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Transition Metal and Rare-Earth Co-Doped Glasses and Glass Ceramics for Solid-State Laser Applications

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ABSTRACT

Transition metal and rare-earth co-doped glasses have emerged as promising candidates for lasing applications owing to their tunable optical and spectroscopic properties. Present study presents a comprehensive review of the recent developments and applications of transition-metal and rare-earth co-doped glasses in the field of laser technology. Such glass systems have demonstrated enhanced optical, thermal, and laser properties, making them promising candidates for various lasing applications. Firstly, fundamental principles of lasing in glasses, including key parameters influencing laser performance, such as emission wavelengths, gain coefficients, and lifetime of excited states, are described. Subsequently, the synthesis methods of transition metal and rare earth co-doped glasses have been explained. Contributions of transition metals and rare earth elements in enhancing lasing characteristics have also been highlighted. The study is finally concluded by presenting challenges and future perspectives in the field. The study is highly valuable for researchers and engineers working in the field of laser technology.

KEYWORDS Lasers, Glasses, J-O parameters, Photonic Glasses

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INTRODUCTION

Diode pumped solid state lasers are quite prevalent in the markets these days. Solid state lasers (SSLs) consist of ions dispersed in an optically transparent matrix. Ever since the Einstein reported the probability of spontaneous and stimulated emission, many researchers have discovered the novel active medium for lasers [1]. The performance and quality of solid-state lasers depends largely upon the laser gain medium. Moreover, this medium is made up of a transparent solid host with added active ions that are optically pumped for excitation. The ideal gain medium should have excellent thermal-mechanical and thermal-optical properties [2]. The 1960, was a time period of discovery and Maiman introduced the first solid-state ruby laser, which used a flash lamp for power [3]. Following that, in 1961, Snitzer reported the activity of laser action in glasses [4]. In 1970, laser spectroscopy started posing new insights into the structure of glass. Presently, the most commonly used material for solid-state lasers is neodymium-doped yttrium aluminium garnet (Nd:YAG), which typically operates at a laser wavelength of 1.06µm [5]. Nowadays, glass is widely used in various laser systems by playing active and passive roles [6]. For the advancement of light based electronic components, variety of glasses, such as, borate, phosphate, telluride and silicate have been turned to be proper host materials [7].

Rare earth ions (REI) have become the subject of recent research in engineering and technology owing to its luminescent properties and energy up-conversion (UC)/down-conversion (DC) efficiencies [8]. Such ions when incorporated in various hosts, have discovered numerous applications in highly relevant fields of photonics [9,10]. Development of fibre optic lasers and amplifiers is one of the most popular applications of REIs over a long period due to its ability to achieve high-speed and high-volume transmission [11].

In the realm of optical materials, glasses doped with transition metal and rare-earth ions have emerged as pivotal candidates for various photonic applications, especially in the domain of lasers. Incorporation of transition metal and rare-earth ions into glass matrices offers an enhancement of optical properties, making them indispensable in the development of high-performance laser systems [12]. Over the years, significant strides have been made in understanding the intricate interplay between dopant ions and host matrices, leading to remarkable advancements in the design, fabrication, and utilization of these co-doped glasses for lasing applications.

This comprehensive review aims to provide an in-depth analysis of the recent progress and key developments in transition metal and rare earth co-doped glasses and glass ceramics for lasing applications. It elucidates the fundamental principles governing the optical properties, and also explores the diverse strategies employed for enhancing the spectral properties, optical gain, and laser efficiency of these materials, thereby facilitating their integration into cutting-edge laser technologies. It also talks about the growing use of co-doped glasses in many areas, such as telecommunications, sensors, medical imaging, and environmental monitoring. This review gives a clear and complete picture of the latest developments in the field. It aims to guide future research and technology to make the best use of transition metal and rare earth co-doped glasses, especially in laser-related applications.

FUNDAMENTAL PRINCIPLES OF LASING IN GLASSES

Transition metal and rare earth ions exhibit unique optical properties when incorporated into glass matrices, making them attractive candidates for laser applications. Such glasses, in the form of cylindrical rods, fibres and sheets with highly polished ends or with anti-reflection coatings at ends, can serve as laser gain medium. Their lasing action is based on the processes of stimulated emission, population inversion, and optical amplification. In a typical laser system, rare-earth ions such as Nd^{3+}, Er^{3+}, Yb^{3+}, or Tm^{3+} are doped into a glass host matrix. When these dopant ions are excited by an external energy source (e.g., flash lamps or laser diodes), electrons are promoted from a lower energy state to a higher excited state. After a brief period, electrons in the excited state relax non-radiatively to a metastable state, which has a relatively longer lifetime. From this metastable state, stimulated emission can occur when a photon of the same energy interacts with the excited ion, resulting in the release of another coherent photon. This process leads to optical amplification and, with the incorporation of an optical resonator (mirror-based cavity), coherent laser emission is achieved [13]. Such glass lasers have advantage of long luminescent lifetime and high gain. These can be fabricated in a variety of geometries.

Laser glasses differ from crystalline laser hosts in that, they possess an amorphous structure, which offers greater flexibility in shaping, composition, and fabrication. Glass hosts allow for higher rare-earth ion doping concentrations without significant clustering or quenching effects. Among various glass hosts, phosphate glasses are particularly suitable for high-power laser applications due to their high solubility for rare-earth ions, good thermal and mechanical properties, and lower phonon energy compared to silicate glasses, which reduces non-radiative decay and improves luminescence efficiency [14].

SYNTHESIS TECHNIQUES FOR CO-DOPED GLASSES

The optical and spectroscopic properties of co-doped glasses are heavily influenced by the synthesis technique employed during fabrication. These fabrication techniques include conventional melt-quenching technique, sol-gel processing, and chemical vapour deposition method.

Sol-Gel Method

The sol-gel method is a way to make high-purity glasses using a wet chemical process. It starts by mixing metal compounds with a liquid to make a solution. Then, through chemical reactions, this solution turns into a gel. The gel is dried to remove all the liquid. After that, it's heated at temperatures a bit higher than the glass-making temperature to form the final glass. This method is great because it can make very pure glasses, and it doesn't need extremely high temperatures [15]. The sol-gel method, although effective for making glasses for biomedical uses [16], is generally not practical for other applications because it's expensive and takes a long time to produce large pieces of glass.

Chemical Vapour Deposition (CVD)

The chemical vapour deposition (CVD) process for making glass involves heating metal halide vapours until they react and form tiny particles of glass material called soot. These soot particles are then heated further to form solid glass without any impurities. This method allows the creation of glass which is otherwise difficult to make using traditional melting techniques. For example, researchers have made high-purity TeO_2-ZnO glasses using CVD at lower temperatures than with melting methods [17].

Melt-Quenching Technique

It is commonly used method for the preparation of glasses. It includes the mixing of raw materials, followed by melting into a viscous liquid and then pouring of molten material (watery consistency) into a mould of desired shape and further quenching it finally at room temperature. The glass is then annealed at certain temperature (slightly greater than glass transition temperature) in order to reduce the thermal stress occurred during its formation and subsequent cooling [18].

STRATEGIES TO IMPROVE LASING ACTION IN GLASSES

It is crucial to have high value of gain coefficient per unit length of laser material, and it depends on emission cross-section of the dopant. High emission cross-section requires high absorption cross-section of the gain medium. Also, various losses in laser cavity, that are function of absorption cross-section of dopant, tend to reduce its gain. It is therefore necessary to have high lifetime of levels from which stimulated emission is going to take place to maximise gain. Concentration of rare-earth ions in laser matrix is another important parameter affecting gain per unit length. These ions behave as defect centres in the medium of light amplification. There is an inclusive range of materials which can serve as host for accommodating RE ions for lasing applications [19,20]. Among all hosts, RE doped glasses have a larger gain band width, large stimulated cross-section, high gain efficiency and low dispersion. Oxide glasses are evidently suitable host for incorporating REIs due to its ease of fabrication in desired shape (rod, fibre and planar waveguide), high refractive index, low transition temperature, high transparency in visible and IR regions, high thermal and chemical stabilities, and low phonon energy [21,22]. Glasses of borate, silicate, tellurite and phosphate have extensively been used as host materials. In fact, RE co-doped glasses are witnessed to have superior luminescent properties than singly-doped glasses due to energy transfer from sensitizer to activator [23]. Co-doped glasses find diverse applications in various lasing technologies, including telecommunications, optical amplification, solid-state lasers, and biomedical imaging. Various applications of TM-RE co-doped glasses are depicted in **Fig. 1**.

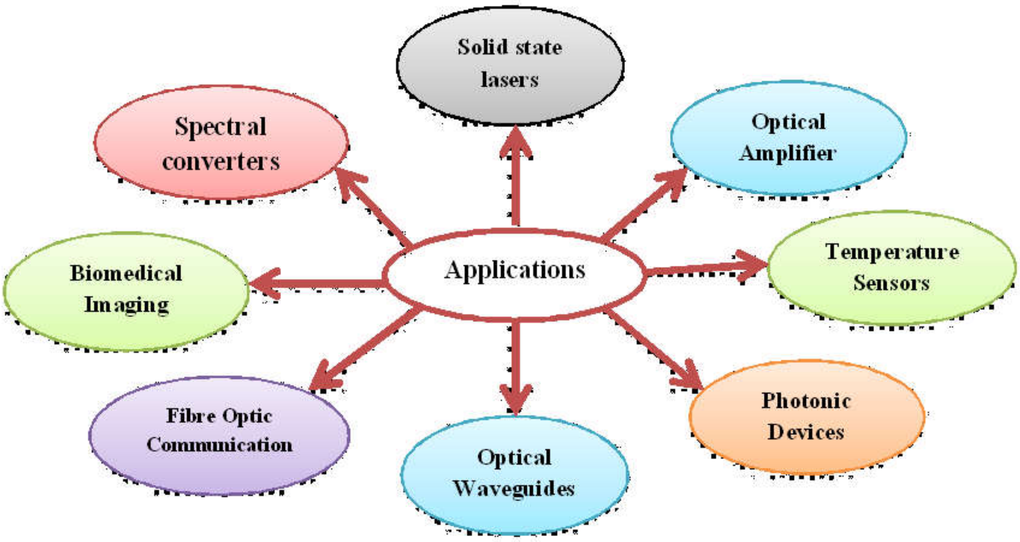

Figure 1: Various applications of TM-RE co-doped glasses

However, such materials are witnessed to have spectroscopic limitations which affect their usage as laser active medium. Standard silicate glasses, which are in use for optical communication, have very little solubility of rare-earth ions. Phosphate glasses exhibit extremely high solubility of rare-earth ions, but poor chemical durability limits its applications in the field of photonics. On the other hand, borate glasses have high phonon energy which adversely affects the gain per unit length of a laser medium. Moreover, RE ions in oxide glasses exhibit poor efficiency of radiative decay as it suffers from high non-radiative losses in the form of multiphonon relaxation, cross relaxation and co-operative up-conversion. Also, such glass systems have very short life time of the excited state and have limited solubility of RE ions.

Several strategies have been employed to enhance the spectral properties, optical gain, and laser efficiency of co-doped glass laser materials. Transparent glass ceramics are alternative to oxide glasses for better luminescent properties [24]. Glass ceramics are produced by controlled nucleation and crystallisation of glass. It introduces one or more crystalline phases in the glass network and has improved mechanical, electrical, optical and thermal properties than the oxide glass matrix. Glass ceramics can be made highly transparent by carefully controlling crystal size (less than the wavelength of light) which reduces scattering losses by confining rare-earth ions in crystalline environment of low phonon energy. As a result, lifetime of excited state and absorption cross-section increases.

The luminescence of rare-earth (RE) ions can further be enhanced by incorporating nano-particles in the glass network. It has been observed that optical behavior of rare earth ions (REI) is influenced by the local crystalline structure. Nanoparticles incorporated optical materials may result into size and surface effects that offers negligible scattering for enhanced beam collimation, minimal back scattering to the source and minimal internal scattering loss. Reduction in size of the local structure to nanoscale may lead to the formation of enhanced surface states which affects optical characteristics [25]. Luminescence of glass ceramics is comparable to that of a single crystal. However, the search for extra competent glass composition for solid state lasers is still continuing, and investigations are on to understand the ion-ligand interaction and minimising the nonradiative relaxations to improve the performance of active medium.

CO-DOPED GLASSES AND GLASS CERAMICS AS LASING MEDIUM

Crystalline nanoparticles incorporated in amorphous glass matrix is referred as Transparent Glass Ceramic (TGC). The size of the nanoparticle (NP) is significant in deciding gain per unit length and amplifying action of glass fibre for laser applications to keep scattering losses at bay. Lasing properties of Nd^{3+} doped barium crown glass was first demonstrated in 1961 [26]. Since then, a great number of researchers throughout the world have explored the suitability of transparent glass ceramics for solid-state laser applications by studying their lasing properties, such as, gain, luminescent efficiency, radiative properties etc. It has been established that the transformation of a glass into glass ceramic results in enhancement of luminescent lifetime of excited state and narrowing of spectral lines. F. Auzel et al. have prepared rare-earth doped oxyfluoride glass ceramics and reported its up-conversion efficiency to be twice than that of commercially available LaF_2:Yb:Er phosphors [27]. Oxyflouride glass precursors have combined properties of low phonon energy fluoride host and thermally stable oxide glass. Fluorescence and laser gain spectrum of Nd^{3+} ions glass fibers have witnessed drastic change by ceramizing process [28]. Rare earth (Pr, Nd, Eu, Dy, Er, Tm) doped lead borate glasses and glass ceramics are reported to be potential candidates for solid state laser materials owing to their favourable spectroscopic properties [29]. High transparency of glass ceramics for guided wave applications is highly relevant. It can be achieved by minimizing the optical scattering losses in the material. Low scattering losses can be achieved either by matching refractive index of crystalline phases and residual glass, or by low birefringence of the crystal. W. Blanc. et al. synthesized Er^{3+} doped TGC with in-situ grown Mg-nanoparticles of 40 nm size by MCVD method without requiring ceramizing stage for low-loss fibre applications [30]. S. Chenu et al. observed that the glass ceramics can be made highly transparent by tailoring the size of nano crystallite through careful control of composition. The authors confirmed that the addition of up to 2.5 mole % of Na_2O to zinc gallogarmanate glass has fairly improved its transparency [31]. Different microstructure configurations may result by modifying constituent of glasses and thermal treatment condition. T. Ouyang et al. have synthesized Er^{3+} -ion doped sodium borosilicate glass ceramics enriched with $NaYF_4$ nanocrystals and observed great enhancement in its luminescent properties on realizing microsphere cavity [32]. They further emphasized on the significance of minimising the refractive index difference between glass matrix and nanocrystal to obtain high quality factor of synthesized glass samples. The growth of $NaYF_4$ nanocrystals have accelerated on increasing the temperature of heat treatment and resulted in broadening of 2.7 μm emission of Er^{3+} ion in Er^{3+}-Ho^{3+} co-doped oxyfluoride germanosilicate glass ceramics due to multiple local structures developed around rare-earth ions [33]. Glass ceramics have recently been analysed for optical amplifiers, photovoltaic devices, colour display, optical limiters and random laser [34]. In addition to melt-quenching and heat treatment technique, top-down and bottom-up fabrication methods are also in use for synthesizing high spectroscopic quality low-loss nanocrystal glass ceramics for integrated optics applications [35].

Many researchers working in the field of solid-state lasing materials have dedicated their attention to oxyhalide glasses. Oxyhalide glasses are suitable hosts for observing laser transitions due to their low phonon energy. D. Ramachari et al. observed NIR emission in oxyfluorosilicate glasses doped with neodymium, which makes them potential candidate for solid state lasing devices [36]. Y.C. Ratnakaram et al. observed NIR emission in Nd-doped fluorophosphate glasses also [37]. But such glasses have considerable disadvantages in terms of some significant properties, such as, poor chemical, thermal and mechanical stability, which limit their usage.

A few authors have focused on the potential of highly stable alternative glass forming materials, viz. tellurite glasses and glass ceramics. A significant enhancement in Stark splitting and intensity of emission bands is observed as a consequence of up-conversion in Er^{3+}-Yb^{3+} co-doped oxyhalide ceramics modified with tellurite as compared to corresponding glass and glass ceramic [38]. A. Tarafder et al. have observed enhanced photoluminescence in Eu-doped transparent willemite glass ceramic nanocomposites synthesized by controlled crystallization [39]. Authors further found increasing hardness of the ceramic with progressive heat treatment. In order to ensure optical quality of glass ceramic, high homogeneity of the sample and low scattering need to be taken care of.

It is concluded that rare-earth doped glass ceramics are demonstrated to have strong emissions in wide range of electromagnetic spectrum. Glass ceramics hinder chemical clustering and luminescent quenching of rare-earth ions by careful control of chemical environment around them. However, commercialization of such materials as laser active medium poses a challenge owing to its high scattering loss by dispersed crystallites, particularly in visible region. Further, glass ceramics often lose their transparency with increasing annealing time and temperature. Also, OH residual content may have absorption band overlapping with lasing transitions of luminescent ions. It speeds up the nonradiative energy loss rate from upper laser level (metastable level) to OH vibrational modes [40]. Additionally, Surface imperfections and laser-induced damages can greatly damage precursor glass by seeding thermal fracture. Hence, an inclusion-free gain medium with improved thermal, mechanical and optical properties need to be found. Excellent thermal shock resistance is highly desirable for such materials. Hence, development of improved laser glass composition that can be readily commercialize is still far from realization. Judd–Ofelt (JO) intensity parameters (Ω_2, Ω_4, and Ω_6) are significant in evaluating the optical quality and emission behaviour of rare-earth doped glass systems. These parameters are affected by the local environment around the dopant ions and offer insights into the asymmetry, covalency, and rigidity of the host matrix. A comparative analysis of JO parameters of various rare-earth doped glass systems is presented in **Table 1**.

Table 1: Comparative Analysis of Judd–Ofelt Intensity Parameters (Ω_2, Ω_4, Ω_6) in Various Rare-Earth Doped Glass Systems

Glass	Composition (mol%)	Ω_2 (X 10^{-20} cm^2)	Ω_4 (X 10^{-20} cm^2)	Ω_6 (X 10^{-20} cm^2)	I(Ω_4/ Ω_6)	Observation	Ref.
LSZBN1.2	$20Li_2CO_3$-5SrO-5ZnO-$68.8B_2O_3$-$1.2Nd_2O_3$	0.4459	1.4217	1.1348	1.2528	Ω_4> Ω_6> Ω_2	[41]
$5Nd_2O_3$	$54.5P_2O_5$-$30Na_2O$-$10Al_2O_3$-0.5CoO-$5Nd2O_3$	3.63	9.11	2.65	0.29	Ω_4> Ω_2> Ω_6	[42]
PZSMSm0.5	$59.5P_2O_5$-20MgO-$20ZnSO_4$-$0.5Sm_2O_3$	13.3	5.02	3.62	1.39	Ω_2> Ω_4> Ω_6	[43]
PNZSm0.5	$42.25P_2O_5$-$42.25Na_2O$-15ZnO-$0.5Sm_2O_3$	4.46	6.79	10.91	0.62	Ω_6> Ω_4> Ω_2	[44]
Nd0.5	$34.5B_2O_3$-$10P_2O_5$-	1.94	0.17	7.00	0.02	Ω_6> Ω_2> Ω_4	[45]

	$30Li_2O_3$- 15ZnO- 10SrO- $0.5Nd_2O_3$						
OFLZBSD1.0	$10Li_2O$- $9ZnF_2$- $50B_2O_3$- $30SiO_2$- $1Dy_2O_3$	2.42	0.80	2.65	0.30	$\Omega_6 > \Omega_2 > \Omega_4$	[46]
TZPNEu5	$60TeO_2$- $20ZnF_2$- 12PbO- $3Nb_2O_5$- $5Eu_2O_3$	3.58	5.91	1.94	3.04	$\Omega_4 > \Omega_2 > \Omega_6$	[47]
TeEu1.5	$83.5TeO_2$- $5La_2O_3$- $10TiO_2$- $1.5Eu_2O_3$	6.22	5.01	-	-	$\Omega_2 > \Omega_4$	[48]
TBZLN	$77TeO_2$- $4.5Bi_2O_3$- 5.5ZnO- $10.5Li_2O$- $1.5Nb_2O_5$- $1.0Yb^{3+}$	4.94	2.69	5.51	0.48	$\Omega_6 > \Omega_2 > \Omega_4$	[49]
EuBiPBa	$0.5Eu_2O_3$- $20Bi_2O_3$- $1.5Al_2O_3$- $58P_2O_5$- 20BaO	7.95	4.05	-	-	$\Omega_2 > \Omega_4$	[50]

It is noted that in LSZBN1.2 glass system, the observed order $\Omega_4 > \Omega_6 > \Omega_2$ indicates a moderately asymmetric local environment with a well-structured network, likely due to the borate matrix. However, Ω_4 dominates in $5Nd_2O_3$ glass sample, followed by Ω_2 and Ω_6. This indicates high polarizability and strong covalency around Nd^{3+} ions, enhanced by the phosphate structure and the presence of CoO as a potential modifier. In PZSMSm0.5 glass sample, Ω_2 is strikingly higher than the other two parameters, indicating a highly asymmetric and covalent environment around Sm^{3+}. This high value of Ω_2 is often associated with hypersensitive transitions, which can be utilized for sensor and display technologies [51]. The trend $\Omega_2 > \Omega_4 > \Omega_6$ is similarly observed in TeEu1.5 and EuBiPBa glasses, implying the role of TeO_2 and Bi_2O_3 in enhancing asymmetry and electron cloud distortion around Eu^{3+} ions—important characteristics for intense red emission.

Conversely, glass samples PNZSm0.5 and Nd0.5 exhibit the order $\Omega_6 > \Omega_4 > \Omega_2$, a pattern suggesting more symmetric, ionic environment around the dopants. Notably, the Nd0.5 glass shows an extremely low Ω_4 value (0.17×10^{-20} cm^2) and high Ω_6 (7.00×10^{-20} cm^2), with Ω_4/Ω_6 ratio of just 0.02, pointing toward a highly rigid glass network that resists local distortions. Similarly, in OFLZBSD1.0 glass sample, Ω_6 is again dominant, emphasizing the idea that borate–silicate–fluoride hosts tend to provide more symmetric environments for Dy^{3+}. In the TZPNEu5 glass, a high Ω_4 (5.91×10^{-20} cm^2) coupled with a notable Ω_4/Ω_6 ratio of 3.04 suggests strong asymmetry and potential for efficient forced electric dipole transitions in Eu^{3+} ions. This is a desirable feature for red-emitting phosphors in lighting or display applications. Further, TBZLN exhibits $\Omega_6 > \Omega_2 > \Omega_4$, showing a relatively more symmetric coordination for Yb^{3+}, which may benefit upconversion processes requiring long-lived intermediate states. It is found that the glasses rich in phosphate and tellurite exhibit higher Ω_2 values, suggesting stronger hypersensitive transitions and greater asymmetry. Such insights are crucial for tailoring glass materials for specific photonic and optoelectronic applications.

The **Table 2** presents an overview of the optical behaviour of various rare-earth doped glass systems by listing key spectroscopic parameters that influence their performance in photonic applications. These include the emission wavelengths (λ_p), transition probabilities (A_R), emission cross-sections (σ_{em}), and quantum efficiencies (η). Among all the samples, PZSMSm0.5 glass shows a strong emission at 644 nm with a fairly broad bandwidth of about 21 nm. It also exhibits a high radiative transition rate, suggesting efficient radiative decay—a property highly desirable in designing efficient emitters. The OFLZBSD1.0 sample is even more remarkable, showing one of the highest transition rates, along with a strong emission cross-section and an impressive experimental quantum efficiency of 80%. These characteristics indicate that this glass could be especially promising for high-performance optical amplifiers or solid-state lasers.

On the other hand, Nd0.5 glass emits in the near-infrared region at 1060 nm and has a relatively long radiative lifetime. While its emission strength is moderate, it could be useful in specific laser applications requiring emissions in this spectral region. Glass sample PNZSm0.5 also presents a good balance of emission characteristics, suggesting its utility in visible light emission applications. Europium-doped samples such as TeEu1.5 and TZPNEu5 show emissions in the red region (~613–615 nm), characteristic of the $^5D_0 \rightarrow {}^7F_2$ transition. Sample TeEu1.5 shows encouraging results with a notable emission cross-section and decent quantum efficiency of 74%, making it an attractive candidate for red LEDs or display technologies.

Table 2: Comparative study of radiative properties of above mentioned rare-earth doped glasses

Glass Sample	Transition	λ_p (nm)	$\Delta\lambda_p$ (nm)	A_R (s^{-1})	σ_{em} (X 10^{-22})	τ (μs)		β_R		η(%)
						Exp	Cal	Exp	Cal	
LSZBN1.2	---	---	---	---	---	---	---	---	---	---
5Nd_2O_3	$^4F_{5/2}\rightarrow{}^4I_{9/2}$	---	---	704	---	---	0.904	---	0.68	---
PZSMSm0.5	$^4G_{5/2}\rightarrow{}^6H_{9/2}$	644	21.0926	925.9953	21.7987	---	---	30.0931	47.4840	-
PNZSm0.5	$^4G_{5/2}\rightarrow{}^6H_{7/2}$	600	---	198.65	4.15	2.42	2.98	---	0.59	81.20
Nd0.5	$^4F_{3/2}\rightarrow{}^4I_{11/2}$	1060	32.50	290.8	6.39	0.228	---	0.49	0.66	-
OFLZBSD1.0	$^4F_{9/2}$-$^6H_{13/2}$	575	14.86	2595.17	37.3	165	---	0.624	0.5254	80
TZPNEu5	$^5D_0$-$^7F_2$	615	---	---	---	---	---	0.495	---	-
TeEu1.5	$^5D_0$-$^7F_2$	613	10.44	537.97	23.19	0.88	1.18	0.64	---	74
TBZLN	$^1G_4\rightarrow{}^3H_5$	1334	106.47	982	88	---	---	---	0.61	---
EuBiPBa	$^5D_0$-$^7F_2$	630	---	755.52	23.18	---	0.918	0.694	---	---

Although data is limited for samples TBZLN and EuBiPBa, their branching ratios and emission wavelengths suggest that further study could uncover valuable laser or display material properties. The EuBiPBa glass, exhibiting the prominent $^5D_0 \rightarrow {}^7F_2$ transition at 630 nm, shows a high spontaneous emission probability, significant emission cross-section, and a strong branching ratio. These values highlight its excellent potential for red-emitting photonic devices. Overall, the findings highlight the diverse emission characteristics of rare-earth doped glasses, influenced heavily by both the host matrix and dopant ion. Glasses like OFLZBSD1.0 and TeEu1.5 stand out for their strong optical responses and high quantum efficiencies, making them excellent candidates for future photonic devices. These insights can guide further material design tailored to specific applications in lighting, lasers, and optical amplifiers.

CHALLENGES AND FUTURE PROSPECTS

Challenges in this type of study include controlling the glass composition to ensure homogeneity, optimizing dopant concentration to avoid concentration quenching, and maintaining the structural stability of the glass matrix under various thermal or irradiation conditions [52]. Additionally, accurate measurement of spectroscopic parameters like emission cross-section and radiative lifetime can be complex due to overlapping transitions and matrix effects.

Future perspectives involve tailoring glass hosts for enhanced luminescence efficiency, exploring novel co-doping strategies to improve energy transfer mechanisms, and integrating these glasses into photonic devices such as lasers, optical amplifiers, and sensors. With advancements in nanostructuring and fabrication techniques, such studies can lead to the development of smart, compact, and efficient luminescent materials for next-generation optoelectronics and quantum technologies.

CONCLUSION

The comparative spectroscopic analysis of rare-earth-doped glass systems highlights how subtle changes in glass composition significantly impact their radiative transition probabilities, emission cross-sections, lifetimes, and overall quantum efficiencies. Sm^{3+}- and Nd^{3+}-doped phosphate and borate glasses such as PZSMSm0.5 and Nd0.5 show strong emissions in the visible and near-infrared regions, respectively, indicating their suitability for laser and amplifier applications. Notably, the Eu^{3+}-doped EuBiPBa glass demonstrates a high emission cross-section and a favourable branching ratio, making it a potential candidate for red-emitting photonic devices. The observed data clearly establish the influence of host matrices—especially phosphate, tellurite, and borate compositions—on key optical parameters such as asymmetry ratio and stimulated emission probabilities. The measured and calculated lifetimes further confirm the radiative dominance of certain transitions, suggesting these systems can be optimized for specific optoelectronic functions. Overall, this study provides a deeper understanding of structure-property relationships in doped glasses, which is vital for tailoring materials for lasers, sensors, and display technologies.

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