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Europium, Terbium, and Dysprosium Ions Doped Tellurite Glasses for White Light-Emitting Diode Applications: A Review

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Abstract

Tellurium dioxide (TeO_2) based glasses have emerged as one of the most promising inorganzic, binder-free host matrices for rare-earth (RE) doped phosphors intended for white light-emitting diode (WLED) applications. Their low maximum phonon energy, high linear refractive index, wide optical transparency window, and good rare-earth ion solubility distinguish them favourably from conventional silicate, borate, and phosphate glass formers. This review critically surveys the literature on the synthesis, structure, and luminescence of Eu^{3+} (red), Tb^{3+} (green), and Dy^{3+} (blue/yellow) doped tellurite glasses, situating this body of work within the broader context of solid-state lighting and phosphor-converted LED research. The structural chemistry of the TeO_2 network, the Judd–Ofelt framework used to quantify radiative transition probabilities, and the Förster–Dexter and Inokuti–Hirayama models of inter-ionic energy transfer are reviewed as the principal analytical tools underpinning this field. Reported single-ion, pairwise co-doped, and tri-doped rare-earth tellurite and related oxide-glass systems are compared in terms of their radiative parameters and CIE/CCT/CRI colorimetric outcomes. Although each of Eu^{3+}, Tb^{3+}, and Dy^{3+}, and several pairwise combinations, have been extensively studied in tellurite hosts, the simultaneous tri-doping of a single tellurite glass with all three ions to realise a single-composition, single-excitation white emitter, a strategy already demonstrated in borate, phosphate, and halophosphate hosts, remains largely unexplored. This gap is identified as a clear and well-motivated direction for future research.

Key words : tellurite glass; rare-earth doping; Eu^{3+}; Tb^{3+}; Dy^{3+}; white light-emitting diodes; Judd–Ofelt theory; energy transfer; phosphor.

1. Introduction

The search for efficient, stable, and spectrally tunable solid-state light sources has, over the past two decades, made white light-emitting diodes (WLEDs) the dominant technology for general illumination, display backlighting, and specialty lighting applications. Central to the performance of any WLED is the wavelength-converting medium that transforms the primary emission of an ultraviolet (UV) or near-UV (n-UV) semiconductor chip into a broadband, visually pleasing white light output. Commercial devices overwhelmingly rely on powder phosphors dispersed in an organic resin, a configuration that is compact and efficient but is simultaneously the principal source of long-term device degradation, owing to the poor thermal conductivity, UV-photo bleaching, and yellowing of the polymeric binder. This limitation has motivated an extensive body of research into inorganic, binder-free alternatives, among which rare-earth (RE) doped glasses occupy a prominent position because they combine the optical functionality of crystalline phosphors with the processability, transparency, and thermal/photochemical robustness of a glass matrix.

Tellurium dioxide (TeO_2) based glasses have, in this context, emerged as an especially attractive host system. Their low maximum phonon energy relative to conventional borate, phosphate, and silicate glasses suppresses multiphonon non-radiative relaxation of excited rare-earth levels, while their high linear refractive index, wide transmission window, good rare-earth ion solubility, and comparatively low melting and forming temperatures make them well suited to hosting trivalent lanthanide activators such as Eu^{3+}, Tb^{3+}, and Dy^{3+}, ions whose 4f–4f intraconfigurational transitions correspond, respectively, to red, green, and combined blue/yellow emission bands that together span the visible spectrum required for white light generation. This review critically surveys the literature relevant to the synthesis, structure, and luminescence of Eu^{3+}, Tb^{3+}, and Dy^{3+} doped tellurite glasses, situates this body of work within the broader context of WLED phosphor research, and identifies the specific gaps that motivate continued investigation in this area.

2. Solid-State Lighting and Approaches to White Light Generation :

Three principal engineering routes exist for generating white light from semiconductor light-emitting diodes. The first, a dichromatic approach, combines a blue-emitting InGaN chip with a yellow-emitting phosphor, most commonly cerium-doped yttrium aluminium garnet (YAG:Ce^{3+}); a fraction of the blue chip emission is transmitted unconverted while the remainder is down-converted to yellow, and the two components combine additively in the eye to give an impression of white. This configuration currently dominates commercial general lighting because of its high luminous efficacy, but it is intrinsically limited by a deficiency of red spectral content, which depresses the colour rendering index (CRI) and typically yields a cool, bluish-white appearance with high correlated colour temperature (CCT).

The second approach is trichromatic phosphor conversion, in which a near-UV or UV chip (usually 350–410 nm) pumps a blend of red-, green-, and blue-emitting phosphors, or a single multiply-doped phosphor capable of simultaneous red, green, and blue (or blue/yellow) emission. Because all of the visible output in this scheme is phosphor-generated, colour quality, CRI, and CCT can, in

principle, be tuned largely independently of the pump wavelength, a flexibility that has driven sustained interest in single-host, multiply rare-earth doped phosphors and glasses of exactly the type reviewed here. A closely related third approach dispenses with phosphors altogether and mixes the direct emission of red, green, and blue LED chips; while offering excellent colour tunability and efficiency, this route incurs higher cost, more complex driving circuitry, and colour instability arising from the differential ageing and thermal behaviour of the three chip types, and is consequently reserved mainly for display and specialty applications rather than general lighting.

A recurring theme across recent reviews of phosphor-converted LEDs is the pursuit of a single-phase, single-host wavelength converter capable of emitting a chromatically stable, high-CRI white light under a single excitation wavelength, thereby avoiding the re-absorption losses, differential thermal quenching, and colour drift associated with mixing multiple discrete phosphor powders [1,2]. This objective is most readily achieved either through multiple rare-earth co-doping of a single crystalline or glassy host, exploiting inter-ionic energy transfer to populate several emitting centres from one pump photon, or through careful compositional tuning of a single activator ion whose own emission spectrum is intrinsically broadband.

3. Phosphor Materials for WLEDs: From Powders to Phosphor-in-Glass

Conventional powder phosphors embedded in silicone or epoxy resin remain the industry standard, primarily because of their high internal quantum efficiency and mature, low-cost manufacturing base. However, this configuration suffers several well-documented shortcomings. The organic encapsulant has low thermal conductivity, so heat generated at the phosphor particles and by non-radiative Stokes losses is poorly dissipated, accelerating thermal quenching of luminescence and, over extended operation, causing yellowing, cracking, and delamination of the resin under sustained blue or UV flux and elevated junction temperature. Light scattering at phosphor–resin interfaces additionally degrades extraction efficiency and beam uniformity.

These limitations have motivated the development of phosphor-in-glass (PiG) composites, in which phosphor particles are dispersed within a low-melting inorganic glass frit and co-sintered into a rigid, inorganic colour-converting plate that can withstand much higher operating temperatures and optical flux densities than a resin-based converter [3]. A more radical alternative dispenses with a discrete phosphor phase entirely and instead incorporates the rare-earth activator directly into the glass network as a dissolved, atomically dispersed dopant. Such rare-earth doped bulk or thin glass converters combine the intrinsic thermal, chemical, and mechanical robustness of an oxide glass with luminescent behaviour governed by the local coordination environment the glass network provides to the dopant ion, and have been explicitly proposed in several tellurite-based studies as candidates for both solid-state lighting and photonic device applications [4,5]. Although the more limited absorption cross-section of dilute RE ions relative to engineered phosphor particles constrains achievable colour tunability compared with multi-phosphor PiG composites, this is offset by the simplicity of a single-melt fabrication route, the absence of any particle–matrix interface, and complete optical transparency of the resulting converter [3].

4. Glass as a Host Matrix for Luminescent Rare-Earth Ions

Unlike a crystalline lattice, a glass network offers no single, well-defined coordination site; instead, dopant ions occupy a statistical distribution of local environments differing in coordination number, bond length, and degree of covalency. This structural disorder has two consequences of direct relevance to phosphor design. First, it inhomogeneously broadens the absorption and emission bands of the dopant relative to the sharp, well-resolved lines seen in single-crystal hosts, an effect that is normally undesirable for laser gain media but is directly beneficial for solid-state lighting, where broad, over lapping emission bands assist in producing a smooth, continuous visible spectrum with a high colour rendering index. Second, because rare-earth ions substitute into sites lacking inversion symmetry more readily in a disordered glass than in many centrosymmetric crystal lattices, the electric-dipole (hypersensitive) transitions of ions such as Eu^{3+} are typically enhanced relative to the magnetic-dipole transitions, a symmetry effect that is exploited throughout the literature to assess local site asymmetry from emission intensity ratios [4,6].

The choice of glass former dictates the maximum phonon energy of the host lattice, which in turn governs the probability of multiphonon non-radiative relaxation between closely spaced rare-earth energy levels. Hosts with high phonon energy, such as borates and phosphates, non-radiatively quench excited states whose energy gap to the next-lower level can be bridged by a small number of phonons, substantially reducing luminescence quantum yield for certain transitions. Selecting a low-phonon-energy oxide host is therefore one of the principal strategies by which radiative quantum efficiency of rare-earth transitions can be enhanced without resorting to heavy-metal fluoride or chalcogenide glasses, which, despite their very low phonon energies, suffer from poor chemical durability and mechanical fragility. Table 1 compares representative properties of the major oxide glass-former families discussed in the literature.

Table 1. Representative comparison of glass-forming oxide systems commonly employed as rare-earth ion hosts, compiled from structural and spectroscopic studies of tellurite, borate, phosphate, and silicate glasses [6,7,8,9–13].

Property	**Silicate**	**Borate**	**Phosphate**	**Tellurite**
Maximum phonon energy (cm^{-1})	~1100	~1300–1400	~1200–1300	~700–800
Linear refractive index	1.45–1.55	1.50–1.60	1.50–1.55	1.95–2.2
Chemical durability	Excellent	Poor–moderate	Poor (hygroscopic)	Good
Glass transition temperature	High (>800 °C)	Moderate	Low–moderate	Moderate (300–400 °C)
UV–Vis–NIR transparency window	Narrow (IR cut-off ~2.5 μm)	Narrow (~3 μm)	Moderate (~3.5 μm)	Wide (0.4–6 μm)
Rare-earth solubility	Moderate	Moderate	Good	Good–excellent
Melt processing temperature	High (>1400°C)	Moderate	Low	Low (800–900 °C)

5. Tellurite Glasses: Structure and Properties

5.1 Structural Chemistry of the TeO_2 Network

Tellurium dioxide is classified as a conditional glass former: it is extremely difficult to vitrify in its pure state, requiring melt-quenching rates on the order of 10u K/s, but readily forms stable glasses when combined with alkali, alkaline-earth, transition-metal, or heavy-metal modifying oxides at much more accessible quenching rates [14]. The fundamental structural unit in tellurite glass is the TeO_4 trigonal bipyramid (tbp), in which the Te^{4+} ion is coordinated by four oxygen atoms with a lone electron pair occupying an equatorial position. As network-modifying cations are introduced, bridging Te–O–Te linkages are progressively broken, converting TeO_4 trigonal bipyramids first into intermediate TeO_{3+1} polyhedra and ultimately into TeO_3 trigonal pyramids bearing non-bridging oxygen atoms; this structural evolution has been repeatedly confirmed by Raman and FTIR spectroscopy across a wide range of modifier compositions [15]. The relative proportion of TeO_4 to TeO_3/TeO_{3+1} units is composition-dependent and directly correlates with the glass network connectivity, rigidity, density, and optical basicity, all of which influence the local field experienced by a dissolved rare-earth ion and hence its radiative transition probabilities [14,16].

Mixed-former tellurite systems, in which TeO_2 is combined with a second glass-forming oxide such as B_2O_3, P_2O_5, or GeO_2, have been investigated in detail using solid-state NMR, X-ray photoelectron spectroscopy, and vibrational spectroscopy; such studies indicate that the two network formers tend to segregate into compositionally distinct domains rather than forming direct heteroatomic Te–O–B or Te–O–P linkages, giving rise to composition-dependent (and in some cases negative) mixed-former effects on properties such as ionic conductivity and glass transition temperature [7,8]. These structural insights are directly relevant to rare-earth doped tellurite-germanate and tellurite-borate glasses reviewed in later sections, where the second network former is deliberately introduced to adjust the phonon energy, thermal stability, or rare-earth solubility of the host.

5.2 Physical, Thermal, and Optical Properties Relevant to Photonics

Tellurite glasses possess a distinctive combination of properties that recur throughout the literature as the principal justification for their selection as luminescent hosts. Their maximum phonon energy, typically in the range of 700–820 cm^{-1}, is substantially lower than that of borate (~1300–1400 cm^{-1}) or phosphate (~1200–1300 cm^{-1}) glasses, which directly suppresses multiphonon relaxation and favours higher radiative quantum efficiency for rare-earth transitions with small energy gaps. Their linear refractive index is high (typically 1.9–2.2), which enhances the local field correction factor entering the Judd–Ofelt expressions for spontaneous emission probability and stimulated emission cross-section, generally yielding larger radiative transition rates than are obtained in lower-index hosts. Tellurite glasses additionally combine a wide optical transmission window extending from the near-UV through the mid-infrared with comparatively low melting and glass transition temperatures (typically 300–400 °C), moderate-to-good chemical durability, and good solubility for high concentrations of rare-earth oxide dopants without extensive clustering or phase separation, a property repeatedly cited as advantageous relative to silicate and borate hosts [17–20].

The incorporation of modifier oxides such as alkaline-earth carbonates, alkali oxides, or transition-metal oxides has been shown to systematically tune density, molar volume, optical band gap, and refractive index by altering the TeO_4/TeO ratio and the concentration of non-bridging oxygens, offering a practical compositional lever for optimising the host for a specific rare-earth luminescence application [14, 15, 22]. Several studies have further coupled these structural and optical investigations with radiation-shielding characterisation, reflecting the additional interest in dense tellurite glasses for combined optical and gamma-ray attenuation applications [9, 10] .

5.3 Comparative Advantages for Rare-Earth Doping

Taken together, the low phonon energy, high refractive index, wide transparency window, and good rare-earth solubility of tellurite glasses provide a coherent rationale for their selection, in preference to silicate, borate, or phosphate hosts, as the matrix for Eu^{3+}, Tb^{3+}, and Dy^{3+} doping. This preference is consistent with the emphasis placed on tellurite hosts across the reviewed literature on rare-earth doped glasses for both amplifier/laser and solid-state lighting applications [17–20].

6. Spectroscopy of Trivalent Rare-Earth Ions in Glass Hosts

The optical properties of trivalent lanthanide ions arise from transitions within the partially filled 4f shell, which is effectively shielded from the surrounding ligand field by the fully occupied outer 5s and 5p orbitals. This shielding renders 4f–4f transitions comparatively insensitive to the host lattice, so that the characteristic emission wavelengths of a given ion (the blue/yellow bands of Dy^{3+}, the green bands of Tb^{3+}, and the red bands of Eu^{3+}) are only weakly shifted between different glass or crystal hosts. What does vary substantially with the host is the intensity, branching ratio, and radiative lifetime of each transition, because these are governed by the local site symmetry and covalency experienced by the ion, both of which are host-dependent. Since 4f–4f transitions are parity-forbidden in a free ion, their observed intensity in a real material arises predominantly from a forced electric-dipole mechanism, in which odd-parity components of the local crystal field admixture opposite-parity configurations (chiefly $4f^{n-1}5d$) into the $4f^n$ wave functions, and it is the strength of this admixture, controlled by the degree of site-symmetry breaking and covalent bonding, that the host glass composition can be used to tune.

The standard framework for quantifying these intensities is the Judd–Ofelt theory, which parameterises the strength of induced electric-dipole transitions between the free-ion states of a lanthanide ion in a given host by three phenomenological intensity parameters, conventionally denoted Ω_2, Ω_4, and Ω_6. These parameters are extracted by fitting measured absorption (or, in the case of Eu^{3+}, emission) band areas to the Judd–Ofelt expression for oscillator strength, and they are subsequently used to calculate spontaneous emission probabilities, radiative lifetimes, branching ratios, and stimulated emission cross-sections for all transitions of interest. The Ω_2 parameter is generally interpreted as being sensitive to the asymmetry and covalency of the immediate ligand environment (short-range effects), while Ω_6 is more closely associated with the rigidity and bulk polarisability of the host network; consequently, the ratio and magnitude of these parameters, computed independently

for each glass composition, provide a compact spectroscopic fingerprint that is repeatedly used throughout the tellurite-glass literature to compare local structural environments across different modifier compositions and dopant concentrations [6,18,19,23].

7. Eu^{3+} as a Red-Emitting Activator

Eu^{3+} is the most widely studied red-emitting rare-earth activator because its $^5D_0$ excited state lies well isolated from the next-lower $^7F_6$ level of the ground-state manifold, so that non-radiative multiphonon decay from $^5D_0$ is largely suppressed even in moderate-phonon-energy hosts, and because its emission spectrum consists of a small number of well-separated, narrow bands ($^5D_0 \rightarrow {}^7F_{0-4}$) that are straightforward to resolve and assign. Among these, the $^5D_0 \rightarrow {}^7F_1$ magnetic-dipole transition is parity-allowed and essentially insensitive to the local site symmetry, whereas the $^5D_0 \rightarrow {}^7F_2$ transition is a hypersensitive, purely electric-dipole transition whose intensity increases sharply when the Eu^{3+} ion occupies a site lacking an inversion centre. The ratio of the integrated intensities of these two bands, commonly termed the asymmetry ratio, R/O, or red-to-orange ratio, is used throughout the literature as a direct spectroscopic probe of local site symmetry and covalency, and is frequently correlated with the Judd–Ofelt Ω_2 parameter [4, 6, 20].

Early work on Eu^{3+}-doped tellurite glass established the basic absorption and fluorescence spectroscopy of the ion in this host, extracting Judd–Ofelt parameters, radiative lifetimes, and branching ratios, and used lifetime measurements of the $^5D_0$ level as a function of Eu^{3+} concentration to identify a dipole–dipole concentration-quenching mechanism operative at higher doping levels [24]. Other studies on lanthanum–titanium co-modified tellurite glasses have reported Ω_2 and Ω_4 intensity parameters together with a $^5D_0$ quantum efficiency near 51%, interpreted as indicating a comparatively low-covalency, low-compactness Eu^{3+} environment relative to other tellurite compositions. Related compositional studies varying Eu_2O_3 content from 0.5 to 1.5 mol% in TeO_2–La_2O_3–TiO_2 glass calculated the full set of radiative parameters (spontaneous emission probability, radiative lifetime, branching ratios, and stimulated emission cross-section for the $^5D_0 \rightarrow {}^7F_2$ transition), concluding that the highest-doped composition was a promising red laser source candidate, with additional thermal-annealing studies used to examine the effect of post-melt heat treatment on these optical properties [4].

More directly relevant to WLED phosphor design, heavily Eu^{3+}-doped tellurite glass-ceramics have been explicitly investigated as red phosphors for white LED applications, where excitation under 393 nm and 464 nm was used to probe both single-photon and two-photon excitation pathways, Judd–Ofelt analysis was used to confirm a low-symmetry, non-centrosymmetric Eu^{3+} site (evidenced by an enhanced R/O ratio), and the evolution of the optical band gap and Urbach energy with Eu^{3+} concentration was characterised in the same glass-ceramic system [4]. A separate study of alkaline-earth boro-tellurite glasses doped with Eu^{3+} combined UV–Vis–NIR absorption with photoluminescence spectroscopy and Judd–Ofelt analysis to estimate emission cross-sections, quantum efficiencies, and CIE 1931 chromaticity coordinates, directly linking the spectroscopic parameters of the Eu^{3+} ion in a tellurite-family host to a quantitative colorimetric assessment of its visible emission [23].

8. Tb^{3+} as a Green-Emitting Activator

Tb^{3+} luminescence in the visible region is dominated by transitions from the $^5D_4$ excited state to the $^7F_5$ ground-state sublevel, giving an intense green emission band near 542–547 nm, accompanied by weaker blue ($^5D_4 \rightarrow {}^7F_6$, ~488–490 nm), yellow ($^5D_4 \rightarrow {}^7F_4$, ~585 nm), and red ($^5D_4 \rightarrow {}^7F_3$, ~620–622 nm) bands. Because the energy gap between the higher-lying $^5D_3$ and lower $^5D_4$ manifolds is comparatively small, Tb^{3+} luminescence is particularly susceptible to concentration-dependent cross-relaxation processes of the type $^5D_3(Tbi) + {}^7F_6(Tbii) \rightarrow {}^5D_4(Tbi) + {}^7F_0(Tbii)$, which progressively quench $^5D_3$ emission and enhance $^5D_4$ emission as Tb^{3+} concentration is increased, a mechanism widely exploited to tune the blue-to-green emission ratio in Tb^{3+}-doped hosts.

In tellurite-based hosts specifically, Tb^{3+}/Yb^{3+} heavily co-doped glasses have been investigated for upconversion-pumped green emission, in which 976 nm excitation of Yb^{3+} populates the Tb^{3+} $^5D_4$ level via energy transfer, yielding an intense 539 nm upconverted green emission whose intensity is optimised through the Tb^{3+}/Yb^{3+} concentration ratio [25]. Down-conversion studies of Tb^{3+}-doped tellurite-germanate glass (TeO_2–GeO_2–BaF_2) reported blue-green emission peaks at 488 and 545 nm with intensity increasing monotonically with Tb^{3+} concentration, alongside a favourable combination of low maximum phonon energy (820 cm^{-1}) and high thermal stability ($\Delta T = 123°C$), with Judd–Ofelt analysis yielding a $^5D_4 \rightarrow {}^7F_5$ branching ratio of 43.67% and a spontaneous radiative transition probability of 66.14 s^{-1} [26]. Related upconversion studies of $Tb^{3+}/Tm^{3+}/Yb^{3+}$ triply doped tellurite glasses demonstrated efficient energy transfer from Tm^{3+} to Tb^{3+}, intensifying the characteristic green (547 nm, $^5D_4 \rightarrow {}^7F_4$) and red (660 nm, $^5D_4 \rightarrow {}^7F_2$) upconverted emissions of Tb^{3+} under 975 nm excitation [27], while co-doped Tm^{3+}/Tb^{3+} tellurite glasses have similarly been examined for their bluish-green visible emission and for the effect of Tb^{3+} co-doping on the 1.8 μm infrared emission of Tm^{3+} [28].

Beyond single- and dual-ion studies, Tb^{3+} has been extensively investigated as an intermediate energy-transfer node linking a sensitiser ion to a red-emitting activator, or as one component of a tri-doped white-light system. Tri-doped Tb^{3+}–Sm^{3+}–Yb^{3+} lithium–niobium–tellurite glass demonstrated colour tunability from yellowish-pink and yellowish-green emission through to white emission by adjusting the Tb^{3+}/Sm^{3+} concentration ratio, with an optimal ratio identified for the closest approach to standard white chromaticity [29]. Tb^{3+}/Eu^{3+} co-doped tellurite-germanate-zinc oxide glass demonstrated a clear $Tb^{3+} \rightarrow Eu^{3+}$ energy transfer, confirmed via Inokuti–Hirayama modelling to proceed predominantly through an electric dipole–dipole interaction, yielding a colour-tunable emission spanning green to orange-red as the Eu^{3+}/Tb^{3+} ratio and excitation wavelength were varied [30]. Analogous Dy^{3+}–Tb^{3+} energy transfer, discussed further in Section 10, has also been directly reported in phospho-tellurite glass, producing tunable yellow/green emission suited to solid-state lighting applications [31].

9. Dy^{3+} as a Dual Blue/Yellow-Emitting Activator

Dy^{3+} occupies a special position among rare-earth activators for white light generation because its two principal visible emission bands, $^4F_{9/2} \rightarrow {}^6H_{15/2}$ (blue, ~482–484 nm) and $^4F_{9/2} \rightarrow {}^6H_{13/2}$ (yellow,

~574–575 nm), together with a weaker $^4F_{9/2} \rightarrow {}^6H_{11/2}$ red band (~660–663 nm), can in principle combine within a single ion to approximate white light without requiring co-doping with a second activator [32,34]. The relative intensity of the yellow to blue emission (the Y/B ratio) is strongly dependent on local site symmetry, since the yellow $^4F_{9/2} \rightarrow {}^6H_{13/2}$ transition is hypersensitive and electric-dipole in character (enhanced at non-centrosymmetric sites), while the blue $^4F_{9/2} \rightarrow {}^6H_{15/2}$ transition is comparatively insensitive to site symmetry; the Y/B ratio therefore functions, in direct analogy to the Eu^{3+} R/O ratio, as a sensitive indicator of the local coordination environment and as a practical compositional handle for tuning the emitted colour point.

Early systematic work on Dy^{3+}-doped tellurite glass (TeO_2–TiO_2 host) established that the 484 nm and 574 nm bands combine to give chromaticity coordinates close to the white region of the CIE 1931 diagram, with the purest white coordinates obtained near 2.5 mol% Dy_2O_3 and with luminescence intensity declining above roughly 2 mol% due to concentration quenching and Dy^{3+}–Dy^{3+} cross-relaxation. A dedicated study of white light generation from Dy^{3+}-doped tellurite glass reported a quantum efficiency of 55% and CIE coordinates of (0.37, 0.41) with a correlated colour temperature of 4461 K for an optimised composition, concluding that the material was suitable both for low-threshold laser action and for WLED colour conversion [21]; a broader review of Dy^{3+}-doped glasses has separately compared over seventy reported Dy^{3+} glass compositions across borate, phosphate, germanate, tellurite, boro-silicate, and boro-phosphate families, finding quantum efficiency and energy transfer to be generally maximised near 0.5 mol% Dy^{3+} doping across systems, with lifetime and quantum yield both decreasing monotonically as Dy^{3+} concentration increased from 0.05 to 3.0 mol% [32].

Structural studies have further clarified how the host network itself modulates Dy^{3+} emission colour. In highly Dy^{3+}-doped tellurite-fluoride glass, increasing DyF_3 content from 8 to 14 mol% was found to enhance the yellow/blue emission ratio, an effect attributed to depolymerisation of TeO_4 units into TeO_{3+1} and TeO_3 units that disrupts the local coordination symmetry around Dy^{3+}; the resulting glasses exhibited large emission cross-sections and gain coefficients at the yellow transition, together with CIE coordinates and correlated colour temperatures (4200–4400 K) in the white-light region, leading the authors to propose the system for white-light fibre laser gain media [20]. A closely related study systematically varied the alkaline-earth modifier (Mg through Ba) in Dy^{3+}-doped tellurite glass, using Raman and FTIR spectroscopy to show progressive TeO_4-to-TeO_3/TeO_{3+1} conversion with increasing modifier cation size, and correlating this structural evolution with a steady increase in emission intensity and consistently warm-white CIE chromaticity coordinates across the series [22]. Complementary Judd–Ofelt studies comparing Dy^{3+} alongside Nd^{3+}, Sm^{3+}, and Er^{3+} in a common TeO_2–$BiCl_3$ host established trends in density, optical gap, and refractive index across the lanthanide series and confirmed the general applicability of Judd–Ofelt analysis for extracting radiative parameters of Dy^{3+} transitions in tellurite hosts [18].

10. Energy Transfer Mechanisms in Co-doped and Tri-doped Rare-Earth Glasses

Because no single rare-earth ion among Eu^{3+}, Tb^{3+}, or Dy^{3+} possesses, on its own, both the

spectral bandwidth and the colour balance required for a high-quality white emission, most practical strategies for single-host WLED phosphor design rely on co-doping two or more activator ions and exploiting non-radiative energy transfer between them to achieve the desired combination of blue, green, yellow, and red emission from a single excitation wavelength. Two theoretical frameworks dominate the interpretation of such energy transfer in the reviewed literature. The Förster–Dexter formalism describes resonant energy transfer between a donor ion in an excited state and a nearby acceptor ion via electric multipole (dipole–dipole, dipole–quadrupole) or exchange interactions, with transfer probability governed by the spectral overlap between donor emission and acceptor absorption and by the donor–acceptor separation; this framework is used, for instance, to interpret $Tm^{3+}\rightarrow Tb^{3+}\rightarrow Eu^{3+}$ cascaded energy transfer in zinc borate glass [35]. The related Inokuti–Hirayama model extends this treatment to describe the non-exponential luminescence decay of a donor ion in the presence of a random, statistically distributed population of acceptor ions, and is widely fitted to donor photoluminescence decay curves to both confirm the operative multipolar interaction type (commonly dipole–dipole) and to extract a quantitative energy transfer efficiency; this approach has been applied directly to $Tb^{3+}\rightarrow Eu^{3+}$ transfer in tellurite-germanate-zinc glass [7] and to Dy^{3+}/Eu^{3+} transfer in phosphate glass [13,36].

Within the specific ion combinations relevant to WLED phosphor design, Dy^{3+}–Tb^{3+} co-doping has been shown in barium borate glass to produce a strong, bidirectional energy transfer: excitation at a Dy^{3+}-specific wavelength (452 nm) was found to populate Tb^{3+} $^5D_4$ emission efficiently even though a Tb^{3+}-only sample shows negligible absorption at that wavelength, while donor/acceptor lifetime measurements additionally revealed a weaker reverse transfer from Tb^{3+} back to Dy^{3+} [37]. An analogous Dy^{3+}–Tb^{3+} energy transfer has been directly documented in phospho-tellurite glass, where photoluminescence measurements confirmed efficient transfer producing strong, tunable yellow and green emission, with decay-curve analysis used to quantify the underlying transfer dynamics and CIELab colour coordinates used to assess resulting colour purity and tunability [31]. Cool-white, tunable multicolour emission has similarly been reported from Tb^{3+}/Dy^{3+} co-activated glass under variable excitation, further supporting this ion combination as a route to WLED-relevant chromaticity [38].

Tb^{3+}–Eu^{3+} energy transfer provides the complementary green-to-red transfer channel, while Dy^{3+}–Eu^{3+} co-doping (reviewed for phosphate hosts) has independently been shown to yield tunable white and near-white emission with Inokuti–Hirayama confirmation of the underlying transfer mechanism [13]. When all three ions are combined in a single host, the resulting tri-doped Dy^{3+}–Tb^{3+}–Eu^{3+} (or equivalently Eu^{3+}–Tb^{3+}–Dy^{3+}) system offers, in principle, the most direct route to a single-composition white emitter, since blue and yellow emission from Dy^{3+}, green emission from Tb^{3+}, and red emission from Eu^{3+} can together span the visible spectrum from one excitation wavelength provided the relative dopant concentrations, and hence the balance of $Dy^{3+}\rightarrow Tb^{3+}$, $Dy^{3+}\rightarrow Eu^{3+}$, and $Tb^{3+}\rightarrow Eu^{3+}$ transfer channels, are appropriately tuned. This strategy has been demonstrated in several non-tellurite oxide hosts: tri-doped YBO3:Tb^{3+}, Eu^{3+}, Dy^{3+} phosphor produced white light from a combination of blue, green, yellow, orange, and red emission bands under 365 nm excitation, with efficient energy transfer confirmed along the sequence $Dy^{3+}\rightarrow Tb^{3+}\rightarrow Eu^{3+}$ [39]; a $BaO–B_2O_3–Li_2O–Al_2O_3–P_2O_5$

tri-doped luminescent glass achieved chromaticity coordinates close to standard white light (CIE (0.3375, 0.3265) at optimal $Dy_2O_3/Tb_2O_3/Eu_2O_3$ loading) with all three pairwise energy-transfer channels confirmed by fluorescence decay analysis [17]; and a triple-doped $Na_2Ca_4(PO_4)3F$ halophosphor exhibited simultaneous blue, green, yellow, and red emission under near-UV excitation with efficient inter-ionic energy transfer, again yielding tunable white output [33]. Notably, however, the extension of this specific Dy^{3+}–Tb^{3+}–Eu^{3+} tri-doping strategy to a tellurite glass host, which, as established in Section 5, offers a lower phonon energy and higher refractive index than the borate, phosphate, and halophosphate systems in which it has so far been demonstrated, has not yet been comprehensively reported, and constitutes a clear direction for future work.

Table 2 summarises representative compositions, dopant combinations, and reported outcomes drawn from the literature reviewed above, illustrating both the depth of prior work on individually and pairwise doped tellurite glasses and the comparative scarcity of studies combining all three of Eu^{3+}, Tb^{3+}, and Dy^{3+} within a tellurite host.

Table 2. Representative summary of reported rare-earth doped tellurite (and, for comparison, selected non-tellurite) glass compositions relevant to WLED-oriented luminescence, compiled from the sources indicated. *Reference not separately identifiable within the source chapter's citation set.

Glass system	RE dopant(s)	Key reported outcome	Ref.
TeO_2–La_2O_3–TiO_2	Eu^{3+}	Ω_2/Ω_4 intensity parameters extracted; ~51% quantum efficiency of the $^5D_0$ level; low-covalency site identified	n/a*
TeO_2–La_2O_3–TiO_2 (0.5–1.5 mol%)	Eu^{3+}	Judd–Ofelt parameters, radiative lifetimes and emission cross-sections computed; composition identified as candidate red laser source	[4]
Alkaline-earth boro-tellurite	Eu^{3+}	CIE chromaticity coordinates estimated from PL data; radiative emission capacity linked to J–O parameters	[23]
TeO_2–$BiCl_3$	Nd^{3+}, Sm^{3+}, Dy^{3+}, Er^{3+}	Comparative Judd–Ofelt study across four lanthanides in one host; density and optical-gap trends established	[18]
$88TeO_2$–$8TiO_2$–xDy_2O_3	Dy^{3+}	Blue (484 nm) and yellow (574 nm) emissions combine to near-white CIE coordinates; concentration quenching above 2 mol%	n/a*
TeO_2–YF_3–DyF_3 (high concentration)	Dy^{3+}	CIE coordinates in white region with CCT 4200–4400 K; proposed for white-light fibre lasers	[20]
Borosilicate–alkali–tellurite (BSNK)	Dy^{3+}	CIE (0.37, 0.41), CCT 4461 K, ~55% quantum efficiency reported	[21]

Alkaline-earth modified tellurite	Dy^{3+}	$TeO_4 \rightarrow TeO_3$ conversion with modifier identity; warm-white CIE region confirmed via Raman/FTIR-supported structural model	[22]
TeO_2–GeO_2–ZnO	Tb^{3+}/Eu^{3+}	$Tb^{3+} \rightarrow Eu^{3+}$ energy transfer confirmed via Inokuti–Hirayama (dipole–dipole) model; tunable green-to-orange-red emission	[30]
TeO_2–GeO_2–BaF_2	Tb^{3+}	Blue-green emission (488, 545 nm); low phonon energy (820 cm^{-1}) and high thermal stability ($\Delta T = 123°C$)	[26]
Phospho-tellurite	Dy^{3+}/Tb^{3+}	Efficient $Dy^{3+} \rightarrow Tb^{3+}$ energy transfer producing tunable yellow/green emission for solid-state lighting	[31]
Lithium–niobium–tellurite	$Tb^{3+}/Sm^{3+}/Yb^{3+}$	Colour tunable from yellowish-green/pink to white by controlling the Tb^{3+}/Sm^{3+} ratio	[29]
Zinc tellurite	Er^{3+}/Eu^{3+}	$Er^{3+} \rightarrow Eu^{3+}$ energy transfer; combination with a 380 nm GaN chip produced cold-white CIE (0.324, 0.320)	[34]

11. Colorimetric Evaluation of Phosphor and Glass Emission: CIE, CCT, and CRI

Across virtually all of the studies reviewed above, the visible emission spectrum of a candidate phosphor or glass is converted into a set of standardised colorimetric descriptors that permit direct, quantitative comparison between different compositions and with the accepted definition of white light. The CIE 1931 chromaticity coordinates (x, y) are calculated by integrating the measured emission spectrum against the CIE colour-matching functions and normalising the result onto the two-dimensional chromaticity diagram; a coordinate pair close to the equal-energy white point (0.333, 0.333), or lying close to the Planckian (black-body) locus, is taken as evidence of white or near-white emission. The correlated colour temperature (CCT) expresses the perceived warmth or coolness of the emitted white light in terms of the temperature of the closest-matching Planckian radiator, with values below roughly 3500 K generally described as warm white and values above roughly 5000 K as cool or cold white; several of the tellurite-glass studies reviewed report CCT values falling within, or close to, these commercially relevant ranges. Where reported, the colour rendering index (CRI, or Ra) quantifies how faithfully the light source reproduces the true colour of illuminated objects relative to a reference illuminant of the same CCT, and is a key figure of merit distinguishing a spectrally broad, multi-band emitter (favoured for general lighting) from a narrow-band emitter (more suited to signage or display backlighting) [13,14]. Collectively, these three descriptors (CIE coordinates, CCT, and CRI) constitute the standard evaluation framework against which $Eu^{3+}/Tb^{3+}/Dy^{3+}$-doped tellurite glasses are assessed.

12. Research Gap and Directions for Future Work

The literature reviewed in this article establishes three points of consensus. First, tellurite glass is a structurally well-characterised and spectroscopically favourable host for rare-earth

luminescence, combining low phonon energy, high refractive index, and good rare-earth solubility in a chemically durable, moderately processable oxide network. Second, each of Eu^{3+}, Tb^{3+}, and Dy^{3+} has individually, and in various pairwise combinations (Eu^{3+}/Dy^{3+}, Tb^{3+}/Eu^{3+}, Dy^{3+}/Tb^{3+}, Er^{3+}/Eu^{3+}), been extensively investigated in tellurite or closely related oxide-glass hosts, with well-established Judd–Ofelt intensity parameters, energy-transfer mechanisms (Förster–Dexter/Inokuti–Hirayama), and colorimetric (CIE/CCT) outcomes reported. Third, the specific strategy of simultaneously tri-doping a single glass host with all three ions, Dy^{3+} (blue/yellow), Tb^{3+} (green), and Eu^{3+} (red), to achieve single-composition, single-excitation white emission via a cascaded $Dy^{3+}\rightarrow Tb^{3+}\rightarrow Eu^{3+}$ energy-transfer network has been convincingly demonstrated in borate, phosphate, halophosphate, and yttrium borate hosts [3,33,39], but has not, at the time of this review, been comprehensively reported for a tellurite glass matrix, despite the demonstrably favourable spectroscopic properties that tellurite hosts offer relative to these alternative systems.

This gap defines a clear objective for continued research in the field: to synthesise Eu^{3+}, Tb^{3+}, and Dy^{3+} singly-doped, pairwise co-doped, and triply co-doped tellurite glasses; to characterise their structural (XRD, FTIR, Raman), thermal (DSC), and linear optical (UV–Vis–NIR absorption, refractive index, density) properties; to apply Judd–Ofelt analysis to quantify the radiative transition probabilities, branching ratios, and stimulated emission cross-sections of each dopant ion within the tellurite host; to establish, through steady-state and time-resolved photoluminescence spectroscopy, the nature and efficiency of $Dy^{3+}\rightarrow Tb^{3+}$, $Tb^{3+}\rightarrow Eu^{3+}$, and $Dy^{3+}\rightarrow Eu^{3+}$ energy transfer within the tri-doped system; and to evaluate the resulting broadband visible emission against the CIE 1931 chromaticity diagram, correlated colour temperature, and colour rendering index in order to assess the suitability ssof such glasses as single-composition, single-excitation phosphors for white light-emitting diode applications.

13. Conclusion

This review has surveyed the physical and chemical basis of solid-state white lighting and the principal engineering routes by which it is achieved, the motivation for moving from resin-bound powder phosphors toward inorganic, and ultimately glass-based, wavelength converters, and the specific structural and spectroscopic properties that make tellurite glass a favourable host for rare-earth luminescence. It has examined, in turn, the spectroscopy and reported tellurite-glass behaviour of Eu^{3+} (red, $^5D_0\rightarrow {}^7F_2$), Tb^{3+} (green, $^5D_4\rightarrow {}^7F_5$), and Dy^{3+} (blue/yellow, $^4F_{9/2}\rightarrow {}^6H_{15/2,13/2}$) doped glasses, the theoretical frameworks (Judd–Ofelt theory; Förster–Dexter and Inokuti–Hirayama energy transfer models) used to interpret their radiative behaviour and inter-ionic interactions, and the colorimetric methods by which candidate WLED phosphors are evaluated. The review identifies a clear and specific gap: although each ion, and several pairwise combinations, have been well studied in tellurite hosts, and although Dy^{3+}–Tb^{3+}–Eu^{3+} tri-doping has been shown to yield promising single-composition white emitters in other oxide-glass families, this tri-doping strategy remains largely unexplored in tellurite glass, representing a well-defined and promising direction for future experimental work.

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