Investigation of the Optical Properties of Er^{3+} -Doped Fluoroindate Glass

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Adriano Almeida da Silva ; Nefe Jefferson De Brito e Silva ; Francisco Eroni Paz dos Santos ; Tomaz Catunda **All Authors**

Abstract:
This study investigates the optical properties of erbium (Er^{3+}) doped fluoroindate glasses, focusing on absorption and emission processes in the near-infrared (NIR) and visible regions. Doping glass matrices with rare-earth ions enables the exploration of phenomena such as luminescence and frequency upconversion, with promising applications in photonics, optical sensors, and solid-state lasers. Fluoroindate glasses are particularly noteworthy as host materials due to their wide optical transparency, low phonon energy, and high solubility for rareearth dopants. These characteristics effectively reduce nonradiative losses and significantly enhance luminescence efficiency. The main objective of this work is to understand the energy transfer mechanisms, upconversion processes, and luminescence efficiency, thereby contributing to the development of advanced optical devices. The results show that the average lifetime for the ${}^4I_{13}/2 \rightarrow {}^4I_{15}/2$ transition is 10.1 ms, indicating a quantum efficiency close to 100 %. This high quantum efficiency confirms the material's potential for developing advanced photonic devices, such as efficient solid-state lasers and optical amplifiers.

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Adriano Almeida da Silva
Programa de pos-graduação em Física
UFPI
Teresina -PI, Brasil
Adrianofísica@ufpi.edu.br

Nefe Jefferson de Brito e Silva
Programa de pos-graduação em Física
UFPI
Teresina -PI, Brasil
nefebrito@gmail.com

Francisco Eroni Paz dos Santos
Programa de pos-graduação em Física
UFPI
Teresina -PI, Brasil
franciscoeroni@gmail.com

Tomaz Catunda
Instituto de Física de São Carlos
Universidade de São Paulo
São Carlos, Brazil
tomaz@ifsc.usp.br

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This study investigates the optical properties of erbium (Er^{3+})-doped fluoroindate glasses, focusing on absorption and emission processes in the near-infrared (NIR) and visible regions. Doping glass matrices with rare-earth ions enables the exploration of phenomena such as luminescence and frequency upconversion, with promising applications in photonics, optical sensors, and solid-state lasers. Fluoroindate glasses are particularly noteworthy as host materials due to their wide optical transparency, low phonon energy, and high solubility for rare-earth dopants. These characteristics effectively reduce non-radiative losses and significantly enhance luminescence efficiency. The main objective of this work is to understand the energy transfer mechanisms, upconversion processes, and luminescence efficiency, thereby contributing to the development of advanced optical devices. The results show that the average lifetime for the $^4I_{13/2} \rightarrow {^4I_{15/2}}$ transition is 10.1 ms, indicating a quantum efficiency close to 100%. This high quantum efficiency confirms the material's potential for developing advanced photonic devices, such as efficient solid-state lasers and optical amplifiers.

Keywords—fluoroindate glass, optical properties, upconversion.

I. Introduction

The study of the optical properties of glassy materials has significantly contributed to the development and technological advances in photonics, lasers, optical sensors and light-emitting devices. [1]. The incorporation of rare-earth ions into glass matrices allows the exploration of a diverse range of optical phenomena, such as luminescence, upconversion and mid-infrared emission, resulting in promising applications ranging from telecommunications to temperature sensors and solid-state lasers. [1] [2].

Different types of glass matrices, such as fluorindate, tellurides, borates, phosphates and germanates, have characteristics that have attracted the attention of researchers, such as phonon energy, thermal stability, dopant solubility and quantum emission efficiency. These properties directly influence the efficiency of optical processes, such as reducing non-radiative relaxation and improving luminescence intensity. Glasses with low phonon energy, for example, are particularly advantageous for minimizing energy losses and favoring efficient optical transitions of rare-earth ions. [3][4].

Among the most widely used dopants, the Er^{3+}, Yb^{3+}, Tm^{3+} and Nd^{3+} ions stand out for presenting well-defined electronic transitions and energy levels favorable to light conversion. Er^{3+}, in particular, has been widely applied to increase efficiency due to presenting emitting ions, which contribute to energy transfer processes. [5] [6]. Fluoroindate glass, for example, have emerged as promising hosts for upconversion processes, due to their wide optical transparency window, low phonon energy and high solubility for dopant ions such as Erbium (Er^{3+}) [1]. These characteristics significantly reduce non-radiative losses due to phonon relaxation, favoring emission efficiency at visible and near-infrared wavelengths. [7]

However, investigating the optical properties of fluoridate glasses doped with Erbium ions (Er^{3+}), with emphasis on the absorption and emission processes in the near infrared (NIR) and visible regions is crucial. The present study aims to understand the mechanisms of energy transfer and luminescence efficiency, evaluating the impact of the dopant, in spectroscopic parameters on the optical performance for applications in photonics, sensors and light-emitting devices.

II. Methodology

The fluoridate glass samples doped with Er^{3+} ions were prepared by conventional melting according to [1], followed by controlled cooling to ensure the homogeneity and optical transparency required for spectroscopic measurements. The optical characterization was performed with a focus on investigating the emission processes, upconversion and calculating the lifetime of the excited states of erbium.

The lifetime was determined using a modulated optical excitation technique, followed by an analysis of the temporal decay of the emission. A 1.53 µm laser was used for excitation. The laser beam was focused onto the sample using a converging lens with a focal length of 15 cm. The modulation of the excitation beam was performed with a mechanical chopper positioned in the optical path of the laser, operating at a fixed frequency, allowing periodic interruption of the beam and the consequent observation of the decay of the emission after the excitation was switched off. To ensure that only the emission originating from a given electronic transition was analyzed, appropriate optical filters were inserted before the detection system, for the detection of the spectral range corresponding to the transition of interest. The emission signal was monitored as a function of time, and the temporal intensity data were fitted by a decreasing exponential function of the type:

$$I(t) = I_0 e^{(-t/\tau)} \qquad (1)$$

where τ represents the lifetime of the excited state.

Absorption and emission spectra were recorded using an Ocean Optics spectrometer with a fiber optic detector in the visible to near infrared region.

III. Results

The absorption spectrum presented in Figure 1 shows several discrete and well-defined bands, characteristic of the electronic transitions between 4f levels to the (Er^{3+}) ion, prominent absorption bands are observed in the visible region, associated with transitions from the ground state $^4I_{15/2}$ to higher excited states.

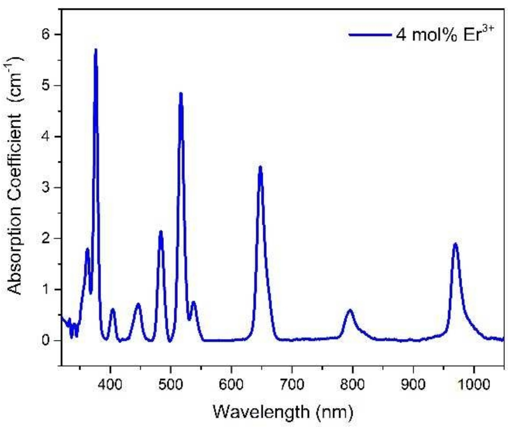

Figure 1 Figure 1: Absorption spectrum of the fluoroindate glass doped with 4 mol% Er^{3+}. The bands correspond to transitions from the ground state ($^4I_{15/2}$) to the indicated excited states, as observed at room temperature.

Figure 2 shows the emission spectrum of fluoride (fluorindate) glass doped with Erbium ions (Er^{3+}), under excitation at 1.53 µm. Well-defined emission bands centered at 550 nm, 660 nm and 820 nm are observed, attributed, respectively, to the electronic transitions $^4S_{3/2} \rightarrow {}^4I_{15/2}$, $^4F_{9/2} \rightarrow {}^4I_{15/2}$ e $^4I_{9/2} \rightarrow {}^4I_{15/2}$.

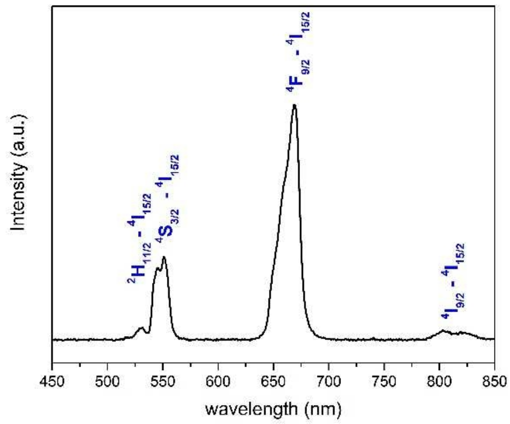

Figure 2 Visible emission spectrum of the fluoroindate glass doped with 4 mol% Er^{3+}, obtained under excitation at 1.53 µm. The peaks centered at 530 nm, 550 nm, 670 nm, and 820 nm correspond to the upconversion transitions $^2H_{11/2} \rightarrow {}^4I_{15/2}$, $^4S_{3/2} \rightarrow {}^4I_{15/2}$, $^4F_{9/2} \rightarrow {}^4I_{15/2}$, and $^4I_{9/2} \rightarrow {}^4I_{15/2}$, respectively.

Figure 3 presents the emission spectrum of fluorindate glass doped with Erbium ions (Er^{3+}), showing well-defined emission bands in the near-infrared region. The emissions centered at 980 nm and 1520 nm are attributed, respectively, to the electronic transitions $^4I_{11/2} \rightarrow {}^4I_{15/2}$ e $^4I_{13/2} \rightarrow {}^4I_{15/2}$. Such transitions are characteristic of the Er^{3+} ion and of particular interest for applications in optical telecommunications and infrared emitting devices.

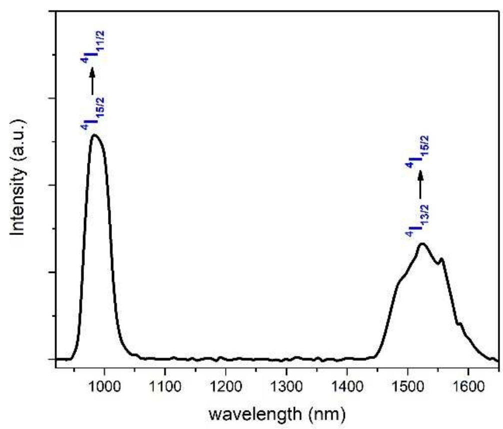

Figure 3 Near-infrared emission spectrum of the fluoroindate glass doped with 4 mol% Er^{3+}, showing characteristic emissions at 980 nm and 1550 nm. These bands are assigned to the transitions $^4I_{11/2} \rightarrow {}^4I_{15/2}$ and $^4I_{13/2} \rightarrow {}^4I_{15/2}$, respectively, under 1.53 µm excitation

Figure 4 shows the emission intensity curves as a function of the incident power density, used to determine the number of photons involved in the upconversion processes corresponding to different electronic transitions. The angular coefficients obtained from the log-log fit indicate experimental values of 2.3, 2.9, 1.6, and 0.85, corresponding to the emissions centered at 550 nm, 670 nm, 980 nm and 1520 nm, respectively. These results reflect, in a qualitative way, the effective number of photons absorbed in the excitation process for each transition.

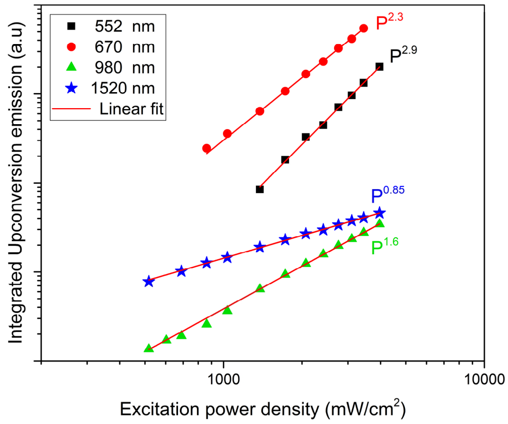

Figure 4 Log-log plot of the upconversion emission intensities as a function of the incident laser power density (excitation at 1.53 µm). The slopes of the linear fits indicate the number of photons involved in each upconversion process

Figure 5 shows the emission intensity recorded during lifetime measurements for the transition centered at 1520 nm, attributed to the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ radiative relaxation of the Er^{3+} ion. An average lifetime of 10.1 ms was observed. This value, which is very close to the radiative lifetime calculated via the Judd-Ofelt method, indicates a quantum efficiency of ~100%.

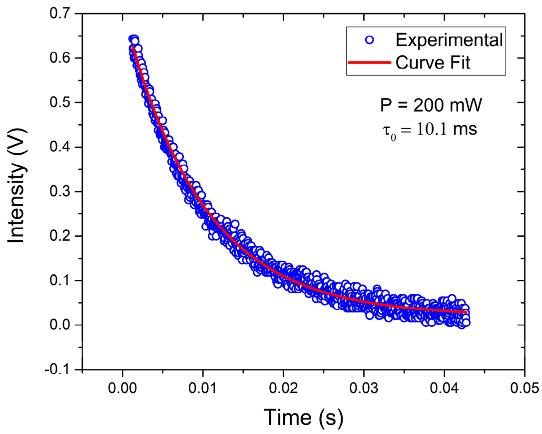

Figure 5 Time decay profile of the $^4I_{3/2} \rightarrow {}^4I_{5/2}$ emission (~1520 nm), measured under excitation at 1.53 µm. The solid red line represents the single exponential fit used to determine the experimental lifetime (10.1 ms).

IV. Conclusion

The results demonstrate that the Er3+-doped fluoroindate glass matrix is a highly efficient host for optical applications. We observed well-defined emissions in both the infrared and visible regions. A key finding is the average lifetime of 10.1 ms for the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition, which is remarkably close to the calculated radiative lifetime. This indicates a near 100% quantum efficiency for this emission, confirming a very low rate of non-radiative processes within this matrix. This high luminescence efficiency, combined with the matrix's ability to preserve the excited states of erbium, makes fluoroindate glass a promising material for advanced photonic devices, such as optical amplifiers and upconversion-based sensors

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