

Er³⁺/Yb³⁺ Co-Doped Optical Glasses and Glass-Ceramics: Advances in Luminescence, Energy Transfer, Lasers, Optical Amplification and Sensing

Pramod Saket*, Purnima Singh

Department of Physics, Govt MVM College, Barkatullah University, Bhopal, India

E-mail id: pramodkumarr320@gmail.com

Abstract

Er³⁺/Yb³⁺ co-doped glasses and glass-ceramics have attracted considerable attention as multifunctional photonic materials because of their efficient near-infrared emission, visible upconversion, broad gain bandwidth, and compatibility with compact optical devices. The incorporation of Yb³⁺ as a sensitizer provides an efficient route for absorbing 980 nm excitation and transferring energy to Er³⁺, thereby enhancing the population of radiative Er³⁺ states. This review summarizes recent progress in Er³⁺/Yb³⁺-activated phosphate, tellurite, fluorophosphate, silicate, bismuth-containing, fluoride, chalcogenide and mixed-anion glass systems. Particular emphasis is placed on the relationship between glass composition, local structure, phonon energy, rare-earth concentration, energy-transfer processes and optical performance. Phosphate glasses provide high rare-earth solubility and favorable gain characteristics, whereas tellurite and fluorotellurite systems offer high refractive indices, broad emission and relatively low phonon energies. Controlled crystallization further improves luminescence by concentrating rare-earth ions in low-phonon nanocrystalline environments. Optimization of Er/Yb ratios is essential because excessive dopant concentrations can introduce energy-transfer upconversion, back-energy transfer and concentration quenching. Additional strategies, including halide modification, heavy-metal oxide incorporation, dehydration, laser sintering, silver nanoparticle incorporation and multi-ion doping, have provided further improvements in emission efficiency and device functionality. Beyond conventional 1.5 μm lasers and optical amplifiers, Er³⁺/Yb³⁺ glasses are increasingly being investigated for optical thermometry, UV monitoring, random lasing, strain sensing and integrated photonics. Overall, the literature demonstrates that simultaneous control of composition, rare-earth concentration, nanocrystallization and photonic architecture provides a versatile strategy for engineering high-performance Er³⁺/Yb³⁺-based optical materials.

Keywords: Er³⁺; Yb³⁺; rare-earth-doped glasses; tellurite glass; phosphate glass; glass-ceramics; upconversion luminescence; near-infrared emission; energy transfer; optical amplifiers; optical temperature sensing; photonic materials

1. Introduction

Rare-earth-doped glasses represent an important class of functional optical materials because their disordered structure permits broad spectral emission, flexible compositional modification and relatively straightforward fabrication into fibers, waveguides and bulk optical components. Among the various rare-earth combinations investigated, Er³⁺/Yb³⁺ co-doping is particularly important because it combines the technologically relevant 1.5 μm Er³⁺ emission with the strong absorption capability of Yb³⁺ around 980 nm. Energy transfer from Yb³⁺

to Er^{3+} can substantially increase the population of Er^{3+} excited states and consequently improve near-infrared emission and visible upconversion. Studies of bismuth borophosphate and phosphate hosts have demonstrated that Yb^{3+} sensitization can significantly strengthen the 1.53 μm emission while maintaining favorable radiative characteristics.^{1,2}

The performance of $\text{Er}^{3+}/\text{Yb}^{3+}$ -activated materials is strongly dependent on the host glass. Network composition determines the phonon energy, refractive index, rare-earth solubility, local symmetry and structural environment surrounding the dopant ions. These parameters directly influence radiative transition probabilities, multiphonon relaxation, energy-transfer efficiency and emission bandwidth. Phosphate glasses are particularly attractive because of their high rare-earth solubility and ability to accommodate substantial dopant concentrations while maintaining useful optical properties.^{3–5} Tellurite glasses, in contrast, combine high refractive index with relatively moderate phonon energy and have therefore emerged as important hosts for broadband emission, upconversion and optical sensing.^{6–8}

The development of glass-ceramics has provided another route to improve the optical response. Controlled precipitation of low-phonon-energy nanocrystals can selectively incorporate Er^{3+} and Yb^{3+} ions into crystalline regions, reducing non-radiative losses and enhancing upconversion.^{6,7,9,10} Similar improvements have been achieved through fluorination, halide modification and the incorporation of heavy-metal oxides.^{11,12}

In parallel with improvements in fundamental spectroscopy, $\text{Er}^{3+}/\text{Yb}^{3+}$ -doped materials have progressed toward practical lasers, fiber amplifiers, waveguides, thermometers, UV sensors and multifunctional photonic devices.^{13–18} This review therefore examines the development of $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped glasses from the perspectives of host composition, energy-transfer mechanisms, concentration optimization, processing strategies and emerging applications.

2. Fundamental Role of $\text{Er}^{3+}/\text{Yb}^{3+}$ Co-Doping

The central advantage of $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doping is the sensitization of Er^{3+} by Yb^{3+} . Yb^{3+} possesses a comparatively simple electronic structure and a strong absorption band near 980 nm. Following excitation, energy can be transferred from Yb^{3+} to Er^{3+} , increasing the population of Er^{3+} excited states responsible for both the 1.5 μm emission and higher-energy upconversion pathways.^{1,2}

The effectiveness of this process depends on the spectral overlap between donor and acceptor transitions, the average separation of the rare-earth ions and the local structural environment. Förster-type energy transfer, lifetime analysis and rate-equation modeling have been employed to quantify these interactions.^{2,8,15,19} At suitable concentrations, increasing Yb^{3+} enhances pump absorption and Er^{3+} excitation. However, excessive Yb^{3+} or Er^{3+} concentrations can promote energy-transfer upconversion and back-energy transfer, ultimately reducing the desired luminescence.^{20,21}

The importance of concentration control has been demonstrated across several glass systems. In phosphate glasses, increasing Yb^{3+} concentration initially improves 1.53 μm emission, but at sufficiently high concentrations energy-transfer upconversion and back-energy transfer become important quenching pathways.^{20,21} Similar concentration-dependent behavior has been observed in fluorophosphate and fluorotellurite systems.^{4,22}

3. Phosphate Glasses as $\text{Er}^{3+}/\text{Yb}^{3+}$ Laser and Amplifier Hosts

Phosphate glasses constitute one of the most extensively investigated host families for $\text{Er}^{3+}/\text{Yb}^{3+}$ systems. Their principal advantage is their ability to dissolve relatively high concentrations of rare-earth ions while maintaining a stable glass network.^{3,23} This characteristic is particularly valuable for compact lasers and amplifiers, where high dopant concentrations permit efficient pump absorption over short propagation lengths.

Zhang et al. demonstrated strong 1.53 μm emission from $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped phosphate glasses under 980 nm excitation and related the emission enhancement to efficient $\text{Yb}^{3+} \rightarrow \text{Er}^{3+}$ energy transfer.² The phosphate environment also provided a favorable optical platform for high-gain amplifiers and short-cavity lasers. Langar et al. subsequently demonstrated that increasing Yb^{3+} content can substantially increase absorption at 980 nm and generate broad and relatively flat gain profiles suitable for wavelength-division multiplexing.³

The structural role of the phosphate network is equally important. Network modifiers such as Na_2O and BaO can modify the local environment of rare-earth ions and influence Judd–Ofelt intensity parameters, radiative transition probabilities and fluorescence lifetimes.¹⁷ Phosphate content also affects refractive index, covalency and local asymmetry. Kolobkova et al. showed that increasing phosphate content in fluorophosphate glasses can broaden the 1.53 μm emission and increase Ω_2 , although excessive phosphate may increase phonon-assisted relaxation and reduce fluorescence lifetime.²²

The laser performance of phosphate glasses has been confirmed experimentally. Liu et al. reported slope efficiencies approaching 30% in optimized $\text{Er}^{3+}/\text{Yb}^{3+}$ phosphate glasses under 980 nm pumping.¹⁷ Veasey et al. demonstrated continuous-wave operation near 1.53 μm in phosphate-glass waveguides, with Er/Yb co-doping providing substantially higher gain than singly doped configurations.¹⁸ Highly doped phosphate fibers have subsequently emerged as important platforms for compact high-power lasers and amplifiers.¹³

Further optimization has involved the addition of Y_2O_3 , which can increase network connectivity, glass transition temperature and chemical durability while modifying the spectroscopic and laser characteristics.²⁴ Similarly, systematic laser studies have indicated that moderate Er^{3+} concentrations combined with relatively high Yb^{3+} concentrations can provide a useful balance between pump absorption and suppression of upconversion losses.²⁵

4. Tellurite and Fluorotellurite Glasses

Tellurite glasses have become particularly attractive because of their high refractive index, broad emission characteristics and relatively low phonon energy compared with many conventional oxide glasses. These properties make them suitable for both infrared amplification and visible upconversion. Leal et al. demonstrated that Yb^{3+} concentration strongly influences the 1.53 μm emission of $\text{Er}^{3+}/\text{Yb}^{3+}$ -doped tellurite glasses.⁸ Emission increased with Yb^{3+} loading until a critical concentration was reached, after which concentration quenching became dominant. The study highlighted the importance of balancing enhanced pump absorption against back-energy transfer and other non-radiative pathways.

Tellurite composition can also be manipulated through the incorporation of fluorides and other network modifiers. Reddy et al. reported strong and broad 1.53 μm emission in sodium-zinc-bismuth fluorophosphate glasses, attributing the favorable optical response to the combined contribution of high refractive index from bismuth and reduced phonon energy from fluoride.²⁶ Halide modification of tellurite glasses has similarly been shown to enhance green and red upconversion by lowering multiphonon relaxation.²⁷ Fluorotellurite glasses are particularly promising because they combine the structural advantages of tellurite networks with the lower

phonon energy of fluoride components. Zhu et al. reported $\text{Er}^{3+}/\text{Yb}^{3+}$ -doped fluorotellurite fibers with exceptionally broad emission extending across the C- and L-bands.²⁸ Recent work has further demonstrated that Yb^{3+} concentration can be optimized to maximize 1.53 μm emission, with excessive Yb^{3+} eventually producing concentration quenching.²⁹ The spectral flexibility of tellurite systems has also encouraged multi-ion doping. Pinto et al. demonstrated that simultaneous incorporation of Er^{3+} , Tm^{3+} and Yb^{3+} can generate an exceptionally broad emission window extending from approximately 1450 to 1650 nm.³⁰ Such broad gain media could potentially simplify future communication systems by reducing the requirement for multiple discrete amplifiers.

5. Fluorophosphate, Silicate and Other Glass Hosts

Fluorophosphate glasses provide an intermediate material strategy in which the chemical and structural stability of phosphate glasses is combined with the lower phonon energy associated with fluoride-containing environments. Kolobkova et al. demonstrated that relatively small changes in phosphate content can substantially modify $\text{Er}^{3+}/\text{Yb}^{3+}$ luminescence, energy-transfer rates and the balance between red and green upconversion.^{4,22} Silicate glasses remain technologically relevant because of their mechanical stability, established processing technologies and compatibility with waveguide fabrication. Hehlen et al. compared $\text{Er}^{3+}/\text{Yb}^{3+}$ -doped soda-lime silicate and aluminosilicate systems and found that the aluminosilicate environment could provide broader emission, larger stimulated emission cross-sections and somewhat improved energy transfer.³¹ Righini et al. demonstrated net optical gain around 1.53 μm in Er- and Er/Yb-doped silicate waveguides, emphasizing the role of Yb^{3+} sensitization in obtaining sufficient gain in short devices.³² Multicomponent silicate compositions containing GeO_2 , Al_2O_3 and ZnO have subsequently been explored to modify refractive index, phonon energy, rare-earth dispersion and thermal behavior.³³ Alternative hosts have also been explored. Germanate glasses offer intermediate phonon energies and can provide strong 1.53 μm emission while retaining good mechanical and thermal characteristics.³⁴ Chalcogenide glasses possess exceptionally low phonon energies and can therefore support highly efficient upconversion and infrared emission, although their lower thermal stability and comparatively high refractive indices create processing challenges.³⁵

6. Glass-Ceramics and Controlled Crystallization

Controlled crystallization represents one of the most effective strategies for improving rare-earth luminescence. In glass-ceramics, heat treatment produces nanoscale crystalline phases within an amorphous matrix. If Er^{3+} and Yb^{3+} preferentially partition into these low-phonon crystals, multiphonon relaxation can be reduced and radiative emission can be enhanced. Tellurite glass-ceramics containing $\text{Bi}_2\text{Te}_4\text{O}_{11}$ crystals have demonstrated substantially stronger upconversion emission than their parent glasses.^{6,36} The improvement has been associated with the preferential incorporation of rare-earth ions into the crystalline environment and the resulting reduction in non-radiative relaxation. Similarly, controlled crystallization of $\text{Yb}^{3+}/\text{Er}^{3+}$ tellurite glasses has been shown to generate nanocrystalline phases that enhance green and red upconversion.⁷

Fluoride nanocrystals provide an especially favorable environment because of their low phonon energies. Velázquez et al. demonstrated the precipitation of NaLuF_4 nanocrystals in $\text{Er}^{3+}/\text{Yb}^{3+}$ -doped glasses, producing a substantial increase in upconversion quantum yield.⁹ Tikhomirov et al. further demonstrated that the optimum Er/Yb ratio differs depending on whether upconversion or 1.53 μm down-conversion emission is the primary target.¹⁰ The broader literature confirms that the improvement produced by glass-ceramics arises from multiple factors, including lower phonon energy, modified local symmetry, selective rare-earth partitioning and changes in energy-transfer rates.¹⁴ These advantages must nevertheless be balanced against the need to control nanocrystal size and distribution so that transparency is not compromised.

7. Concentration Quenching and Optimization of Dopant Ratios

Dopant concentration is one of the most critical parameters controlling $\text{Er}^{3+}/\text{Yb}^{3+}$ optical performance. At low concentrations, increasing Yb^{3+} generally improves absorption at 980 nm and increases energy transfer to Er^{3+} . Beyond an optimum concentration, however, additional Yb^{3+} may increase back-energy transfer, energy-transfer upconversion and other non-radiative processes.^{20, 21, 37} Zhao et al. systematically examined highly concentrated phosphate glasses and reported an optimum $\text{Yb}^{3+}/\text{Er}^{3+}$ ratio of approximately 10:1 for maximum luminescence efficiency.²¹ Kolobkova et al. similarly demonstrated that upconversion intensity initially increases with Yb^{3+} concentration before declining at high concentrations because of concentration quenching and back-energy transfer.²² The optimum dopant ratio is also application dependent. Tikhomirov et al. demonstrated that the concentration conditions favoring visible upconversion are not necessarily the same as those required for maximizing 1.53 μm emission.¹⁰ Thus, dopant optimization cannot be considered independently of the intended application.

Er^{3+} concentrations can also introduce cooperative upconversion. Hwang et al. found that cooperative upconversion from the $\text{Er}^{3+} {}^4\text{I}_{13/2}$ level becomes important at high Er^{3+} concentrations, reducing the quantum efficiency of the 1.53 μm emission.¹⁵ These observations emphasize the importance of combining concentration-dependent spectroscopy with quantitative rate-equation analysis when designing highly doped materials.

8. Structural and Processing Strategies for Luminescence Enhancement

Beyond changing the Er/Yb ratio, several processing and compositional strategies have been developed to improve luminescence. One important approach is reduction of hydroxyl contamination. OH groups act as efficient vibrational quenchers and can substantially decrease the lifetime of Er^{3+} excited states. Tian et al. demonstrated that dehydration of $\text{Er}^{3+}/\text{Yb}^{3+}$ phosphate laser glass increased fluorescence lifetime from approximately 6 ms to more than 9 ms while improving gain characteristics.³⁸

Laser sintering provides another processing strategy. Zhang et al. demonstrated that laser-sintered Yb/Er-doped silica glasses can exhibit luminescence comparable to or better than conventionally melted materials, partly because the localized processing minimizes incorporation of water and other quenching species.³⁹ Network modification can also produce significant changes. Addition of WO_3 to tellurite glasses has been associated with broader near-infrared emission, flat gain profiles and improved thermal stability.⁴⁰ Tungsten-containing tellurite glasses also show strong visible upconversion, particularly when Yb^{3+} is incorporated as a sensitizer.⁴¹ Heavy-metal oxide components such as PbO , Bi_2O_3 and WO_3 can increase density, polarizability and refractive index, thereby modifying local fields and radiative transition probabilities.⁴²

9. Upconversion Luminescence and Visible Emission

Although the 1.5 μm Er^{3+} emission is the principal target for many telecommunications applications, $\text{Er}^{3+}/\text{Yb}^{3+}$ systems also provide efficient visible upconversion. Under 980 nm excitation, sequential energy-transfer and excited-state absorption processes can populate higher Er^{3+} levels, generating green and red emission.

Amjad et al. demonstrated both strong green upconversion and 1.53 μm near-infrared emission in novel phosphate glasses, with power-dependent measurements indicating contributions from two- and three-photon processes.⁴³ Kumari et al. similarly observed strong green and red upconversion in tungsten tellurite glasses, with Yb^{3+} incorporation producing a substantial increase in emission intensity.⁴¹ The relative intensities of green and red emission depend strongly on host composition and dopant concentration. Fluorophosphate

systems, for example, exhibit changes in red-to-green emission ratios as phosphate content and Er/Yb concentrations are modified.^{4,22} Such spectral tunability is valuable for displays, optical labeling, anti-counterfeiting and sensing.

10. Optical Amplifiers, Lasers and Integrated Photonics

The broad emission bandwidth and favorable transition characteristics of Er^{3+} make these glasses particularly useful for optical amplification around 1.5 μm . Phosphate fibers are especially attractive for high-concentration doping and compact amplifier designs.¹³ The high rare-earth solubility allows short active lengths while maintaining substantial pump absorption. Waveguide architectures further reduce device size. Veasey et al. demonstrated Yb/Er-codoped phosphate waveguide lasers operating near 1.53 μm , while Righini et al. demonstrated net optical gain in Er/Yb-doped silicate waveguides.^{18,32} These results illustrate the compatibility of $\text{Er}^{3+}/\text{Yb}^{3+}$ glasses with integrated optical circuits. Photo-thermo-refractive glass provides another interesting platform. Nasser et al. demonstrated 1.54 μm laser oscillation with Er/Yb doping and emphasized the combination of low thermal expansion, favorable fluorescence properties and compatibility with intracavity holographic structures.⁵ The development of broadband fluorotellurite fibers has further expanded the application space. Zhu et al. reported emission extending across the C- and L-bands, while Pinto et al. demonstrated even broader emission through $\text{Er}^{3+}/\text{Tm}^{3+}/\text{Yb}^{3+}$ tri-doping.^{28,30}

11. Optical Temperature Sensing

The temperature dependence of Er^{3+} upconversion provides a powerful basis for optical thermometry. In particular, the fluorescence intensity ratio (FIR) between the thermally coupled $^2\text{H}_{11/2}$ and $^4\text{S}_{3/2}$ levels follows a temperature-dependent Boltzmann relationship, allowing temperature to be inferred from emission intensities. Dagupati et al. demonstrated optical temperature sensing in $\text{Er}^{3+}/\text{Yb}^{3+}$ oxyfluorotellurite glasses over approximately 300–700 K.⁴⁴ The fluoride component reduced phonon energy and improved the stability of the upconversion signal. Subsequent work demonstrated high sensitivity, low hysteresis and reliable operation under repeated heating and cooling cycles.⁴⁴

Tang et al. reported a sensitivity approaching 1.5% K^{-1} at 500 K and further demonstrated the potential for simultaneous temperature and strain sensing through changes in emission characteristics.⁴⁵ Lisiecki et al. investigated the temperature dependence over a broad 10–600 K interval and confirmed the suitability of oxyfluorotellurite glasses for thermometry.⁴⁶ Recent developments have moved beyond bulk spectroscopic measurements toward fiber-integrated devices. Narro-García et al. proposed and experimentally validated a fiber-coupled $\text{Er}^{3+}/\text{Yb}^{3+}$ tellurite temperature sensor with an accuracy of approximately ± 0.5 $^{\circ}\text{C}$ over 25–300 $^{\circ}\text{C}$.⁴⁷ Wang et al. developed an all-fiber probe capable of rapid measurements under demanding thermal conditions, demonstrating the potential of Er/Yb tellurite materials for practical industrial and medical monitoring.⁴⁸

12. Multifunctional Sensing and Portable Devices

The development of portable optical sensors represents an important transition from material-level research toward practical applications. Tu et al. developed a portable all-fiber thermometer using rare-earth-doped $\text{TeO}_2\text{--WO}_3\text{--La}_2\text{O}_3\text{--Na}_2\text{O}$ glass and integrated optical filtering, photodetection and signal-processing components into a compact system.⁴⁹ Manzani et al. similarly developed a portable luminescent thermometer based on green $\text{Er}^{3+}/\text{Yb}^{3+}$ upconversion and incorporated a smartphone interface for real-time temperature display and data logging.⁵⁰ These developments illustrate how the spectroscopic characteristics of Er/Yb glasses can be translated into low-cost and user-oriented sensing platforms. Liu et al. expanded this concept

by developing a composite photoluminescent probe capable of simultaneously sensing temperature and UV radiation.⁵¹ The Er/Yb tellurite glass powder was incorporated into a polymer matrix to create a flexible sensing film, demonstrating the potential of these materials beyond conventional laser and amplifier applications.

13. Plasmonic Enhancement Using Silver Nanoparticles

Metal nanoparticles provide another route for modifying rare-earth luminescence. Silver nanoparticles can generate strong local electromagnetic fields through surface plasmon resonance, potentially increasing excitation and emission rates of nearby rare-earth ions. Stanek et al. investigated silver ion exchange in Er-Yb silicate glasses and found that optimized silver incorporation could increase 1.53 μm emission intensity by approximately 50%.⁵² However, excessive silver nanoparticle concentration resulted in luminescence quenching, demonstrating the importance of nanoparticle size and density. Zhang et al. investigated Ag nanoparticle-containing tellurite glasses and combined experimental spectroscopy with Mie theory and Judd–Ofelt analysis to examine the contribution of local-field enhancement.⁵³ The results indicated enhanced absorption and emission cross-sections and increased $\text{Yb}^{3+} \rightarrow \text{Er}^{3+}$ energy transfer. Dousti et al. subsequently demonstrated up to approximately 2.5-fold enhancement of NIR emission in Ag-containing zinc tellurite glasses under optimized conditions.⁵⁴ Wu et al. reported a similar plasmonic enhancement of the 1.53 μm fluorescence, with an approximately 1.8-fold increase at optimum Ag concentration and relatively small changes in lifetime, suggesting that local excitation-field enhancement was an important contributor.⁵⁵

14. Emerging Applications

The increasing control over composition and processing has expanded $\text{Er}^{3+}/\text{Yb}^{3+}$ glasses into several emerging photonic applications. Random lasing is one such area. da Silva et al. demonstrated random laser emission around 1.53 μm in rare-earth-doped tellurite and germanate glasses and glass-ceramics.⁵⁶ The introduction of crystalline phases modified scattering and could reduce the random-lasing threshold. Optical sensing is another rapidly developing field. Er/Yb glasses have been investigated for temperature measurement, strain sensing, UV monitoring and remote fiber-based sensing.^{47–51} Multi-element doping provides an additional pathway toward multifunctionality. Mo^{6+} tri-doping, for example, has been shown to enhance green upconversion and improve the sensitivity of $\text{Er}^{3+}/\text{Yb}^{3+}$ fiber temperature sensors.⁵⁷

The combination of broadband emission and multiple rare-earth ions is also promising for next-generation optical communications. $\text{Er}^{3+}/\text{Tm}^{3+}/\text{Yb}^{3+}$ tellurite glasses have demonstrated broad emission spanning major telecommunications windows, suggesting the possibility of multifunctional gain media capable of covering multiple wavelength bands.³⁰

15. Future Perspectives

Future development of $\text{Er}^{3+}/\text{Yb}^{3+}$ optical glasses will increasingly depend on simultaneous optimization of composition, structure and device architecture rather than optimization of individual parameters in isolation. The existing literature clearly shows that increasing Yb^{3+} concentration does not indefinitely improve luminescence; instead, an optimum region exists beyond which concentration quenching, energy-transfer upconversion and back-energy transfer become significant.^{20–22, 29} A major future direction is therefore the development of predictive composition–structure–property relationships. Judd–Ofelt analysis, rate-equation modeling, lifetime measurements and temperature-dependent spectroscopy should be integrated with structural characterization to distinguish radiative enhancement from changes caused by non-radiative processes.

Glass-ceramics are likely to remain particularly important because selective incorporation of Er^{3+} and Yb^{3+} into low-phonon nanocrystals provides an effective means of suppressing multiphonon relaxation. However, future work should focus on precise control of nanocrystal size, spatial distribution, rare-earth partitioning and residual scattering to maintain optical transparency while maximizing emission. For telecommunications, the development of broadband and flat-gain materials remains a major objective. Tellurite, fluorotellurite and multi-rare-earth systems appear particularly promising because they can provide broad spectral coverage beyond the conventional C-band.^{28, 30, 40} Another important direction is integration with compact sensing platforms. Fiber-coupled thermometers, smartphone-compatible devices and multifunctional polymer composites demonstrate that Er/Yb glasses can move from laboratory spectroscopy toward real-world applications.⁴⁷⁻⁵¹ Future devices should focus on miniaturization, calibration stability, low-power excitation, resistance to environmental interference and long-term reproducibility. Plasmonic enhancement also deserves further investigation. Although silver nanoparticles can improve luminescence, excessive loading can introduce quenching.⁵²⁻⁵⁵ A more systematic understanding of nanoparticle size, spacing, surface chemistry and rare-earth–nanoparticle distance could help maximize electromagnetic enhancement while minimizing energy-loss pathways. Sustainable and scalable fabrication should become a stronger consideration. Processing methods such as laser sintering, controlled crystallization and lower-temperature synthesis may provide routes toward reproducible production while reducing processing time and energy consumption. Integration of these materials with silicon photonics and other compact optical platforms may ultimately determine their technological impact.

16. Conclusion

The literature demonstrates that $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped glasses and glass-ceramics constitute highly versatile photonic materials whose properties can be engineered through coordinated control of host composition, dopant concentration, local structure and processing conditions. Yb^{3+} sensitization is central to their performance because it improves 980 nm pump absorption and facilitates energy transfer to Er^{3+} , supporting strong 1.53 μm emission and efficient visible upconversion.^{1, 2}

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