Optical amplification in Er^{3+}-doped fluoroindate glass at 840 nm and 1550 nm

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ABSTRACT

Er^{3+}-doped transparent fluoroindate glasses have been measured in a pump and probe setup in order to get optical amplification. High power laser pulses at 532 nm have been used as the pump source to strongly populate the $^4S_{3/2}$ ($^2H_{11/2}$) levels of Er^{3+} ions due to ground state absorption. Low signal beam cw laser radiation at 850 nm was used to stimulate the emission associated with the $^4S_{3/2}$ ($^2H_{11/2}$) → $^4I_{13/2}$ electronic transition. The high power pump pulses allowed achieving population inversion between the Er^{3+} levels of the transition $^4S_{3/2}$ ($^2H_{11/2}$) → $^4I_{13/2}$. Under these conditions, positive optical gain around 1.33 cm^{-1} (5.7 dB/cm) has been measured in Er^{3+}-doped fluoroindate during the first 200 μs.

Using a similar setup experiments of gain have been carried out for the $^4I_{13/2}$ → $^4I_{15/2}$ transition of the Er^{3+} ions (at 1.5 μm). The obtained values are greater than 1.2 cm^{-1} (5.2 dB/cm) during the first 200 μs. Under these conditions and using the net cross-section simulation, the inversion population of the $^4I_{13/2}$ ↔ $^4I_{15/2}$ transitions could be estimated as 60% in order to obtain optical gain.

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1. Introduction

Among the new glasses which can be fibered, the fluoroindate glasses are very good promising materials due to their large transparency from 200 nm to 8 μm and the low emission rates for the doping rare earth ions. Therefore, these glasses have been extensively studied as upconverters with different ions [1–3]. However, to our knowledge, in the literature only two papers appear with experimental amplification results in these glasses [4,5]. In one of them, amplification in the violet and blue emissions of Nd^{3+} ions has been recorded, and in the another one, with Er^{3+} ions, the authors obtain at 633 nm an increase about 12% of the signal in a sample with a thickness of 1.25 cm.

In this work, the optical amplification in Er^{3+}-doped transparent fluoroindate glasses has been reported at room temperature for the low loss telecommunication windows at 850 nm and 1550 nm. Moreover, the net cross-sections at 1550 nm have been simulated in order to estimate the population inversion necessary to get optical amplification.

2. Experimental

The samples of this study have been reported in a previous work [6]. Pump and probe experiment has been designed to deter-

mine net optical gain. The sample was pumped with high energy pulses of about 5 ns of duration at 532 nm by using a frequency-doubled Nd-YAG pulsed laser. The intensity of the pump beam does not appreciably reduce when it passes through the sample; which is 1.1 mm long, due to the relatively low absorption at 532 nm and the $^2H_{11/2}$, $^4S_{3/2}$ levels are populated. Therefore, intensity of the pump beam can be considered to be a constant throughout the sample. The large energy gap from the $^2H_{11/2}$, $^4S_{3/2}$ to the next lower energy level, around 5000 cm^{-1}, prevents multiphonon de excitation; therefore efficient radiative relaxation of this level is expected.

The radiative transition from the $^4S_{3/2}$($^2H_{11/2}$) levels to the $^4I_{13/2}$ metastable level of the Er^{3+} ion gives rise to an intense emission centred at 850 nm. For amplification at this wavelength, the probe, or signal, was provided by a cw tunable Ti: sapphire laser, centred at this wavelength. Homogeneous pump and probe beams were obtained after a 3 mm diameter pinhole placed just in front of the sample. In order to cover only the whole area of the pinhole, the pump beam was focused with a converging lens. The energy levels diagram shows the proposed mechanisms to get optical amplification in a pump and probe set up (Fig. 1). This is a four levels system which is known to allow the optical gain. The signal was passed through a monochromator and then detected with a photomultiplier tube located at the output of the monochromator and analyzed in a digital oscilloscope. The incidence of both pump and probe beams was practically normal to the surface of the sample. Neutral density filters were placed in front of the signal beam to achieve an unsaturated signal regime.

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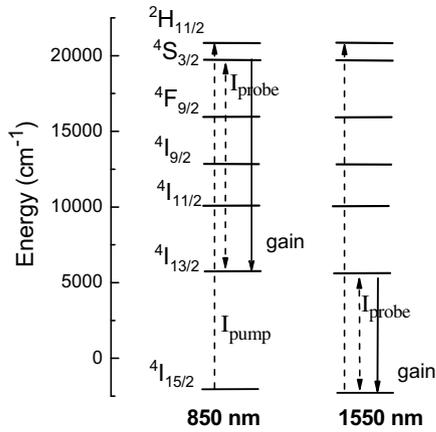E-mail address: patharo@ull.es (P. Haro-González).

Fig. 1. Energy levels diagram of Er^{3+} ions in transparent fluoroindate glasses. Dashed lines show the transitions which are produced by using Nd-YAG pulsed laser (I_{pump}) and tuneable cw Ti: sapphire laser at 850 nm or lamp at 1550 nm (I_{probe}). Solid line shows the optical gain transitions in the four (850 nm) or three levels (1550 nm) schemes.

Fig. 2. Emission spectrum for the 2.5 mol% of Er^{3+} doped sample. The solid line corresponding to I_{pp} and the dashed line shows I_p.

For optical amplification at 1550 nm the measurements have been developed by pump and probe experiment setup similar to the experiments at 850 nm. The scheme is also shown in Fig. 1 taking into account that erbium laser at 1550 nm operated on a three level scheme [7]. The probe was provided by a light from a 250 W incandescent lamp passing through a monochromator at 1550 nm. The sample was pumped with high energy pulses of about 5 ns of duration at 532 nm by the Nd-YAG pulsed laser. The output signal was passed through a monochromator and then detected with an InGaAs detector located at the output of the monochromator and analyzed in a digital oscilloscope.

3. Results and discussion

3.1. Optical amplification at 850 nm

To determine the net optical gain, the signal enhancement (SE) is defined as the ratio of the intensity of the pump and probe spectrum (I_{pp}) to the intensity of the probe (I_{probe}), where I_p represents the spontaneous emission intensity at the same wavelength when the probe is blocked before the sample [8].

$$SE = \frac{I_{pp} - I_p}{I_{probe}} \qquad (1)$$

It can be experimentally measured and it is related to the net gain coefficient by

$$SE = \exp(gL) \qquad (2)$$

where L is the length of the sample and g is the internal gain coefficient. The wavelength of the signal beam, 850 nm, matches the $^4I_{15/2}$$^4I_{9/2}$ ground state absorption. This transition, however, is strongly forbidden. It has been found that it is several orders of magnitude lower than other electronic transitions and, consequently, the absorption coefficient of the sample at the probe's wavelength can be disregarded.

The spectrum in the Fig. 2 shows the evidence of signal amplification for the 2.5 mol% sample. The dashed line shows the spontaneous emission of the sample measured after the pump pulse when the signal beam is blocked before the sample. The solid line gives the emission measured under the same pump conditions but when the signal beam is present. The SE parameter has been measured just after the pump pulse for a signal power density of 120.5 μW/cm². The values of the g coefficient have been calculated

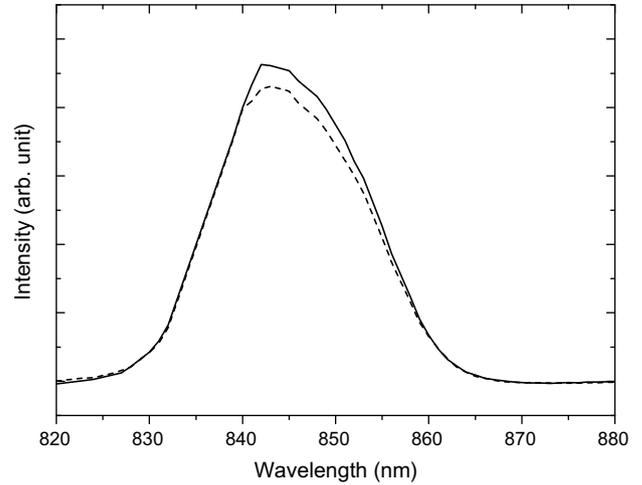using (2), as a function of the pump energy density, are shown in Fig. 3. The maximum optical gain is observed with a pump energy density of 0.104 mJ/cm², which corresponds to 1.33 cm⁻¹ (5.7 dB/cm) for the 2.5 mol% sample. Whereas, for the 0.5 mol% sample, the maximum gain corresponds to 0.63 cm⁻¹ (2.7 dB/cm). Assuming a sample with a thickness of 1.25 cm, the gain for the 2.5 mol% doped sample could give an amplification of about 500% for the signal, while the amplification in Ref. [5] was about 12% at 633 nm.

3.2. Optical amplification at 1550 nm

Erbium ions show an optical transition around 1550 nm which is a standard wavelength in silica-based optical fiber telecommunication systems. Optical fibers have been doped with Er^{3+} to develop fiber amplifiers (EDFA – Erbium Doped Fibre Amplifier) that operate in the C- and L-band. For this reason, the study of the $^4I_{13/2}$ $^4I_{15/2}$ transition is important. The propagation equation for the pump and signal field powers in a given direction is:

$$\frac{dP_s}{dz} = (\sigma_{emi}N_2(Z) - \sigma_{abs}N_1(Z))P_s(Z) = g(Z)P_s(Z) \qquad (3)$$
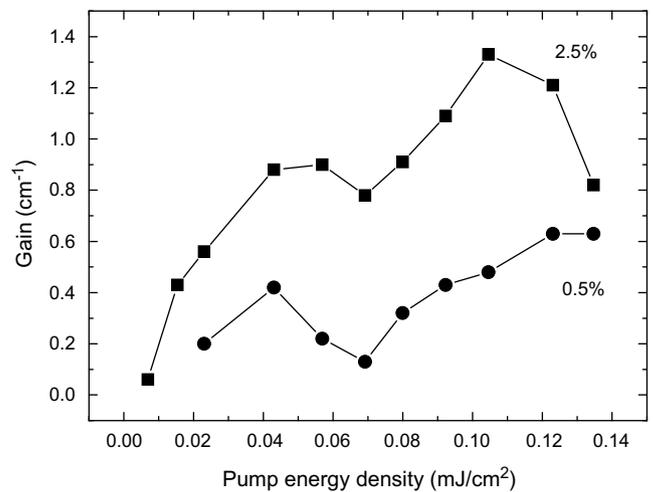

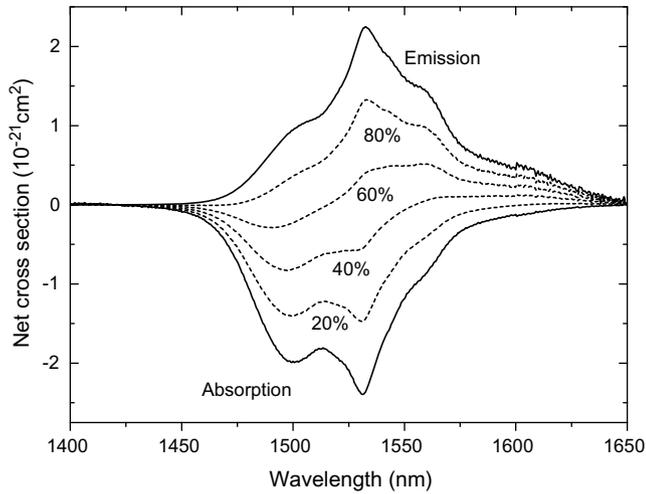Fig. 3. Optical gain vs. pump energy density for 2.5 mol% and 0.5 mol% samples.

Fig. 4. Room temperature gain cross-section spectrum for the $^4I_{13/2} \rightarrow {^4I_{15/2}}$ transition corresponding to different rate of population inversion.
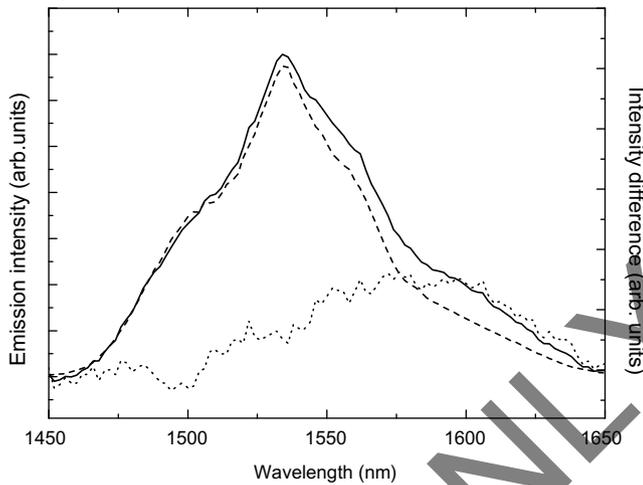

Fig. 5. Emission spectrum for the 2.5 mol% Er^{3+} doped sample. The solid line corresponds to I_{pp} and dashed line shows I_p. The dot line is the difference between both spectra.

where σ_{emi} is emission cross-section, σ_{abs} is absorption cross-section at the signal wavelength, N_i the population of the i-level and

$$g(Z) = \sigma_{emi}N_2(Z) - \sigma_{abs}N_1(Z) \qquad (4)$$

The gain cross-section (g) is one of the most relevant parameters for laser application. The emission cross-section can be determined from the absorption spectrum using the MacCumber formula [9].

$$\sigma_{emi} = \sigma_{abs} \exp((E - h\upsilon)/KT) \qquad (5)$$

where h is the Planck constant, E represents the main energy of the transition, k Boltzman constant and T temperature in Kelvin.

In this way, the amplification originated from $^4I_{13/2} \rightarrow {^4I_{15/2}}$ transition of Er^{3+} has been obtained using Eq. (4) and it is shown in Fig. 4 as a function of the wavelength for different values of population inversion.

In this amplifier simulation it is assumed that the $^4I_{13/2} \rightarrow {^4I_{15/2}}$ transition of Er^{3+} is homogeneously broadened. This implies that a signal at any frequency within the $^4I_{13/2} \rightarrow {^4I_{15/2}}$ transition spectrum will increase or decrease the population inversion across the spectral range of the transition and the gain spectrum will change in a uniform fashion. With a population inversion rate of 60%, the gain is obtained between 1515 nm and 1600 nm with a maximum peak around 1550 nm. The gain spectra are nearly flat and correspond to the C- and L-band of telecommunications. This shows the potential application of the fluoroindate glass as EDFA.

Fig. 5 shows the experimental measurements for the 2.5 mol% sample at the $^4I_{13/2} \rightarrow {^4I_{15/2}}$ transition by using the pump and probe experiment. The dashed line corresponds to the spontaneous emission of the sample measured after the pump pulse when the signal beam is blocked before the sample. The solid line gives the emission measured under the same pump conditions but when the signal beam is present. The difference between both is shown in the dot line and shows the evidence of signal amplification in this transition. The SE parameter has been measured by using Eq. (1) and the value of the g coefficient obtained using (2) and is equal to 1.2 cm^{-1} (5.2 dB/cm).

4. Conclusions

Positive optical gain has been observed in Er^{3+}-doped fluorindate by using the pump and probe technique. In the 2.5 mol% sample an optical gain of 1.33 cm^{-1} (5.7 dB/cm) has been measured, and of 0.63 cm^{-1} (2.73 dB/cm) for the 0.5 mol% sample. A double frequency Nd-YAG pulsed laser oscillating at 532 nm was used as the pump source to strongly populate the $^2H_{11/2}$, $^4S_{3/2}$ level. The high power pump pulses provide enough population inversion, and the net gain is observed. This result shows the ability of the Er^{3+} ions to produce optical gain around 850 nm.

The gain cross-section originated from $^4I_{13/2} \rightarrow {^4I_{15/2}}$ transition of Er^{+3} has been simulated for different inversion populations. By using a similar setup, an optical gain of 1.2 cm^{-1} (5.2 dB/cm) has been obtained. This result is in agreement with the simulations and shows the possible application of Er^{3+}-doped fluoroindate glass as an optical amplifier at 1550 nm.

References

[1] A.S. Oliveira, E.A. Gouveia, M.T. De Araujo, A.S. Gouveia-Neto, C.B. De Araujo, Y. Messaddeq, J. Appl. Phys. 87 (2000) 4274.
[2] I.R. Martin, J. Mendez-Ramos, V.D. Rodriguez, J.J. Romero, J. Garcia-Sole, Opt. Mater. 22 (2003) 327.
[3] D.J. Rativa, C.B. de Araujo, Y. Messaddeq, J. Appl. Phys. 99 (2006) 83505.
[4] G.S. Maciel, L.S. Menezes, Cid B. de Araújo, J. Appl. Phys. 85 (1999) 6782.
[5] G.S. Maciel, N. Harkov, C.B. Araujo, Y. Messaddeq, J. Opt. Soc. Am. 16 (1999) 1995.
[6] I.R. Martín, P. Vélez, V.D. Rodríguez, U.R. Rodríguez-Mendoza, V. Lavín. Spect. Acta A 55 (1999) 935.
[7] Becker, N. Ollson, J. Simpson, Erbium Doped Fiber Amplifiers, Fundamentals and Technology, Academic, New York, 1999.
[8] N. Daldosso, D. Navarro-Urrios, M. Melchiorri, L. Pavesi, C. García, P. Pellegrino, B. Garrido, G. Pucker, F. Gourbilleau, R. Rizk, J. Lumin. 121 (2006) 249.
[9] D.E. McCumber, Phys. Rev. 136 (1964) A954.