Optical study on Er-Yb Co-doped boro-tellurite glasses for optical amplifiers

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The Er-Yb co-doped boro-tellurite glasses with the chemical composition (40−x−y)TeO_2+20H_3BO_3+15K_2CO_3+15$SrCO_3$+ +10ZnO+xEr_2O_3 +yYb_2O_3 (where x = 1, y = 0, 0.5, 1 and 2 in wt%) have been prepared and their luminescence properties are studied through absorption and luminescence spectral analysis. Judd−Ofelt (JO) intensity parameters are estimated through the optical absorption spectral measurements. Using McCumbar theory the absorption and emission cross-section values for the $^4I_{13/2}\rightarrow{}^4I_{15/2}$ (1.531μm) transition have been calculated. The high value of gain coefficient and gain band width indicates that the prepared glasses are promising materials for broadband optical amplifier applications.

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1. Introduction

In optical communication network, signals have to travel through fibers for very long distances without significant attenuation. However, when distances become several hundreds of kilometers, it is necessary to amplify the signal during its transmission. An optical amplifier is a device that amplifies an optical signal directly without converting it to an electrical signal. Optical fiber amplifiers provide in–line amplification of input optical signals by effecting stimulated emission of photons by rare earth ions that are implanted in the core of the optical fiber. Optical amplifiers are important in optical communication and laser physics [1]. There are several physical mechanisms that can be used to amplify a light signal and they correspond to the major types of optical amplifiers. In doped fiber amplifiers stimulated emission causes amplification of incoming light [2]. In semiconductor optical amplifiers (SOAs), electron hole recombination occurs. In Raman amplifiers, Raman scattering of the input signal light with phonons in the lattice of the gain medium produces photons. In Parametric amplifiers parametric amplification of the incoming signal takes place.

Doped fiber amplifiers (DFAs) are optical amplifiers that use a doped optical fiber as a gain medium to amplify an optical signal [3]. They are closely related to fiber lasers. The input signal that is to be amplified and a pump laser are multiplexed into the doped fiber, and the signal is amplified by interacting with the doping ions. The best example is the Erbium Doped Fiber Amplifier (EDFA), where the core of a silica fiber is doped with trivalent erbium ions and can be efficiently pumped with a laser at a wavelength range of 980 nm or 1,480 nm [4]. It produces gain in the 1,550 nm wavelength range. Rare Earth (RE) doped materials have greater interest due to their various photonic applications including optical printing and remote sensors [5]. In the past few decades, the erbium doped fiber has played a vital part in the domain of optical communication system [6].Erbium doped glasses are used as interesting materials for active planar waveguide fabrication and in Integrated optical devices due to their extraordinary properties [7]. The optimization of fiber materials for the purpose of fine-tuning the efficiency of absorption can be realized by co-doping ytterbium ions in to the erbium-doped fiber as a sensitizer and double cladding the fiber structure for enlarging the aperture of the pump light. The corresponding fiber is known as erbium-ytterbium doped fiber (EYDF). Concerning EDFA system.$Er3^+$/$Yb3^+$ co-doped glass gives significant response for 1.5μmemission because $Yb3^+$ ions have been proved to be excellent sensitizer for $Er3^+$ ions. In recent yearsYb3^+/$Er3^+$ co-doped glass waveguide amplifier and laser have attracted more interest due to their advantages in cost, size and comparability with planar light wave circuit performance [8]. Host matrix selection is one of the important tasks to optimize the various properties for better performance for possible applications in laser and amplifier [9]. Compared to oxide glasses, boro-tellurite glasses have been preferred as a good choice for fabrication of optical devices due to low phonon energy (~ 750 cm^{-1}), higher refractive indices (~ 2) wide transmission window (0.4 – 5.0 μm) higher mechanical stability, transparency, dielectric constant and RE ion solubility. Boro-tellurite glasses are found to exhibit higher broadened emission profile of the $Er3^+$ ions [10].

$Er3^{+}/Yb3^{+}$ co-doped with different glass materials have been studied and reported by several researchers [11]. In the proposed work, the spectroscopic analysis was done using Judd-Ofelt (JO) and Mc-Cumber theories. The JO parameters are calculated through the absorption spectral analysis using emission spectra and the gain emission properties for amplifiers have been analyzed and reported.

2. Proposed optical glass as amplifier

The Er-Yb co-doped boro-tellurite glasses were prepared by following conventional melt quenching technique with high purity chemicals TeO_2, H_3BO_3, K_2CO_3, $SrCO_3$, ZnO, Er_2O_3 and Yb_2O_3 (99.99% purity grade from Sigma-Aldrich). The chemical compositions of about 15gm per batch were thoroughly mixed in agate mortar to obtain homogeneous mixture. The homogeneous mixture were taken in porcelain crucible and kept in a high temperature electrical furnace at temperature 1050 °C for about 45 minutes. The melt was then poured onto a preheated brass plate and pressed by another brass plate to obtain uniform thickness thought. To improve mechanical strength and to remove strains, the prepared glass was subjected to annealing process for about 7 hours at 350 °C. The glasses were well polished on both sides to obtain a planer faces before further optical measurements. Using CARY 500 spectrophotometer, the optical absorption spectral measurements of the titled glasses were recorded in the wavelength region 340–1650 nm with a spectral resolution of ±0.1 nm. Using EG&G Princeton Applied Research model 5210 the Luminescence spectra of the prepared glasses were recorded with a spectral resolution of ±0.5 nm. All these measurements were carried out at room temperature (RT) only. This homogeneous glass composition exhibits higher phonon energy without sacrificing the optical and thermal stability or chemical durability properties of boro-tellurite glasses. This process is depicted as block diagram in Fig.1

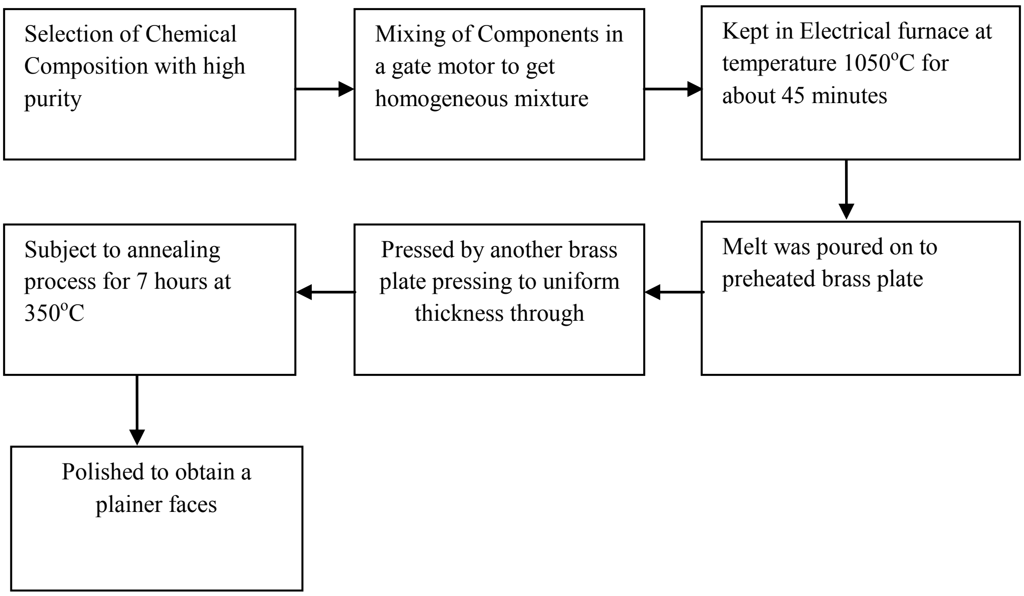

Fig. 1. Block diagram showing the procedure for preparation of the proposed glass

3. Results and discussions

3.1. Absorption spectra and JO analysis

The absorption spectra of the Er-Yb co-doped boro-tellurite glasses recorded in the UV–Vis–NIR region and absorption spectrum of Er1Yb glass is shown in Figure 2. The absorption bands arise from the $^4I_{15/2}$ ground state to the various excited states due to the interaction of Er^{3+} ions[12]. From the absorption spectra twelve absorption transitions was taken under consideration ,such as $^4I_{13/2}$, $^4I_{11/2}$, $^4I_{9/2}$, $^4F_{9/2}$, $^4S_{3/2}$, $^2H_{11/2}$, $^4F_{7/2}$, $^4F_{5/2}$, $^4F_{3/2}$, $(^2G, {}^4F, {}^2H)_{9/2}$, $^4G_{11/2}$ and $^4G_{9/2}$ have been observed. Due to the sufficient energy transfer between $Er3^{+}$ and $Yb3^{+}$ ions, the intense absorption band transition $^2F_{7/2}\rightarrow{}^2F_{5/2}$ of the Yb^{3+} ion possess much broader absorption cross sectional area in the absorption region 980–1060 nm [13].

While increasing the Yb^{3+} ion concentration, the $^2F_{7/2}\rightarrow{}^2F_{5/2}$ transition corresponding to the Yb^{3+} ion overlap with the $^4I_{15/2}\rightarrow{}^4I_{11/2}$ transition of the Er^{3+} ion which appear around 980 nm and as the $Yb3^{+}$ ion concentration increases in the host matrix, the intensity of this transition increases linearly with the increase in Yb^{3+} ion concentration.Ecxept the change in peak intensities of various bands, no sudden change in shape or peak position in the absorption spectra could be observed. Among the observed transitions, $^4I_{15/2}\rightarrow{}^4G_{11/2}$ and $^4I_{15/2}\rightarrow{}^2H_{11/2}$ are hypersensitive in nature which follows the selection rules $|\Delta L| = 2$, $|\Delta J| = 2$ and $\Delta S = 0$.

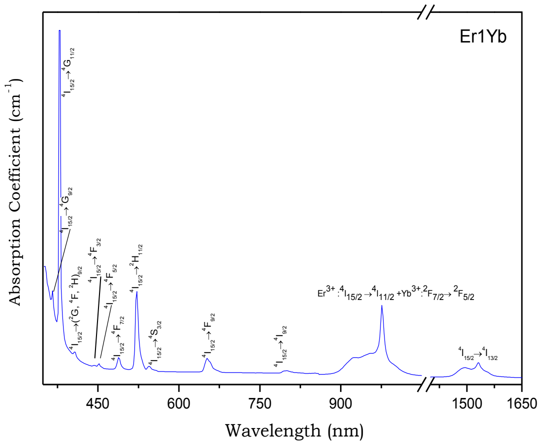

Fig. 2. Absorption spectrum of the Er-Yb co-doped Er1Yb glass in the UV–Vis–NIR region

Table 1 gives the clear picture on the Judd–Ofelt intensity parameters Ω_λ (λ= 2, 4 and 6) derived following the least squares fitting procedure [14] for the Er-Yb co-doped boro-tellurite glasses. Generally the intensity of Ω_2 parameter is related to the symmetry of RE ion around with its surrounding ligands, whereas the Ω_4 and Ω_6 parameters are related to the bulk properties of the glass host like viscosity and optical opacity [15]. Among the JO parameters, Ω_2 intensity parameter is strongly depending on the magnitude of the hypersensitive transition. It is also observed from the table that, the Ω_2 parameter possess higher values for all the prepared glasses and the JO parameters follows the trend as $\Omega_2>\Omega_4>\Omega_6$ uniformly for all the glasses. The higher Ω_2 values of the prepared ErXYb glasses reveal the higher asymmetry around the Er^{3+} ion site [16,17]. In the present work, higher values of Ω_2 and smaller values of Ω_6 for the prepared Er-Yb co-doped glasses indicates the lower symmetry in the prepared glasses. It is observed that, Er1Yb glass possess higher Ω_2 intensity parameter value among the prepared glasses. While adding the Yb^{3+} ion content in the host matrix the Ω_2 parameter is found to increase gradually upto 1 wt % of Yb^{3+} ion concentration in the prepared glasses. It is observed from the table that, the Ω_2 parameter possess higher value and the JO parameters follow trend as $\Omega_2>\Omega_4>\Omega_6$ for all the present glasses.

Table 1. The Judd–Ofelt parameters ($\Omega_\lambda \times 10^{-20}$ cm^2) of the Er-Yb:ErXYb boro-tellurite glasses

Glass code	Ω_2	Ω_4	Ω_6	Trends
Er0Yb	4.567	0.705	0.638	$\Omega_2>\Omega_4>\Omega_6$
Er0.5Yb	4.232	0.779	0.612	$\Omega_2>\Omega_4>\Omega_6$
Er1Yb	4.883	0.982	0.776	$\Omega_2>\Omega_4>\Omega_6$
Er2Yb	4.617	0.863	0.589	$\Omega_2>\Omega_4>\Omega_6$

3.2. NIR luminescence spectra and Mc-Cumber theory

The NIR emission spectra of the Er-Yb co-doped boro-tellurite glasses recorded by monitoring an excitation at 980 nm is shown in Fig. 3. The broader peak corresponding to the $^4I_{13/2}\rightarrow{}^4I_{15/2}$ transition at 1532 nm has been observed from the spectral measurements. It is clearly observed from the luminescence spectra that, the intensity changes with the change in Yb_2O_3 concentration and is due to the process of energy transfer taking place between Yb^{3+} and Er^{3+} ions. It is also observed from the Fig. 3, that, the emission peak position did not change with the Yb^{3+} ion concentration, whereas the broadness of the emission spectra varies with the Yb^{3+} ion content due to the change in the occupation of active ions in the various sites of the prepared glasses and further the change in broadness may occur due to self-absorption and radiation trapping process [18,19]. While designing the amplifier devices, the figure of merit is an important parameter to evaluate the performance of the amplifiers and is defined as the product of lifetime and stimulated emission cross-section [20]. The $\sigma_e \times \tau_R$ values are presented in Table 2. It is observed from the table that, the Er1Yb glass has higher value and potential for amplifier devices.

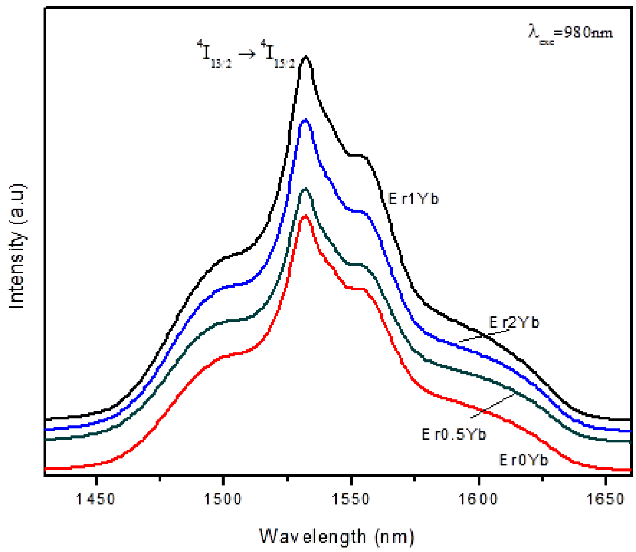

Fig. 3. Near Infrared emission spectra of the Er–Yb codoped boro-tellurite glasses

Mc-Cumber theory [21] has been used to calculate the stimulated emission cross-section for the broad emission transition $^4I_{13/2}\rightarrow{}^4I_{15/2}$ with the assumption that, the time required to establish a thermal distribution within each manifold is shorter compared to the lifetime of the manifold.

Table 2. Absorption cross-section (σ_a $\times 10^{-22}$ cm^2), emission cross-section (σ_e $\times 10^{-22}$ cm^2), FWHM (nm), $\sigma_e \times$FWHM (10^{-25} cm^3), $\sigma_e \times \tau_R$ (10^{-25} cm^2 s) and gain coefficient G corresponding to the $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition of the Er-Yb co-doped boro-tellurite glasses

Parameters	Er0Yb	Er0.5Yb	Er1Yb	Er2Yb
σ_a	6.524	6.668	8.978	7.156
σ_e	7.156	7.654	9.254	8.251
FWHM	55	56	57	56
$\sigma_e\times$**FWHM**	393.58	428.62	527.48	462.056
τ_R	4.233	4.158	3.916	4.055
$\sigma_e \times \tau_R$	30.29	31.82	36.23	33.45
G	4.358	4.657	5.132	4.497

The absorption cross-section of a particular transition between two states of an ion represents the probability for that transition to occur with the concurrent absorption of light [22.23]. The absorption and emission cross-section values corresponding to the $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition of the Er^{3+} ions in the prepared glasses are calculated using Mc-Cumber theory and presented in Table 2. The gain bandwidth of an amplifier is estimated through the width of the emission spectra and is calculated using the formula FWHM × σ_e. The FWHM × σ_e product and the lifetime of the $^4I_{13/2}$ level are the critical parameters for analyzing the performance of EDFA. Larger values of the FWHM × σ_e product and the longer lifetime imply wider gain bandwidth and lower pump threshold power. The FWHM × σ_e values are found to be 393.58, 428.62, 527.48 and 462.05 for the Er0Yb, Er0.5Yb, Er1Yb and Er2Yb glasses respectively. The gain coefficient G can be derived from the σ_a and σ_e values and is presented in Table 2. The gain coefficient of the Er1Yb glass is found to be 5.132 cm^{-1} which suggests that, the prepared Er1Yb glass is more suitable for designing the Er-Yb co-doped broad-band optical amplifiers [24].

4. Conclusion

Er–Yb co-doped boro-tellurite glasses are prepared and characterized by spectroscopic measurements. The JO parameters are calculated and reported. The higher Ω_2 values of the prepared glasses reveal the higher symmetry around the Er^{3+} ion site. Through Mc-Cumber theory optical gain parameters were calculated and reported. The high values of gain coefficient and high gain band width suggest the prepared Er1Yb glass is more suitable for designing the Er-Yb co-doped broad-band optical amplifiers

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