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Enhanced spectroscopic properties in Er^{3+}/Yb^{3+}-activated fluoride glass–ceramics planar waveguides

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ABSTRACT

Bulk and planar waveguides fluoride glass–ceramics activated by erbium and ytterbium ions were prepared in the ZrF_4–LaF_3–ErF_3 system. Waveguides were obtained by use of physical vapor deposition process. All samples were characterized by luminescence spectroscopy. The results are discussed with the aim of assessing the role of ytterbium on the optical and spectroscopic properties of erbium doped glass–ceramics bulk and waveguides.

1. Introduction

Erbium doped waveguide amplifiers (EDWA) are attractive for integrated optical devices operating in metropolitan area networks [1]. Integrated amplifiers should be as short as possible (a few centimeters long) so that high concentrations and/or high absorption and emission cross-sections are required. Although, silica is one of the best low-cost materials, fluoride glasses remain competitive, in terms of rare-earth solubility ($>5 \times 10^{21}$ ions cm^{-3}) and low phonon energy. Moreover, Mortier et al. demonstrated that transparent glass–ceramics could be obtained by spinodal decomposition in ZrF_4–$(La,Er)F_3$-based glass with high erbium content (8 mol%) with absorption cross-section increased by 20% [2]. Fluoride glass waveguides with composition close to bulk glass can be obtained by physical vapor deposition (PVD) [3]. Therefore, it is possible to consider the use of fluoride glass–ceramics materials for photonic application. When only erbium ions are present in short waveguides, the pumping at 980 nm is not very efficient, the Er^{3+} absorption cross-section at this wavelength being quite low. This problem can be overcome by the addition of Yb^{3+} as a sensitizing ion. The strong near-infrared absorption of the Yb^{3+} at 980 nm in combination with efficient Yb → Er energy transfer increases the $^4I_{13/2}$ population density in Er^{3+}/Yb^{3+} activated glasses [4,5]. Since vapor pressure of rare-earth fluoride are quite similar, copoding can be easily reproduced in evaporated ZrF_4–$(La,Er)F_3$-based glass, provided that the type of evaporation of rare-earth mixture (mainly non-congruent) is known [6].

In this work, we present results on the fabrication and spectroscopic features of Er^{3+}/Yb^{3+}-codoped bulk and planar waveguide glass–ceramics prepared by PVD.

2. Experimental

The bulk glasses, called ZELAG *x*Er/*y*Yb, with *x* and *y* the mol% of ErF_3 and YbF_3 were prepared by classical fluoride glass preparation techniques (melting at 850 °C for 15 min – casting of the melted glass rapidly heated at 925 °C) from the following constituents in mol%: 63.3ZrF_4 24.1LaF_3 *x*ErF_3 *y*YbF_3 (6−*x*−*y*)YF_3 0.6 AlF_3 6 GaF_3. Through thermal treatment at 470 °C for 40 min in inert

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atmosphere, transparent glass–ceramics were obtained. ZrF_4–LaF_3–ErF_3–YbF_3 (ZLE and ZLEYb) waveguides stabilized by a few % of AlF_3 were prepared by PVD, in dual configuration. Details of the procedure are described in Ref. [3]. The ceramization of as-deposited films (470 °C – 20 min) was carried out under primary vacuum. Because heating at 470 °C could not be achieved in the evaporation vessel, the film was on contact with air before the heat-treatment.

Optical absorption experiments in the ultraviolet, visible and near-infrared (UV–vis–NIR) regions were performed at room temperature with a double beam spectrophotometer (UV–vis–NIR Cary 5000 Varian) with a resolution of 1 nm. The 514.5 nm line of an Ar^+-ion laser and the 980 nm line of a Ti:Sapphire laser were used as excitation sources for photoluminescence (PL) spectroscopy measurements. The spectra of the waveguides were obtained by exciting the propagation modes by prism coupling technique. Details of the experimental set-up are given in [5]. The lifetime τ was defined as the $1/e$ decay time of the fluorescence intensity because the decay of luminescence was not always single exponential especially for samples with low content of erbium (<1 mol%).

3. Results and discussion

3.1. Bulk glasses and glass–ceramics

The UV–vis–NIR absorption spectrum obtained for the 6 mol% Er^{3+} doped glass is plotted in Fig. 1a. The spectrum is characteristic of Er^{3+}-doped fluoride glasses with absorption bands identified with the transitions from the $^4I_{15/2}$ ground state to the excited states of the Er^{3+} ions. The absorption spectra of the samples codoped with 1 mol% erbium and 1–5 mol% ytterbium are presented in Fig. 1b.

The spectra show, in addition to the bands related to erbium absorption, a strong absorption peak centred at 980 nm, typical of $^2F_{7/2} \rightarrow {}^2F_{5/2}$ Yb^{3+} absorption [7] which indicates clearly the increase of the absorption coefficient at this wavelength for the codoped samples. The absorption due to Yb^{3+} can be estimated to be about four times higher than the erbium one.

Photoluminescence spectra of the bulk glasses activated with 1 mol% of erbium and x mol% of ytterbium (x = 1, 3, 5) which have been measured in the region of the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition upon excitation at 980 nm are reported in Fig. 2a.

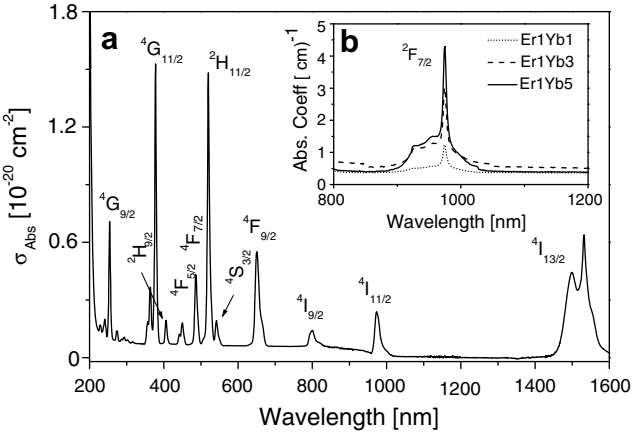

Fig. 1. UV–vis–NIR absorption spectrum of the fluoride glasses (a) doped with 6 mol% Er^{3+} and (b) codoped with 1 mol% Er^{3+}-x mol%Yb^{3+} with x = 1, 3, 5. Some of the final states of the $^4I_{15/2} \rightarrow {}^{2S+1}L_J$ transitions of erbium and transition related to Yb^{3+} absorption are labeled.

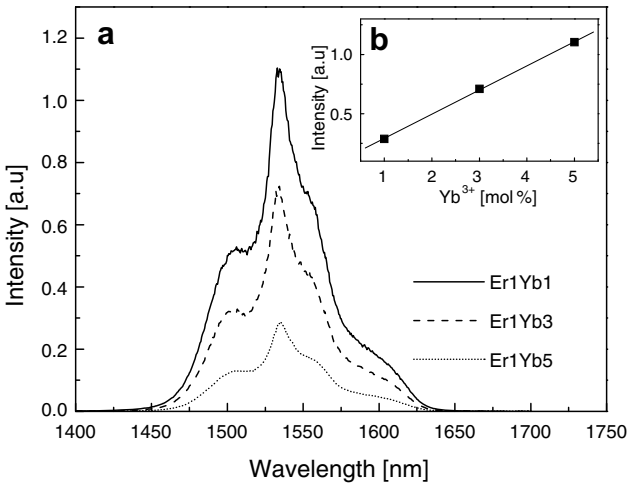

Fig. 2. (a) Photoluminescence spectra of the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition of Er^{3+} in bulk glasses doped with 1 mol% erbium and 1, 3, 5 mol% ytterbium obtained upon excitation at 980 nm and (b) related evolution of the intensity of photoluminescence emission at 1532 nm as a function of ytterbium concentration.

As expected, the shape of the transition $^4I_{13/2} \rightarrow {}^4I_{15/2}$ of Er^{3+} for the glasses activated with erbium and ytterbium ions is the same than that observed for samples without ytterbium [5]. The values of lifetime obtained for the $^4I_{13/2}$ excited state (see Table 1) are close to the radiative one calculated in ZrF_4-based glasses (10.7 ms in ZBLAN [8]) but slightly higher. This result could be related to a process of radiation trapping [9]. This resonant energy transfer process takes place between two neighbouring ions and gives rise to a measured lifetime artificially lengthen for the considered level.

Spectra and lifetimes obtained upon different excitation are almost identical. Small differences in the values of bandwidths measured can be related to different site selection achieved by the different excitation sources. The spectral width of the emission bands is due to inhomogeneous and homogeneous broadening, plus additional Stark splitting of the excited and ground states.

In order to highlight the influence of the ytterbium on the emission yield of the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition, the spectra obtained after excitation at 514.5 nm have been normalized to the main component at 1532 nm of the emission band and the respective coefficients obtained from this normalization have been applied to the spectra obtained after excitation at 980 nm for each sample.

Results are presented in Fig. 2b and show a linear increase of the photoluminescence emission intensity at 1532 nm with the content of ytterbium ions (about four times higher for an Yb/Er ratio of 5). From these results, we can suppose that the optimal concen-

Table 1
Decay time constants of the $^4I_{13/2}$ excited state in the Er^{3+}–Yb^{3+}-codoped glasses and glass–ceramics upon excitation at 980 nm (values reported with $*$ have been obtained upon excitation at 514.5 nm), obtained by a fit at $t = 1/e$ and spectral bandwidth (FWHM) of the transition $^4I_{13/2} \rightarrow {}^4I_{15/2}$of erbium.

Sample	Glass		Glass–ceramic	
	$\tau_{1/e} \pm 0.5$ (ms)	FWHM (nm)	$\tau_{1/e} \pm 0.5$ (ms)	FWHM (nm)
Er1Yb0	13.3*	43.5*	13.1*	36.0
Er1Yb1	10.9	41.0	12.1	33.0
Er1Yb3	10.6	41.0	11.0	30.0
Er1Yb5	10.4	43.0	–	–
Er3Yb0	12.0*	43.0*	12.0*	35.5
Er3Yb3	11.2	46.0	13.3	38.0