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Journal of Alloys and Compounds 275–277 (1998) 276–278

Journal of ALLOYS AND COMPOUNDS

Visible emission processes in heavily doped Er/Yb silica optical fibers

F. Goutaland[a,*], Y. Ouerdane[a], A. Boukenter[a], G. Monnom[b]

[a]*Laboratoire Traitement du Signal et Instrumentation, UMR CNRS 5516, 23 rue du Dr. P. Michelon 42023, Saint-Etienne Cédex 2, France*
[b]*Laboratoire de Physique de la Matière Condensée, CNRS-UA 190, Parc Valrose, 06108, Nice Cédex 2, France*

Abstract

We have studied the spectroscopic behavior of Er^{3+} ion in heavily doped silica optical fibers containing different Yb^{3+} ions concentrations. A combination of experimental spectra in the visible range obtained under visible (488 nm) and infrared (790–900 nm) excitations allows the upconversion processes to be determined. In this way, evidence is given for blue (410 nm), green (548.7 and 561 nm) and red (660 nm) emissions in the different fibers. © 1998 Elsevier Science S.A.

Keywords: Energy transfer upconversion (ETU); Excited state absorption (ESA)

1. Introduction

Multidoped systems using Yb^{3+} ions as sensitizers are already well known and can be used either in telecommunications applications such as Yb–Er at 1.55 μm [1], or in upconversion pumping lasers such as Yb–Tb [2]. In our study, the role of Yb^{3+} ions acting as sensitizers in heavily Er-doped silica optical fibers can be clearly seen in the processes leading to the two blue transitions around 410 nm $^2H_{9/2}\rightarrow{}^4I_{15/2}$ (observed in Er^{3+}:$YLiF_4$ [3]) and $^2P_{3/2}\rightarrow{}^4I_{13/2}$ (observed in ZBLAN fibers [4]). The first one is due to Yb→Er energy transfer (Yb:$^2F_{5/2}$, Er:$^4S_{3/2}$)→(Yb:$^2F_{7/2}$, Er:$^2H_{9/2}$) which leads to populate the $^2H_{9/2}$ emitting level (this population is confirmed by a green emission around 561 nm corresponding to the transition $^2H_{9/2}\rightarrow{}^4I_{13/2}$). The second one, present in the two types of fibers (doped or not with Yb^{3+} ions) is due to ESA signal at 548.7 nm (attributed to the $^4S_{3/2}\rightarrow{}^4I_{15/2}$) from the $^4S_{3/2}$ level to feed the $^2P_{3/2}$ level.

2. Experimental

The silica fibers used in this work were made by the MCVD (modified chemical vapor deposition) technique. Rare earth ions concentration up to 2000 ppm (both for Er^{3+} and Yb^{3+}) can be achieved by the solution doping technique. The emission spectra were performed at room temperature using either a visible excitation (CW Ar^+ laser at 488 nm) or an infrared excitation obtained with a CW titanium–sapphire laser in the (780–900 nm) spectral range. A classical experimental set-up composed of a double spectrometer (HRD1 Jobin-Yvon) equipped with two identical 1800 l/mm gratings, a cooled photomultiplier (Hamamatsu R943-02) and a counting system, is used to record the emission spectra.

3. Results

3.1. Green and red emissions

Figs. 1 and 2 show, respectively, the Er^{3+} and Yb^{3+} energy level diagrams and the spectra recorded at an 819-nm excitation wavelength and 300-mW pump power

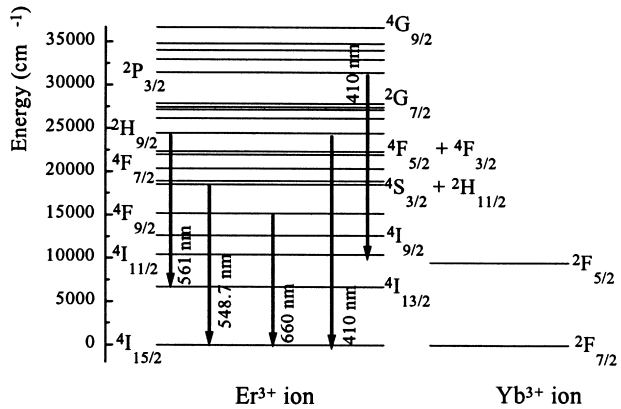

Fig. 1. Er^{3+} and Yb^{3+} energy level diagram in Er:YLiF4 [3].

*Corresponding author. Fax: +33 4 77485120; e-mail: ouerdane@univ-st-etienne.fr

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PII: S0925-8388(98)00326-0

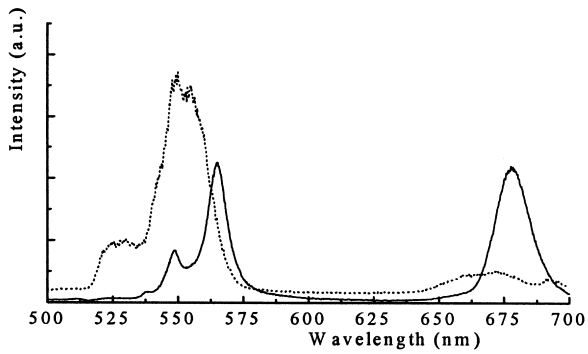

Fig. 2. Part of the upconversion emission spectra recorded at an 819-nm excitation wavelength and 300-mW pump power. Solid line: Er/Yb-codoped fiber (2000/2000 ppm); dotted line, Er-doped fiber (2000 ppm).

for the Er/Yb- and Er-doped fibers. For the codoped one, the spectrum presents two green emissions at 548.7 and 561 nm corresponding, respectively, to the $^4S_{3/2} \rightarrow {}^4I_{15/2}$ and $^2H_{9/2} \rightarrow {}^4I_{13/2}$ transitions, whereas only the 548.7-nm emission band exists in the case of the Er-doped fiber.

Concerning the well-known 548.7-nm emission band in the Er (2000 ppm)-doped fiber, several processes depending on the excitation wavelength can lead to the population of the $^4S_{3/2}$ emitting level. For an infrared excitation wavelength between 800 and 840 nm, the Er^{3+} ions are excited into the $^4I_{9/2}$ level, and a part of them relaxes on the $^4I_{13/2}$ level. Either the following energy transfer upconversion (ETU) ($Er:{}^4I_{9/2}$, $Er:{}^4I_{13/2}$)→($Er:{}^4I_{15/2}$, $Er:{}^4F_{7/2}$) or excited state absorption of pump photons from the $^4I_{13/2}$ metastable level (pump ESA) allows us to populate the $^4F_{7/2}$ level and then the $^4S_{3/2}$ level by non-radiative deexcitation. Notice that the presence of clusters in the fiber, due to high Er^{3+} concentration, enhances the ETU probability because of the strong interaction between different Er^{3+} ions. For higher pump wavelengths, we do not directly populate the $^4I_{9/2}$ level but the $^4I_{11/2}$ one, so the two cases mentioned above cannot occur. Nevertheless, a weak green signal is observed and we can propose two other possibilities to excite the $^4S_{3/2}$ level: ETU between two Er^{3+} ions excited on the $^4I_{11/2}$ level (although its short lifetime) or pump ESA (called intermediate excited state absorption (IESA) by Krug et al. [5]) from the $^4I_{11/2}$ level will permit us to populate the $^4F_{7/2}$ level and consequently the $^4S_{3/2}$ one. In the case of the Er/Yb-codoped fiber, in addition to the two processes existing in the Er-doped fiber, the following energy transfer can occur, as shown by Maurice et al. [6]: ($Yb:{}^2F_{5/2}$, $Er:{}^4I_{11/2}$)→($Yb:{}^2F_{7/2}$, $Er:{}^4F_{7/2}$). The Er^{3+} $^4S_{3/2}$ level is then populated by non-radiative decay.

For all our infrared excitation range, the Er-doped fibers do not present any clear peak emission at 561 nm so there is no signal ESA at 548.7 nm from the $^4I_{13/2}$ level, as proposed by Hebert et al., in Er:$YLiF_4$ [3], to explain this emission. Yb^{3+} ions thus play an important rôle in the population of the $^2H_{9/2}$ emitting level and we can propose the following energy transfer ($Yb:{}^2F_{5/2}$, $Er:{}^4S_{3/2}$)→($Yb:{}^2F_{7/2}$, $Er:{}^2G_{7/2}$) which will feed, after non-radiative deexcitation from the $^2G_{7/2}$ level, the $^2H_{9/2}$ one. Several observations confirm this transfer. First, the green emission (at 561 nm) increases with the excitation wavelength: this can be explained by a better Yb→Er energy transfer due to the enhancement of the Yb^{3+} ions excited by the pump. Moreover, some experiments have been carried out with different concentrations: for a 700/700-ppm Er/Yb-codoped fiber, the 561-nm green emission intensity is rather intense, whereas this intensity is much smaller for a 2000/200-ppm Er/Yb-codoped one. Consequently, the Yb→Er energy transfer is more efficient for the 700/700-ppm codoped fiber. Clustering effects can also lead to an efficient Yb→Er energy transfer as shown by Maurice et al. [6], at a 970 nm excitation wavelength. Furthermore, the Yb→Er energy transfer is still efficient at a 488-nm excitation wavelength (although the Yb^{3+} ions cannot be directly excited by pump photons) because we observed the two green (548.7 and 561 nm) emission bands, whereas we only observe the 548.7-nm one in the case of Er^{3+}-doped fiber.

Under infrared excitation, the 660-nm red emission is strong in the case of the Er/Yb-codoped fiber, but much less intense for Er-doped fiber (Fig. 2). The Yb^{3+} ions play then an important role in the process leading to the population of the $^4F_{9/2}$ emitting level. The power law evolution of the integrated red band as a function of the pump power follows a slope of 1.57 at an 885-nm excitation wavelength. Therefore, the mechanism is not a biphotonic one and we can take into account the process suggested by Wittke et al. [7] in phosphor glass because this emission needs the presence of Yb^{3+} ions. In our case, this phenomenon can be interpreted as follows: the Er^{3+} ions are excited into the $^4F_{7/2}$ level by the mechanism mentioned above via the Yb→Er energy transfer, but an Er^{3+}–Er^{3+} quenching deexcites one ion from the $^4F_{7/2}$ to the $^4F_{9/2}$ and raises the other from the $^4I_{11/2}$ to the $^4F_{9/2}$. The two Er^{3+} ions can emit two red (660 nm) photons but this mechanism requires, overall, three incoming photons. As for the green emission, it should be noted that the red emission intensity is enhanced when we increase the excitation wavelength.

3.2. Blue emission

The blue emission at 410 nm has been observed in the two fibers at the 488-nm excitation wavelength (Fig. 3), and can be attributed to two possible transitions: $^2H_{9/2} \rightarrow {}^4I_{15/2}$ and $^2P_{3/2} \rightarrow {}^4I_{13/2}$.

As mentioned before, for Er-doped fiber, we do not observe the 561-nm emission ($^2H_{9/2} \rightarrow {}^4I_{13/2}$) at the 488-nm excitation wavelength. Consequently, the $^2H_{9/2}$ level is not populated and we can thus assign the 410-nm emission to the $^2P_{3/2} \rightarrow {}^4I_{13/2}$ transition. The $^2P_{3/2}$ emitting level is populated by ESA signals at 548.7 nm from the $^4S_{3/2}$

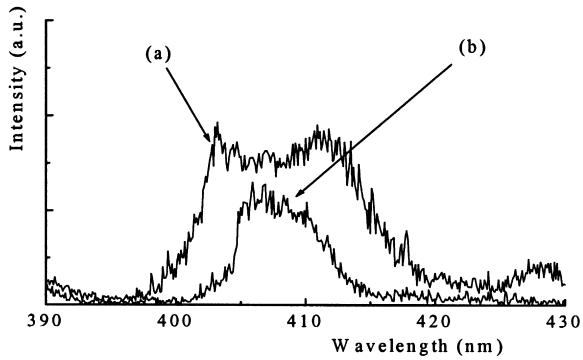

Fig. 3. Blue part of the emission spectra recorded at an 488-nm excitation wavelength and 300-mW pump power. (a) Er/Yb-codoped fiber (2000/2000 ppm); (b) Er-doped fiber (2000 ppm).

level, which will excite the Er^{3+} ions on the $^4G_{9/2}$ level and then on the $^2P_{3/2}$ one after non-radiative deexcitation [8]. The evolution of the integrated blue area as a function of the green emission intensity (at 548.7 nm), which follows a power law of 1, confirms the proposed mechanism. Another signature of the population of the $^2P_{3/2}$ level can be seen on the 470-nm emission line (not shown in our figures) corresponding to the $^2P_{3/2}\rightarrow{}^4I_{11/2}$ transition [4]. In the case of the Er/Yb-codoped fiber, this emission at 470 nm has been observed, so the $^2P_{3/2}\rightarrow{}^4I_{13/2}$ transition is involved in the blue emission at 410 nm. However, the $^2H_{9/2}\rightarrow{}^4I_{15/2}$ transition can also lead to the blue emission at 410 nm because we have observed the 561-nm emission which confirms the population of the $^2H_{9/2}$ level. The process involved in this transition seems to be as follows: after absorption of pump photons (at 488 nm), some Er^{3+} ions can be excited on the $^4I_{11/2}$ level after non-radiative deexcitation and then Er→Yb energy transfer can excite some of the Yb^{3+} ions on the $^2F_{5/2}$ level. ETU ($Yb:{}^2F_{5/2}$, $Er:{}^4S_{3/2}$)→($Yb:{}^2F_{7/2}$, $Er:{}^2G_{7/2}$) (back transfer) will then populate the $^2H_{9/2}$ level after multiphonon deexcitation from the $^2G_{7/2}$ level.

4. Conclusion

This study has shown that efficient ($Yb:{}^2F_{5/2}$, $Er:{}^4I_{11/2}$)→($Yb:{}^2F_{7/2}$, $Er:{}^4F_{7/2}$) and ($Yb:{}^2F_{5/2}$, $Er:{}^4S_{3/2}$)→($Yb:{}^2F_{7/2}$, $Er:{}^2G_{7/2}$) energy transfers can be obtained in heavily codoped Er/Yb optical fibers. While the first transfer has already been observed in such fibers [6], it is the first time to our knowledge that the second one is reported in optical fibers. The different processes proposed in this work to explain the different emission bands as a function of the excitation wavelengths and the pump power are certainly linked to the presence of clusters in the fibers due to high concentrations. Some complementary experiments (for example, lifetime measurements) are in progress in order to confirm these results.

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