as shown in Fig. 2b. Comparing with Fig. 2a it can be seen that the laser at 2.71 μm is above threshold and the increase of the output power with pump power remains unaffected when the ground-state population becomes constant. The laser output power, however, saturates suddenly above a pump power of 480 mW. The bleaching of the ground state therefore cannot be responsible for the saturation of the 2.71 μm laser output.

When only GSA occurred at the pump wavelength, the absorption coefficient would follow the ground-state population. The constant value of the absorption coefficient at the pump wavelength in spite of the ground-state bleaching in Fig. 2b can only be explained by additional absorption due to strong excited-state
absorption processes (ESA) at the pump wavelength. The pump light is also absorbed on the transitions $^{4}I_{13/2} \rightarrow ^{4}S_{3/2}$ and $^{1}I_{11/2} \rightarrow ^{4}F_{3/2}$. The simulation predicts a cross section of $\sigma_{15} = 1 \times 10^{-22}$ cm$^2$ for the ESA on the transition $^{1}I_{13/2} \rightarrow ^{4}S_{3/2}$, which is twice the value of the measured GSA cross section $\sigma_{03}$ and this ratio is in good agreement with results obtained in Ref. [13]. For the ESA cross section at the transition $^{4}I_{11/2} \rightarrow ^{4}F_{3/2}$ a value of $\sigma_{27} = 2 \times 10^{-22}$ cm$^2$ was found in the simulation to be consistent with the experimental data. The pump ESA from level $^{4}I_{11/2}$ has a small cross section but the large population of the upper laser level leads to a significant ESA rate $R_{27}$.

The measured fluorescence intensities are shown in Fig. 2c and the corresponding calculated population densities of the initial levels are shown in Fig. 4. The ground-state fluorescence from the upper laser level at 970 nm saturates above a pump power of approximately 150 mW. This is due to the threshold of the 2.71 $\mu$m laser on the transition $^{4}I_{11/2} \rightarrow ^{4}I_{13/2}$ because the stimulated emission keeps the population of the upper laser level constant. Therefore the population of the $^{4}I_{11/2}$ level saturates and so does the fluorescence intensity from this level. The population density of the lower laser level $^{4}I_{13/2}$ follows this behavior as expected from the threshold condition, because the population difference between upper and lower laser levels remains constant [14]. The same saturation behavior is expected for the fluorescence intensity from the lower laser level. But the 1560 nm fluorescence intensity is not proportional to the population of the $^{4}I_{13/2}$ level. In the simulation, stimulated emission at this wavelength below threshold as a possible explanation could not be confirmed. The fluorescence intensity at 546 nm is also not proportional to the population density of its initial level.

Fig. 4. Calculated laser outputs at 2.71 $\mu$m (■) and 850 nm (●).

Fig. 5. Calculated population densities of $^{4}I_{15/2}$ (●), $^{4}I_{13/2}$ (▲), $^{4}I_{11/2}$ (■) and $^{4}S_{3/2}$ (●).

In the simulation this behavior can be explained by some stimulated emission below laser threshold. From the same saturation behavior of the fluorescence intensities from $^{4}S_{3/2}$ at 546 nm and $^{4}I_{13/2}$ at 1560 nm above 480 mW a coupling between these levels can be expected. The transition $^{4}S_{3/2} \rightarrow ^{4}I_{13/2}$ corresponds to a fluorescence with a wavelength of 850 nm [15]. The drastic increase of the fluorescence intensity at the pump threshold of 480 mW clearly indicates the beginning of lasing at 850 nm.

The calculated laser output at 2.71 $\mu$m and at 850 nm is shown in Fig. 5. The coincidence of saturation of the laser output at 2.71 $\mu$m with the threshold of the 850 nm laser can clearly be seen.

The laser output at 2.71 $\mu$m, the coincidence of the 850 nm laser threshold with the saturation of the 2.71 $\mu$m laser output and the fluorescence intensities, and the behavior of the ground-state population could be simulated with the rate equation system neglecting interionic processes like upconversion and cross relaxation. So we can assume that the major non-linear process in the 5000 ppm doped Er$^{3+}$ ZBLAN fiber laser is ESA.

6. Explanation of the saturation

The 2.71 $\mu$m laser occurs on the transition $^{4}I_{11/2} \rightarrow ^{4}I_{13/2}$. ESA from both laser levels deplete these levels. Since the ESA from $^{4}I_{13/2}$ is stronger, the 2.71 $\mu$m output power rises with increasing pump power. Both ESA processes populate level $^{4}S_{3/2}$, either directly or via the fast multiphonon relaxation from $^{4}F_{3/2}$. Due to the 400 $\mu$s lifetime of level $^{4}S_{3/2}$, an accumulation of
population in this level occurs. At a pump power of 480 mW the laser threshold on the 850 nm transition $^4S_{3/2} \rightarrow ^4I_{13/2}$ is reached and both levels are coupled due to the cw laser emission. Since the lower laser level of the 850 nm laser is identical to that of the 2.71 $\mu$m laser, the populations of levels $^4I_{13/2}$, $^4I_{11/2}$ and $^4S_{3/2}$ are coupled to each other. The ground state has already stabilized to a constant population. Since there are no other metastable levels to, from which energy can be significantly transferred, the whole Er$^{3+}$ system becomes stabilized. All population densities are maintained to their values at the 850 nm laser threshold. As a consequence the 2.71 $\mu$m laser output saturates, fluorescence intensities saturate, and additional pump power is compensated by increased laser output at 850 nm.

To obtain optimized laser operation at 2.71 $\mu$m the emission at 850 nm should be suppressed e.g. by using AR coatings for 850 nm on the fiber ends. In addition, co-lasing on the 1.7 $\mu$m transition $^4S_{3/2} \rightarrow ^4I_{0/2}$ and the subsequent multiphonon relaxation to the $^4I_{11/2}$ level would recycle the energy to the upper laser level of the 2.71 $\mu$m transition. This consequently overcomes the saturation and increases the 2.71 $\mu$m laser output.

7. Conclusion

In conclusion the saturation of the 791 nm pumped 2.71 $\mu$m erbium ZBLAN fiber laser output is due to co-lasing at 850 nm on the $^4S_{3/2} \rightarrow ^4I_{13/2}$ transition. The bleaching of the ground state as a possible explanation for the saturation could be excluded by simultaneously comparing the dependence of laser output and ground-state population on pump power. The saturation of the laser output power was determined in an erbium doped ZBLAN single-mode fiber with an Er$^{3+}$ concentration of 5000 ppm. In a computer simulation the rate equation system was analyzed. The good agreement between the simulation and measurement with the lack of interionic processes like upconversion and cross relaxation lead to the assumption that the major nonlinear process in the 5000 ppm doped Er$^{3+}$ ZBLAN fiber laser is excited-state absorption. From the simulation the ESA cross sections on the transitions $^4I_{13/2} \rightarrow ^4S_{3/2}$ and $^4I_{11/2} \rightarrow ^4F_{3/2}$ could be determined to be $\sigma_{15} = 1 \times 10^{-21}$ cm$^2$ and $\sigma_{27} = 2 \times 10^{-22}$ cm$^2$, respectively.

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