Optics & Laser Technology
Volume 127, July 2020, 106167

Near infrared broadband and visible upconversion emissions of erbium ions in oxyfluoride glasses for optical amplifier applications

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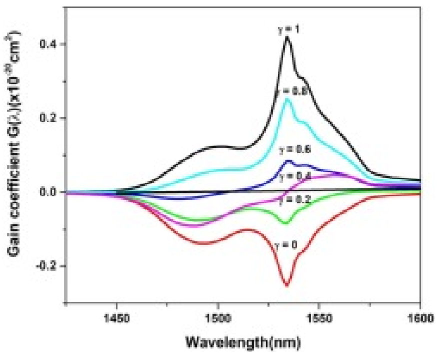
https://doi.org/10.1016/j.optlastec.2020.106167

Abstract

Optical and visible upconversion properties of erbium (Er^{3+})-doped oxyfluoro-titania-phosphate glasses (PCfBfTiEr) with the chemical composition of P_2O_5–CaF_2–BaF_2–TiO_2–Er_2O_3 have been explored. An intense emission at 1.53 µm of Er^{3+}-doped PCfBfTiEr1.0 glass was obtained upon excitation of 980 nm diode laser. In addition, green and red visible upconversion emissions were obtained upon the optical excitation of Er^{3+} ions doped PCfBfTiEr glasses at 980 nm diode laser. Upconversion emission intensities and population densities of respective levels were tuned with the variation of Er^{3+} ion concentration. Fluorescence decay curves of the $^4I_{13/2}$ level of PCfBfTiEr glasses were obtained upon 980 nm laser excitation in the pulsed mode and revealed a mono-exponential behavior. The stimulated emission cross-section (σ_{em}), full width at half maximum (FWHM) and gain bandwidth product (σ_{em}×FWHM) were found to be 9.3×10^{-21} cm^2, 95.61 nm and 889.2 cm^{-2} nm for PCfBfTiEr2.0 glass, respectively. These results recommend that the Er^{3+} ions doped PCfBfTiEr glasses may possibly be worthy for the laser and optical amplification applications at 1.53 µm.

Graphical abstract

Gain cross-section spectra of Er^{3+}-doped PCfBfTiEr20 glass for the $^4I_{13/2}\rightarrow{}^4I_{15/2}$ transition.



Introduction

Lanthanides (Ln^{3+}) doped glasses pay abundant attention for photonic applications due to their merits compared to crystalline materials that involve easy synthesis, low cost, produce a desired shape as well as size and consume less time for synthesis [1]. Among oxide glasses, phosphate glasses unveil several advantages due to the properties such as a low refractive index, good thermal and mechanical stabilities, high gain density, high transparency and relatively low melting temperature [2]. Phosphorus chain forms a bond easily with Ln^{3+} ions and transition metal ions to improve the luminescence properties. Ln^{3+} ions activated phosphate glasses have attracted many researchers to investigate suitable glass composition for the solid state lasers, memory switching, electrical threshold sensors and batteries because of wide technological applications [3].

Erbium (Er^{3+}) is the most substantial ion among the rest of the Ln^{3+} ions for 1.53 µm near infrared (NIR) lasers and optical amplifiers correspond to its emission transition of $^4I_{13/2} \rightarrow {}^4I_{15/2}$. Furthermore, Er^{3+} ion also shows emissions at the wavelengths of green and red are attributable to the $^2H_{11/2}+{}^4S_{3/2} \rightarrow {}^4I_{15/2}$ and $^4F_{9/2} \rightarrow {}^4I_{15/2}$ transitions respectively [4]. A large full width at half maximum (FWHM) of an emission band in the near infrared (NIR) region infers abundant prospective applications in optical amplifiers, waveguides and permitting for simultaneous traffic on quite a few channels of communication [5]. Er^{3+}-doped fiber amplifiers (EDFA) have played a vital role in optical communication for a long distances operated in the C-band region (1530–1565 nm). Furthermore, to extend the region of EDFAs in the prescribed region, Er^{3+} ions are essentially co-doped with other Ln^{3+} ions that includes Yb^{3+}, Tm^{3+}, Nd^{3+} and Pr^{3+} [6], [7], [8], [9]. Present days, commercial EDFA uses silicate glasses for the fabrication of glass fibers which possess a narrow bandwidth of ~40 nm is then causing to limit broadband transmission. A suitable glass composition is substantial to be explored for the purpose of ultrabroadband EDFA applications [10]. Phosphate glasses are the right choice compared to other glasses for which chemical durability can be enhanced easily with the addition of heavy metal ions, Ba^{2+} and Ti^{4+} for the applications of ultrabroadband and high gain EDFA. Besides the oxide glasses, fluoride glasses have shown remarkable development for wide transparency from UV to IR, low Tg, low phonon energy and high fluorescence efficiency. Calcium fluoride (CaF_2) and barium fluoride (BaF_2) modifiers in the phosphate glass network can be used to achieve an efficient emission [11], [12]. At present, researchers focusing on oxyfluoride glasses instead of conventional pure oxide glasses [13], [14], [15].

In the present study, Er^{3+}-doped (P_2O_5+CaF_2+BaF_2+TiO_2+Er_2O_3) PCfBfTiEr glasses were investigated in the perspective of high gain and broadband optical amplification. The mechanical strength of the phosphate network can be enhanced by the addition of TiO_2. An optical band gap, Urbach energy and dispersion of the glasses were estimated by the use of absorption spectrum. For 2.0 mol% Er^{3+} ions doped PCfBfTiEr2.0 glass, Judd-Ofelt (JO) intensity parameters were investigated to analyze the radiative properties such as radiative lifetime, the effective bandwidth, branching ratio and stimulated emission cross-section of the $^4I_{13/2}\rightarrow{}^4I_{15/2}$ transition for the emission band of Er^{3+} ion in the NIR region. Experimental lifetime of the metastable state, $^4I_{13/2}$ is estimated for different Er^{3+} ions concentration by fitting the luminescence decay curves with mono-exponential function. Finally, the results are compared with the other reported Er^{3+}-doped glasses.

Section snippets

Glass preparation

Glass samples were prepared by the conventional melt quenching technique [16] with the chemical composition of (60-y) P_2O_5+20 CaF_2+15 BaF_2+5 TiO_2+$y$$Er_2O_3$ (y=0.05, 0.1, 0.5, 1.0, 1.5, 2.0, 2.5 mol%) and the glasses labeled as PCfBfTiEr0.05, PCfBfTiEr0.1, PCfBfTiEr0.5, PCfBfTiEr1.0, PCfBfTiEr1.5, PCfBfTiEr2.0, PCfBfTiEr2.5, respectively. Phosphorus pentoxide (P_2O_5, 99.9%), calcium fluoride (CaF_2, 99.5%), barium fluoride (BaF_2, 99.9%), titanium dioxide (TiO_2, 99.9%) and erbium oxide (Er_2O_3…

Optical absorption spectrum

Optical absorption spectrum of erbium (Er^{3+}) -doped PCfBfTiEr glasses were measured using UV–visible-NIR spectrometer in the region of 325–1800 nm at room temperature, as shown in Fig. 1(a) & (b). The absorption spectrum consist of twelve absorption peaks due to the transitions of Er^{3+} ions from the ground state ($^4I_{15/2}$) to different higher excited states labeled as $^4G_{9/2}$, $^4G_{11/2}$, $^2G_{9/2}$, $^4F_{3/2}$, $^4F_{5/2}$, $^4F_{7/2}$, $^2H_{11/2}$, $^4S_{3/2}$,$^4F_{9/2}$, $^4I_{9/2}$, $^4I_{11/2}$ and $^4I_{13/2}$. The optical absorption spectra show…

Photoluminescence (PL) emission spectra

PL spectra were recorded at room temperature upon excitation by 980 nm diode laser for different concentration of Er^{3+} ions in PCfBfTiEr glasses, as shown in Fig. 6(a). Emission spectra originated from the meta-stable state to the ground state: $^4I_{13/2}\rightarrow{}^4I_{15/2}$ transition and an emission peak positioned at 1.53 μm in the NIR region. The emission intensity at 1.53 μm increases with increasing Er^{3+} ions concentration up to the 0.1 mol% doped PCfBfTiEr0.1 glass then decreased for PCfBfTiEr0.5…

Decay curve profile

Fig. 7. shows the decay curve profiles of the $^4I_{13/2}$ level of Er^{3+}-doped PCfBfTiEr glasses with respect to Er^{3+} ion concentration. The decay curves exhibit the mono-exponential behavior for all Er^{3+} ions concentration. Lifetime of $^4I_{13/2}$ level found to be 1.64, 2.11, 0.91, 1.34, 0.54, 0.54 and 0.65 ms for the PCfBfTiEr0.05, PCfBfTiEr0.1, PCfBfTiEr0.5, PCfBfTiEr1.0, PCfBfTiEr1.5, PCfBfTiEr2.0 and PCfBfTiEr2.5 glasses, respectively. The PCfBfTiEr0.1 glass has reported a highest lifetime of…

Visible upconversion

Upon 980nm excitation, green and red upconversion emissions of Er^{3+} were revealed and are presented in Fig. 8. The incident photon at 980nm wavelength excites Er^{3+} ions to the $^4I_{11/2}$ level. A similar photon at 980nm is used to excite Er^{3+} ions further via $^4I_{11/2}\rightarrow{}^4F_{7/2}$ transition. Then, the Er^{3+} ion relaxes rapidly to the $^2H_{11/2}$ level to yield emissions. Two emission bands were unveiled at 550nm and 660nm, correspond to the $^2H_{11/2}+{}^4S_{3/2}\rightarrow{}^4I_{15/2}$ (green) and $^4F_{9/2}\rightarrow{}^4I_{15/2}$ (red)…

McCumber's theory

With the use of absorption spectrum, the emission cross-section at 1.53μm corresponds to the transition $^4I_{13/2}\rightarrow{}^4I_{15/2}$ as a function of wavelength has been evaluated by the McCumber's theory using the given equation.$\sigma_e^m = \sigma_a \exp\left(\frac{\varepsilon - h\nu}{kT}\right)$.where ε is the net-free energy used to excite Er^{3+} ions for the $^4I_{15/2}\rightarrow{}^4I_{13/2}$ transition at absolute temperature T, ν is the frequency of the emission band and k is the Boltzmann's constant. For PCfBfTiEr2.0 glasses, the absorption and emission cross-sections…

Conclusion

Er^{3+}-doped PCfBfTiEr glasses with different Er^{3+} ion concentrations have been fabricated and characterized their optical and photoluminescence properties for optical amplification applications. Judd-Ofelt (JO) intensity parameters and radiative parameters were evaluated. The Ω_2 is relatively higher value which indicates higher covelance and/or higher asymmetry of Er^{3+} ion doped PCfBfTiEr glasses and compared to the other phosphate, silicate, tellurite and germinate glasses. The eye-safe…

CRediT authorship contribution statement

Venkata Krishnaiah Kummara: Writing - original draft, Conceptualization, Formal analysis, Writing - review & editing. **Neelima G.:** Writing - original draft, Conceptualization, Formal analysis, Writing - review & editing. **Ravi N.:** Writing - original draft, Conceptualization, Formal analysis, Writing - review & editing. **Nanda Kumar Reddy Nallabala:** Writing - review & editing. **Satish Kumar Reddy H.** Formal analysis, Writing - review & editing. **Dwaraka Viswanath C.S.:** Formal analysis, Writing -…

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

Acknowledgement

Dr. K.Venkata Krishnaiah is obliged to SERB-DST, New Delhi for sanctioning a research project (File Number: EMR/2017/000009). One of the authors Venkatramu is grateful to DST, New Delhi for the sanction of collaborative research project (No. INT/PORTUGAL/P-04/2017) under India-Portugal Bilateral Scientific and Technological Cooperation. The authors thankful to Prof. C.K. Jayasankar, Department of Physics, Sri Venkateswara University, Tirupati for supporting the PL experimental facility. Dr. N.…

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