

REVIEW

From Phosphor Ceramics to Intelligent Light-Conversion Materials: High-Flux Luminescence, Glassy Composite Interface, and Machine-Learning-Guided Design

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ABSTRACT

High-power LED/LD and NIR applications demand phosphors that remain efficient and stable under high-flux excitation, whereas conventional phosphor/organic systems are limited by heat buildup, interfacial degradation, and luminescence saturation. Phosphor ceramics provide a robust all-inorganic alternative, but their photothermal coupling mechanisms and cross-scale design principles remain insufficiently summarized. Here, we review recent advances in phosphor ceramics with a particular focus on photothermal coupling in high-flux light conversion. We establish a composition-structure-photothermal behavior-device performance framework that connects activator ions, host chemistry, defects and grain boundaries with light absorption, scattering regulation, thermal-transport pathways, and device-level output. Recent advances in garnet-based, multiphase, multicolor visible, and NIR phosphor ceramics are discussed, with emphasis on compositional regulation, ceramic processing, microstructure engineering, and LED/LD integration. We clarify key relationships among transparency, absorption efficiency, scattering strength, thermal conductivity, interfacial thermal resistance, and luminescence saturation thresholds, which collectively determine high-brightness reliability under extreme photon and heat loads. Emerging glassy composite interfaces are further highlighted for low-temperature integration, heterogeneous packaging, and multimaterial coupling. Finally, we discuss machine learning as an enabling tool for candidate screening, processing-window optimization, property prediction, and multi-objective device design, offering guidance for next-generation stable, intelligent light-conversion materials.

1 | Introduction

The rapid development of high-power solid-state light sources is reshaping the design logic of light-conversion materials [1–3]. Over the past two decades, the combination of blue chips with $\text{Y}_3\text{Al}_5\text{O}_{12}:\text{Ce}^{3+}$ (YAG:Ce) yellow phosphors has driven the widespread adoption of white light-emitting diode (WLED) technology in general lighting, displays, automotive lighting,

and specialized light sources [4–7]. However, with the emergence of high-brightness laser lighting, laser displays, automotive headlamps, near-infrared imaging, and intelligent spectral recognition, the central requirement for light-conversion materials is shifting from high quantum efficiency under low-power excitation to the coupled optimization of high-flux tolerance, photothermal stability, and device-level reliability [8, 9]. As shown in Figure 1a, high-power light-emitting diode (LED) and laser

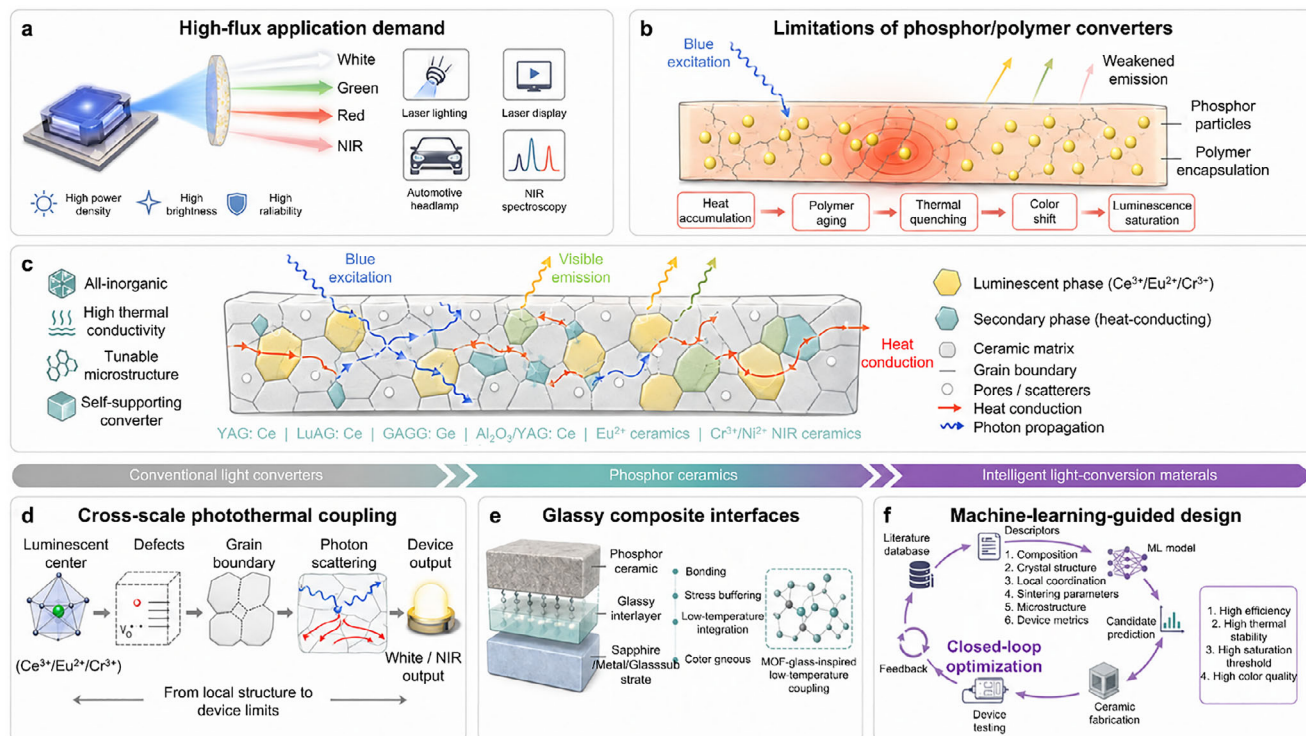


FIGURE 1 | From phosphor ceramics to intelligent light-conversion materials for high-flux luminescence. (a) High-power LED/LD applications require efficient conversion from blue excitation to white, visible, and NIR emissions. (b) Conventional phosphor/polymer converters suffer from heat accumulation, polymer aging, thermal quenching, color shift, and luminescence saturation. (c) Phosphor ceramics provide an all-inorganic, thermally robust, self-supporting platform, where luminescent phases, secondary phases, pores, grain boundaries, photon propagation, and heat conduction jointly govern performance. (d) Cross-scale photothermal coupling links luminescent centers, defects, grain boundaries, scattering, thermal transport, and device output. (e) Glassy composite interfaces enable interfacial bonding, stress buffering, low-temperature integration, and heterogeneous coupling. (f) ML enables closed-loop optimization of composition, processing, microstructure, and device performance.

diode (LD) excitation requires converters that can deliver stable white, visible and near-infrared (NIR) emission under intense blue-light or laser irradiation, rather than merely exhibiting high luminescence efficiency under low-power test conditions [10–13]. Although conventional phosphor/organic encapsulation systems are mature for low-power LEDs, their low thermal conductivity, limited heat resistance, and insufficient photoradiation durability make them unsuitable for high-power-density excitation [14–16]. As illustrated in Figure 1b, intense blue-light or laser excitation readily induces local heat accumulation in the phosphor layer, which further accelerates polymer ageing, phosphor thermal quenching, chromaticity shift, luminous decay and luminescence saturation [17, 18]. These challenges are particularly severe in laser-driven light sources, where the excitation power density far exceeds that of conventional LEDs [19] and where absorption depth, scattering pathways, heat-source distribution, and interfacial heat dissipation all strongly govern device output [20, 21]. Light-conversion materials for high-flux applications must therefore simultaneously address luminescence efficiency, heat dissipation, light extraction, structural stability, and packaging compatibility [1, 2, 9].

Phosphor ceramics have rapidly emerged in response to these demands as a class of all-inorganic light-conversion materials [22, 23]. They typically consist of luminescent phases, ceramic matrices, secondary phases, grain boundaries, and pores or scattering centers [24, 25]. Their all-inorganic architecture, high thermal

conductivity, excellent thermal stability, and self-supporting form enable them to mitigate the failure modes of conventional organic encapsulation systems under high-power excitation (Figure 1c) [26, 27]. Garnet-based phosphor ceramics, represented by YAG: Ce transparent ceramics, were among the first material systems to be systematically investigated and implemented in high-power white LEDs and laser lighting [28, 29]. Subsequently, $\text{Lu}_3\text{Al}_5\text{O}_{12}:\text{Ce}^{3+}$ (LuAG: Ce), $\text{Gd}_3\text{Al}_2\text{Ga}_3\text{O}_{12}:\text{Ce}^{3+}$ (GAGG: Ce) and related garnet ceramics were developed for green emission, broad-band spectral tuning and high-brightness displays [30–32], demonstrating that the emission peak, bandwidth, and thermal-quenching behavior of Ce^{3+} can be effectively regulated by tailoring the local crystal field and energy-level structure through host composition [33, 34]. Single-phase transparent phosphor ceramics, however, cannot resolve all performance trade-offs [35, 36]. High transparency benefits light transmission, but insufficient scattering can limit blue-light absorption. Increasing ceramic thickness or activator concentration enhances absorption, yet may induce concentration quenching, heat accumulation and reduced light extraction [37]. This trade-off has driven the development of multiphase phosphor ceramics as a major direction for high-flux light conversion. In representative aluminum oxide/YAG: Ce ($\text{Al}_2\text{O}_3/\text{YAG: Ce}$) ceramics, the thermally stable and thermally conductive Al_2O_3 secondary phase regulates both scattering pathways and heat-conduction channels, yielding superior photothermal performance compared with single luminescent phases [38, 39]. Subsequent aluminum nitride/YAG: Ce ($\text{AlN}/\text{YAG: Ce}$) and

zirconium oxide/aluminum oxide/YAG: Ce ($\text{ZrO}_2/\text{Al}_2\text{O}_3/\text{YAG: Ce}$) systems further show that secondary phases are not inert fillers, but multifunctional components for heat conduction, scattering control, mechanical support, phase-interface regulation and thermal-stress buffering [40, 41]. Porosity, grain size, grain-boundary phases, secondary-phase distribution, and interfacial bonding collectively govern photon propagation and heat diffusion inside ceramics, thereby determining luminous efficacy (LE), luminous flux, saturation threshold, and long-term stability [42–45]. The central focus of phosphor ceramic research has therefore expanded from the search for efficient emitting phases to the co-design of luminescent, thermally conductive, scattering, and interfacial structures [46]. Spectral quality adds another layer of complexity. Although conventional YAG: Ce yellow ceramics exhibit high efficiency and stability, their limited red component constrains the color rendering and warm-white quality of white light. To meet the demands of high-color-rendering lighting, human-centric illumination and laser displays, red, cyan, green, and multicolor ceramic converters have become increasingly important [47–51]. Eu^{2+} -activated nitride, oxide, silicate and aluminosilicate red ceramics provide effective routes to compensate long-wavelength red emission, reduce correlated color temperature, and improve color rendering index (CRI). The emergence of thermally stable red oxide ceramics and Eu^{2+} -activated cordierite-type red ceramics indicates that high-quality warm-white output can be achieved while preserving all-inorganic stability, provided that the Eu^{2+} local coordination environment, crystal-field strength, and ceramic microstructure are properly controlled [52–56]. In parallel, narrow-band green and cyan transparent composite ceramics can fill specific spectral gaps for laser displays and full-spectrum lighting. These advances show that phosphor ceramics should not be narrowly viewed as YAG: Ce yellow converters, but rather as a multifunctional light-conversion family spanning yellow, green, red, cyan, and NIR emission. The rapid rise of NIR phosphor ceramics has further expanded the application landscape. Transition-metal ions such as Cr^{3+} and Ni^{2+} can generate broad-band NIR and even second near-infrared window (NIR-II) emission in different crystal-field environments, enabling high-power light sources for night vision, deep-tissue penetration, food inspection, medical diagnostics, and intelligent spectral recognition [57–60]. Compared with conventional NIR phosphor powders, ceramic converters are better suited to withstand high-power blue-light or laser excitation and can improve output power and operational stability through thermally conductive matrices and controllable scattering structures. Studies on GAGG: Cr^{3+} , MgAl_2O_4 : Cr^{3+} , Ga/Sc oxides, and spinel-type NIR ceramics show that NIR emission is governed not only by the energy-level structure of the luminescent center, but also by crystal-field strength, cation disorder, defect levels, grain size, and the transmission/scattering behavior of the ceramic [61–64]. In particular, spinel-type Cr^{3+} -activated NIR ceramics integrate broad-band emission, tunable crystal fields, structural robustness, and laser-driving capability, providing a compelling example of how phosphor ceramics can evolve from lighting materials into intelligent spectral materials [65].

Despite these advantages, further advances in phosphor ceramics are constrained by multiscale coupling challenges. As illustrated in Figure 1d, the local coordination, valence stability, and defect landscape of luminescent centers directly determine emis-

sion peak position, bandwidth, lifetime, and thermal-quenching behavior [66–69]. Emitting ions such as Ce^{3+} , Eu^{2+} , Cr^{3+} , and Ni^{2+} are highly sensitive to the local crystal field; even subtle changes in host composition can alter energy-level splitting, electron-phonon coupling and the probability of non-radiative transitions. Ceramic sintering further introduces grain boundaries, residual pores, secondary phases, and possible valence-state changes [70–72]. These microstructural features can enhance light scattering and blue-light absorption, but may also increase thermal resistance, induce defect-assisted quenching and reduce transmittance [73, 74]. Moreover, material-level measurements do not necessarily translate directly into device performance. Room-temperature emission intensity, quantum efficiency, and thermal-quenching curves measured from powders or ceramic plates capture only part of the intrinsic material response. In real high-power devices, excitation area, heat-sink architecture, interfacial contact, ceramic thickness, optical-path design, and cooling configuration can all substantially reshape the final output [21, 75, 76]. Establishing cross-scale correlations among luminescent centers, defect structures, ceramic microstructures, photothermal transport, and device performance is therefore essential for moving phosphor ceramics from empirical optimization toward rational design. At the device level, the evaluation framework for high-power light-conversion materials must also be standardized and expanded [77]. Conventional phosphors are typically assessed using emission spectra, internal quantum efficiency (IQE), external quantum efficiency (EQE), and thermal-quenching temperature. For phosphor ceramics, however, transmittance, scattering coefficient, thermal conductivity, luminous flux, LE, luminous exitance, CRI, correlated color temperature (CCT), temperature rise, saturation threshold, and long-term stability must be considered together. In laser lighting and laser displays, the luminescence saturation threshold is especially critical for assessing whether a ceramic can withstand high-power-density excitation [78, 79]. Some materials perform well at low power but degrade rapidly under high-power excitation because of heat accumulation or absorption saturation. By contrast, multiphase ceramics with optimized scattering and high-thermal-conductivity pathways can maintain more stable output in the high-flux regime [40]. Phosphor ceramic research must therefore move beyond synthesis and spectroscopic characterization, integrating materials design with realistic device-operating conditions to establish application-oriented evaluation standards.

It is important to note that although high-temperature ceramic processing offers clear advantages in high-power stability, it remains limited in low-temperature integration, multimatierial assembly and the construction of complex interfaces [13, 80, 81]. Glassy composite interfaces therefore provide an important bridge between conventional ceramic light converters and future multimatierial intelligent light-conversion systems. Phosphor-in-glass (PiG), phosphor-in-glass film (PiGF), glass-ceramics, and ceramic-glass composite structures have demonstrated that glassy phases can immobilize phosphor particles, provide optical encapsulation and enable interfacial bonding at relatively low temperatures [82–85]. Ceramic-sapphire, ceramic-metal, and ceramic-glass-ceramic architectures further show that interface engineering can simultaneously improve heat spreading, mechanical support, and light extraction [86–88]. Although metal-organic framework (MOF) glasses and their composites

with inorganic glasses have not yet become a mainstream route for phosphor ceramics, their low-temperature glass transition, designable organic–inorganic interfaces, structural flexibility, and compositional compatibility offer conceptual inspiration for low-temperature interfacial bonding, heterogeneous materials integration, and multifunctional light-conversion architectures (Figure 1e) [89–91]. Thus, introducing “glassy composite interfaces” into a broad review of phosphor ceramics is not a departure from the central theme, but a means to address how the high stability of ceramic converters can be coupled with the low-temperature integration required for advanced devices.

Meanwhile, machine learning (ML) is providing a new methodological foundation for the design of phosphors and ceramic light-conversion materials (Figure 1f) [92, 93]. Conventional phosphor ceramic development has relied heavily on empirical trial and error, involving a large and strongly coupled parameter space that includes host selection, activator choice, sintering temperature, atmosphere control, sintering aids, secondary-phase fraction, thickness design, and device architecture. In recent years, ML has been used to predict emission wavelengths, thermal stability, and synthesis conditions of inorganic phosphors, as well as to screen near-infrared emitters and Cr³⁺-activated phosphors [94–99]. For phosphor ceramics, however, the value of ML should extend beyond the discovery of new luminescent hosts to the full-chain optimization of composition, structure, processing, microstructure, properties, and device performance [100–102]. For example, compositional and crystallographic descriptors can be used to predict emission wavelength and thermal quenching; sintering temperature, dwell time, atmosphere, and powder particle size can inform predictions of density, grain size, and transmittance; and thermal conductivity, scattering coefficient, ceramic thickness, and interfacial thermal resistance can be linked to saturation thresholds and device temperature rise. By integrating high-throughput experiments, in situ characterization and device-level feedback, phosphor ceramics may move from experience-driven materials development toward data-driven intelligent design.

Building on this background, this review follows the theme “from phosphor ceramics to intelligent light-conversion materials” to survey the current status and future directions of high-flux luminescent materials. Unlike previous reviews that have mainly focused on transparent luminescent ceramics, garnet ceramics, or ceramic phosphors for laser lighting, this review seeks to establish a more integrated framework. With phosphor ceramics as the central subject, we discuss the material systems, processing strategies, microstructure regulation and device applications of garnet ceramics, multiphase ceramics, red- and cyan-emitting ceramics, and near-infrared ceramics. With photothermal coupling as the core concept, we reveal cross-scale relationships among luminescent centers, defect structures, grain-boundary behavior, scattering centers, heat-conduction pathways, and device output. By extending the discussion to glassy composite interfaces, we highlight the significance of low-temperature integration, multimaterial coupling, and interfacial regulation for future light-converter design. Using ML as an emerging methodology, we further outline new paradigms for materials screening, processing optimization, property prediction, and multi-objective device design. Through this framework, this review aims to move beyond conventional materials-classification surveys and

to define a design logic for phosphor ceramics toward next-generation solid-state light sources with high brightness, high stability, high spectral quality, and intelligent functionality.

2 | Material Scope and High-Flux Evaluation Framework of Phosphor Ceramics

2.1 | New Demands From High-Power Solid-State Light Sources

The early development of solid-state lighting relied largely on the combination of blue LED chips with yellow YAG: Ce phosphors [103, 104]. Owing to its high efficiency, long lifetime, and low energy consumption, this architecture accelerated the widespread deployment of WLED technology [105]. However, as solid-state light sources expand from general illumination to laser lighting, laser displays, automotive headlamps, long-distance projection, plant lighting, near-infrared detection, and intelligent spectral recognition, the operating conditions imposed on light-conversion materials have changed substantially [46, 47, 58, 106, 107]. These materials are no longer required merely to withstand continuous low-power LED excitation; instead, they must maintain stable luminous-flux output, limited temperature rise, controlled chromaticity-coordinate drift, and long-term reliability under high-power-density blue-light or laser irradiation [108]. Accordingly, the central evaluation criterion for light-conversion materials is shifting from high room-temperature quantum efficiency to photothermally stable output under high-power excitation. In this context, high-flux luminescence should be distinguished from high-efficiency luminescence. High-efficiency luminescence mainly describes the efficiency of converting absorbed or incident excitation energy into optical output, typically quantified by the IQE, EQE, or power-conversion efficiency (PCE) under specified excitation conditions. By contrast, high-flux luminescence emphasizes the ability of a light-conversion material to sustain intense and stable emission under high photon flux or high incident power density. This operating regime may involve heat accumulation, luminescence saturation, efficiency droop, reabsorption, spectral shift, and long-term degradation. Therefore, high efficiency under moderate excitation does not necessarily guarantee stable high-flux operation. In this review, high-flux luminescence is discussed as a comprehensive performance concept that includes not only strong optical output, but also photothermal stability, chromaticity stability, and operational reliability under intense excitation. Because the practical high-flux condition depends on the excitation wavelength, illuminated area, sample geometry, absorption characteristics, and heat-dissipation pathway, it is not defined by a single universal power-density threshold.

This transition is illustrated in Figure 2a,b. Figure 2a summarizes the evolution of phosphor materials alongside the changing demands of solid-state lighting: early materials were designed primarily for basic white illumination, whereas later developments have targeted high-color-rendering lighting, high-quality back-lighting, and more advanced high-brightness applications [109]. Figure 2b further shows that WLED spectra can be constructed using several routes, including blue LED/yellow phosphor conversion, blue LED/red-green phosphor conversion and ultraviolet LED/trichromatic phosphor conversion [106]. Among these,

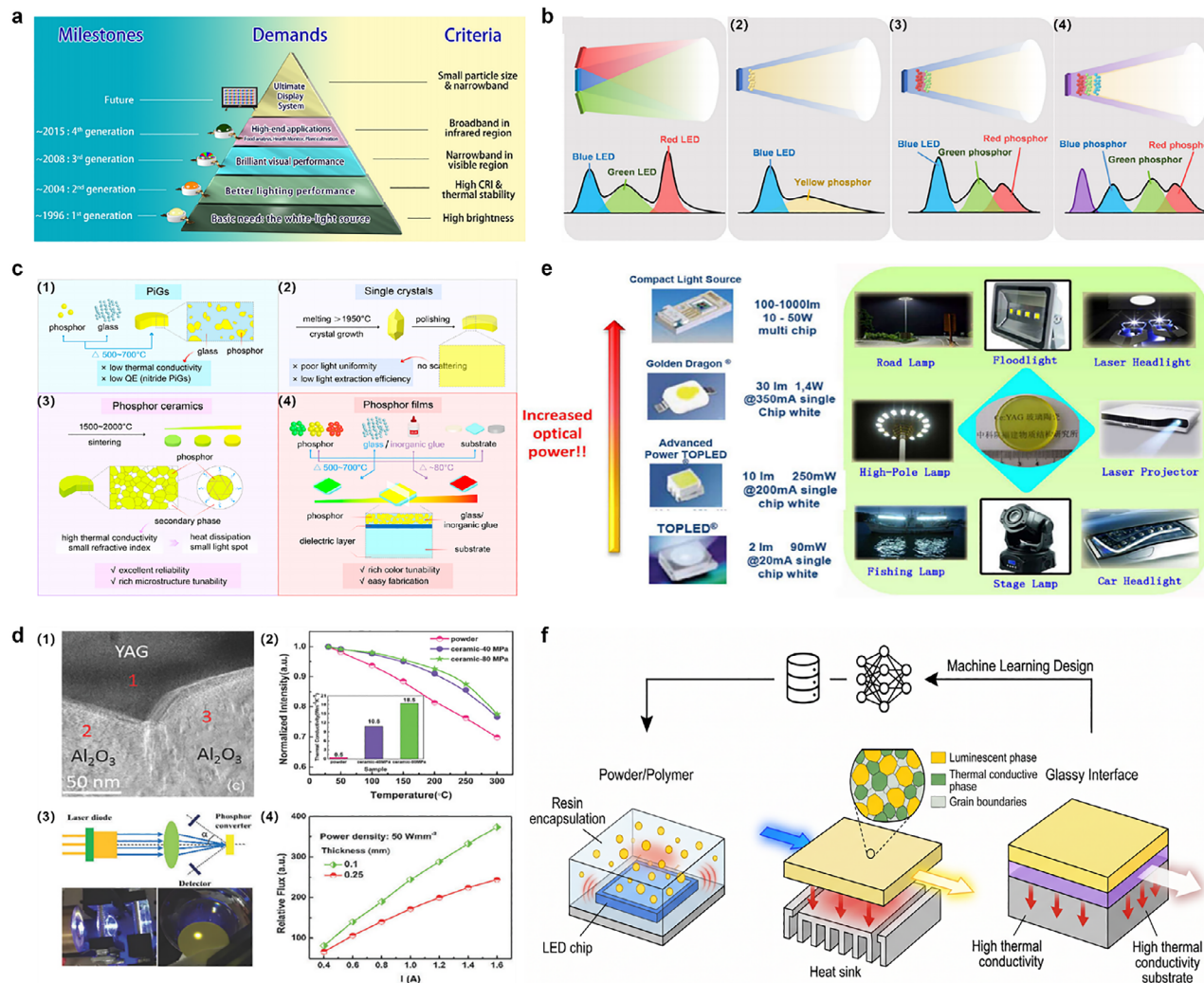


FIGURE 2 | Material boundaries and development logic of phosphor ceramics. (a) Development milestones of phosphor materials for solid-state lighting. (b) Representative white-light conversion strategies. Reproduced with permission from literature [106]. Copyright 2022, American Chemical Society. (c) Comparison of laser-driven color converters, including PiG, single crystals, phosphor ceramics, and phosphor films. Reproduced with permission from literature [2]. Copyright 2022, Shanghai Tech University and American Chemical. (d) Structure and high-power luminescence behavior of YAG/Al₂O₃ composite ceramics. Reproduced with permission from literature [106]. Copyright 2022, American Chemical Society. (e) Stability of YAG-PiG and glass-ceramic converters. Reproduced with permission from literature [7]. Copyright 2018, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (f) Roadmap from phosphor powders to ceramic converters, glassy interfaces, and machine-learning-guided design.

the blue LED/YAG: Ce yellow phosphor configuration remains the most mature. Nevertheless, its insufficient red component, limited color-rendering capability and vulnerability to heat accumulation and encapsulant ageing under high-power-density operation restrict its use in next-generation high-brightness light sources [17, 110]. These limitations make conventional phosphor powder/organic resin encapsulation systems increasingly inadequate for demanding high-power applications.

More importantly, LEDs and LDs exhibit distinct efficiency evolution at high input power densities [111]. As shown in Figure 3a, LEDs are prone to efficiency droop at high current densities, whereas LDs retain advantages in higher-power-density regimes [19]. When the excitation source shifts from LED to LD operation, the light-conversion layer experiences markedly increased optical power density, local thermal load and interfacial heat-dissipation pressure [46, 108]. Under these conditions, high IQE in a

phosphor powder does not necessarily translate into sustained high-flux output in an actual device [74]. Thermal conductivity, absorption depth, scattering pathway, converter thickness, interfacial thermal resistance, and device-level heat-sink architecture collectively determine the final output performance [112]. The development of high-power solid-state light sources is therefore driving light-conversion materials from luminescent-center optimization toward the integrated co-design of emission, heat transport, scattering, and packaging.

2.2 | Conceptual Boundaries and Material Classes of Phosphor Ceramics

Broadly, phosphor ceramics refer to bulk, plate-like or architected light-conversion materials in which luminescent centers are incorporated into ceramic matrices, or phosphor particles

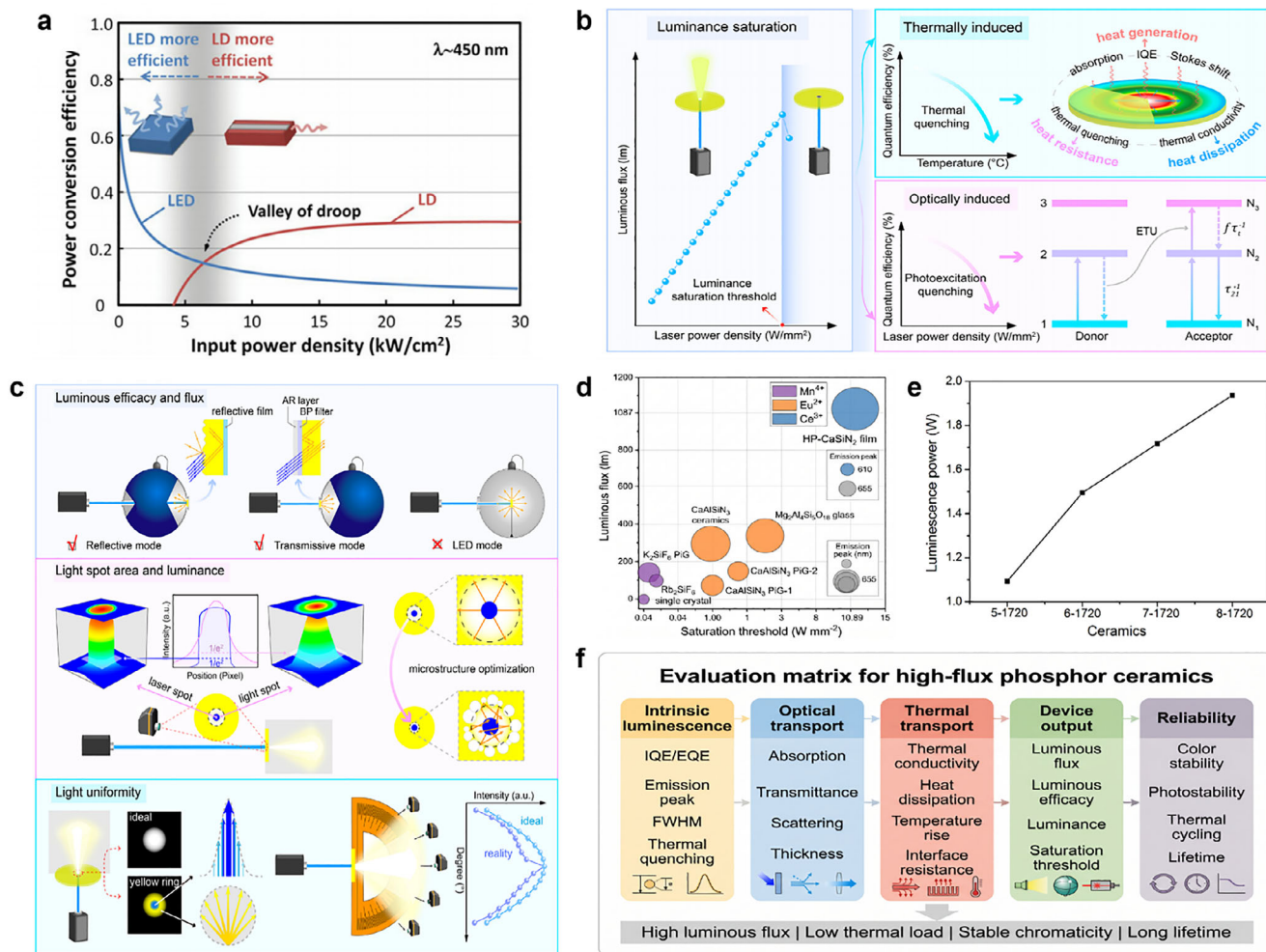


FIGURE 3 | Evaluation metrics and saturation behavior of high-flux phosphor ceramics. (a) Power-conversion efficiency of LEDs and LDs as a function of input power density. Reproduced with permission from literature [19]. Copyright 2013, John Wiley & Sons. (b) Thermally and optically induced luminance saturation. (c) Key parameters for laser-driven white-light sources. Reproduced with permission from literature [2]. Copyright 2022, Shanghai Tech University and American Chemical. (d) Luminous flux and saturation threshold of representative red converters. (e) Laser-power-dependent output of Al₂O₃/YAG: Ce composite ceramics. Reproduced with permission. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [38]. Copyright 2019, The Author(s). Optical Society of America. (f) Evaluation framework integrating luminescence, optical/thermal transport, device output, and reliability.

are integrated with inorganic ceramic phases [113, 114]. Their luminescent centers can include Ce³⁺, Eu²⁺, Mn⁴⁺, Cr³⁺ and Ni²⁺, whereas the host matrices or composite phases may involve garnets, oxides, nitrides, aluminates, silicates, gallates, spinels, Al₂O₃, AlN, sapphire, and glass-ceramics. Compared with conventional phosphor/organic encapsulation systems, phosphor ceramics offer all-inorganic compositions, self-supporting architectures, high thermal stability, strong resistance to optical irradiation, and improved heat conduction [115–117]. Compared with single-crystal phosphors, ceramic materials further provide broader compositional tunability, designable shapes and dimensions, relatively lower fabrication costs, and microstructure control through secondary phases.

Figure 2c compares the advantages and limitations of representative laser-driven color converters [2]. PiG and PiGF offer good low-temperature packaging compatibility and processing flexibility, but their thermal conductivity and ultimate power-handling capability are generally limited by the glass phase [118,

119]. Single-crystal phosphors provide high transparency and relatively high thermal conductivity, yet their compositional regulation and complex structural design remain constrained [120, 121]. Phosphor films are attractive for miniaturization and device integration, but their thermal-management capability under sustained high-power excitation still requires improvement [122, 123]. By contrast, phosphor ceramics offer a more balanced combination of thermal stability, structural designability, optical regulation, and device reliability, making them a key direction for high-flux light-conversion materials [124, 125].

On the basis of composition and structure, phosphor ceramics can be broadly divided into four categories [24]. The first category comprises single-phase or nearly single-phase transparent phosphor ceramics, represented by garnet-based ceramics such as YAG: Ce, LuAG: Ce and GAGG: Ce, which are mainly used for yellow, green, or broad-band visible emission [29, 30]. The second category consists of multi-phase phosphor ceramics, including Al₂O₃/YAG: Ce, AlN/YAG:

Ce, and $\text{ZrO}_2/\text{Al}_2\text{O}_3/\text{YAG}$: Ce, in which secondary phases are used to regulate heat conduction, scattering, mechanical support, and interfacial structures simultaneously. The third category includes functional ceramics for high-color-rendering lighting, full-spectrum emission, or intelligent detection, such as Eu^{2+} -activated red ceramics, Mn^{4+} -activated narrow-band red ceramics, cyan/green ceramics and Cr^{3+} - or Ni^{2+} -activated near-infrared ceramics. The fourth category involves device-level composite light-conversion architectures, such as ceramic@metal, ceramic@sapphire, ceramic@glass, and phosphor@ceramic structures [48, 85, 126, 127]. This classification highlights that phosphor ceramics are not a single material system, but a materials platform constructed from luminescent phases, thermally conductive phases, scattering phases, interfaces, and device architectures [1].

2.3 | From Luminescence Efficiency to Photothermal Co-Design

Early research on phosphor ceramics focused mainly on Ce^{3+} -doped garnet transparent ceramics, with YAG: Ce being the most representative system. Under blue-light excitation, YAG: Ce produces stable yellow emission and exhibits high thermal stability, mechanical strength and chemical durability; it has therefore long served as a model light converter for high-power WLEDs and laser lighting [128–130]. Subsequently, LuAG: Ce, GAGG: Ce and multicomponent garnet ceramics were developed to achieve green emission, broad-band spectral tuning and higher-brightness output. By adjusting the Y^{3+} , Lu^{3+} , Gd^{3+} , Ga^{3+} , and Al^{3+} compositions in YAG, LuAG, and GAGG hosts, the local crystal-field environment around Ce^{3+} can be modified, thereby regulating the 5d energy-level position, emission peak, emission bandwidth, luminescence lifetime, and thermal-quenching behavior of Ce^{3+} [131, 132]. At this stage, research centered primarily on the relationship between luminescent centers and host structures, namely how compositional design can deliver higher luminescence efficiency, more suitable emission color and improved thermal stability.

However, as excitation power density increases, improving the intrinsic efficiency of luminescent centers alone is no longer sufficient to ensure device performance. Transparent ceramics offer low scattering loss and efficient light extraction [29, 133], but their emission output remains limited if blue-light absorption inside the ceramic is insufficient. Conversely, increasing ceramic thickness or Ce^{3+} concentration can enhance absorption, but may induce concentration quenching, heat accumulation, and reduced light-extraction efficiency [134]. The central challenge for high-power light-conversion materials is therefore not simply to maximize transparency or absorption, but to balance excitation-light absorption, emitted-light extraction, internal scattering, and heat diffusion [27].

Multiphase phosphor ceramics have emerged to address this trade-off. In $\text{Al}_2\text{O}_3/\text{YAG}$: Ce multiphase ceramics, for example, Al_2O_3 does not directly contribute to Ce^{3+} emission, but improves thermal stability and heat conduction while introducing moderate scattering through $\text{Al}_2\text{O}_3/\text{YAG}$ interfaces, thereby extending the blue-light propagation path within the ceramic [135]. The results shown in Figure 2d indicate that Al_2O_3 incorpo-

ration modifies not only thermal conductivity and temperature-dependent luminescence, but also the luminescence saturation process under high-power excitation [106]. Secondary phases are therefore not inert diluents of the emitting phase, but functional units that participate in photon transport, heat diffusion, and structural stabilization [136, 137].

Similarly, AlN/YAG: Ce systems further underscore the importance of high-thermal-conductivity secondary phases. AlN can enhance heat diffusion and reduce local temperature rise under high-power excitation, but its interfacial bonding, phase stability, and scattering strength with YAG: Ce must be carefully controlled. If the secondary-phase content is too low, thermal pathways remain discontinuous and heat management is ineffective; if it is too high, the fraction of the emitting phase decreases, weakening blue-light absorption, and emission output. Thus, the key to multiphase phosphor ceramics is not simply increasing the Al_2O_3 or AlN content but identifying an optimal balance among emitting-phase fraction, thermal-phase connectivity, scattering strength, and ceramic densification [138].

From this perspective, the development logic of phosphor ceramics has shifted from efficient luminescent-center design to photothermal structural co-design. Luminescent center determine whether the target spectrum can be generated; the host defines their local environment; the ceramic microstructure governs photon propagation and heat-conduction pathways; and secondary phases and interfaces further determine stability under high-power operation. The glass-ceramics and related all-inorganic composite systems shown in Figure 2e also suggest that low-temperature compositing, interfacial bonding, and multimaterial integration will become important directions for future high-power light converters [7]. The advanced character of phosphor ceramics therefore arises not only from their all-inorganic and high-temperature-resistant nature, but also from their ability to couple composition, phase structure, grain boundaries, pores, interfaces, and heat sinks to achieve integrated optimization of emission, scattering, heat conduction, and device integration.

2.4 | High-Flux Evaluation Metrics and Luminescence Saturation Mechanisms

Conventional phosphor powders are typically evaluated using intrinsic metrics such as emission spectra, quantum efficiency, luminescence lifetime, and thermal-quenching temperature. These parameters are essential for determining whether luminescent centers such as Ce^{3+} , Eu^{2+} , Mn^{4+} , and Cr^{3+} are efficient and whether the host lattice is stable [139, 140]. For phosphor ceramics, however, they are insufficient to assess high-power application potential. A ceramic light converter is not only an emitting material, but also an optical propagation medium, and a heat-conduction structure. Its actual output performance is jointly governed by absorption depth, scattering strength, transmittance, sample thickness, grain size, porosity, secondary-phase distribution, grain-boundary thermal resistance, and device-level heat-dissipation conditions [141].

The evaluation of phosphor ceramics should therefore be organized across three levels. The first level concerns intrinsic luminescence properties, including absorption efficiency, quantum

efficiency, emission peak position, full width at half maximum, luminescence lifetime, temperature-dependent emission intensity, and thermal-quenching activation energy [142, 143]. These metrics determine whether the luminescent center is suitable for the target spectral region. The second level concerns the optical and thermal properties of the ceramic architecture, including transmittance, scattering capability, thermal conductivity, thermal diffusivity, thermal-expansion matching, and interfacial thermal resistance [144]. These parameters determine whether the ceramic can efficiently absorb excitation light, extract emission, and dissipate heat under intense irradiation. The third level concerns device output, including luminous flux, LE, luminance, CRI, CCT, chromaticity stability, saturation threshold, and long-term stability [145–147]. These metrics ultimately determine whether the material has practical value under realistic operating conditions.

Luminescence saturation is one of the most critical issues in evaluating high-power phosphor ceramics [148]. As excitation power density increases, the output luminous flux should ideally rise continuously with input power. In practical devices, however, the output often deviates from linearity, reaches a plateau or even declines. This behavior mainly arises from two mechanisms. The first is thermally induced saturation, in which local temperature rise enhances non-radiative transitions, promotes thermal quenching of luminescent centers and causes chromaticity drift [149]. The second is optically induced saturation, in which absorption or excited-state population of luminescent centers approaches saturation under intense excitation, so that additional input power can no longer be efficiently converted into emission [150]. Figure 3b distinguishes these two saturation pathways, highlighting that high-power light-conversion materials must suppress both thermal losses and nonlinear losses under strong optical excitation. Figure 3c further emphasizes that laser-driven converters should not be evaluated solely by emission intensity. LE, luminous flux, spot area, luminance, and spatial uniformity must also be considered [2]. For practical lighting and display applications, high-brightness output is meaningful only when accompanied by stable chromaticity coordinates and controlled temperature rise. The comparison of luminous flux and saturation threshold for representative red converters in Figure 3d illustrates the power-handling differences among different material forms. Some Eu^{2+} or Mn^{4+} -activated red-emitting materials provide valuable spectral compensation but may exhibit luminescence saturation under high-power excitation. This behavior is not determined by emission wavelength alone; rather, it arises from the combined effects of excitation-to-emission Stokes loss, activator-dependent excited-state lifetimes and population dynamics, thermally activated nonradiative relaxation, and heat-dissipation efficiency. A large Stokes loss and nonradiative relaxation increase heat generation, whereas a relatively long excited-state lifetime can promote population accumulation under intense excitation. If the generated heat is not efficiently dissipated, the resulting temperature rise accelerates thermal quenching and lowers the saturation threshold. Ceramic integration and multiphase design therefore offer effective routes to increase the saturation threshold of red converters. Figure 3e,f further show, from the perspectives of thermal stability in multiphase ceramics and laser-power-dependent output, that high-flux performance must be built on the coupled optimiza-

tion of luminescence efficiency, heat conduction, and optical architecture.

These considerations show that the evaluation of phosphor ceramics cannot remain at the level of whether a powder exhibits high emission intensity or high room-temperature quantum efficiency. The commonly used performance metrics should also be interpreted according to their physical meanings and application scenarios. IQE, defined as the ratio of emitted photons to absorbed excitation photons, primarily reflects the intrinsic radiative-conversion capability of the luminescent material and is useful for assessing host composition, activator concentration, defect control, and thermal-quenching behavior. EQE additionally incorporates the effects of excitation absorption and emission-light extraction and is therefore more relevant to the externally available photon output of a practical converter. PCE describes the conversion from the specified input power to output optical power and is particularly useful for evaluating the optical energy-conversion performance of laser-driven converters; its value should be interpreted according to the definition of the input-power basis. LE represents the visible luminous flux generated per unit input power and is especially relevant to visible-lighting applications because it is weighted by the photopic response of the human eye. These metrics are complementary rather than interchangeable. A meaningful assessment must instead answer three questions: whether the material can sufficiently absorb the excitation light, whether the heat generated after absorption can be efficiently dissipated, and whether the emitted light can remain stable under high-power operation. Only when these three requirements are simultaneously satisfied can phosphor ceramics move beyond laboratory luminescent materials and become engineered light converters for high-power solid-state light sources.

2.5 | Cross-Scale Links Between Material Structure and Device Output

The performance of phosphor ceramics is not governed by a single parameter but arises from coupled structural factors across multiple length scales. At the atomic and local-structure levels, the valence state, coordination environment, crystal-field strength, and defect neighborhood of luminescent centers such as Ce^{3+} , Eu^{2+} , Mn^{4+} , and Cr^{3+} determine emission wavelength, emission bandwidth, luminescence lifetime, and thermal-quenching behavior [151–153]. For example, the 5d energy-level position of Ce^{3+} is highly sensitive to its local coordination environment in YAG, LuAG, and GAGG. The near-infrared emission of Cr^{3+} likewise depends strongly on octahedral crystal-field strength, cation disorder, and defect structure [154]. Compositional design therefore first determines whether a material can generate the target emission band and also affects its intrinsic thermal stability.

At the ceramic microstructure level, the relevant variables become more complex. Sintering determines grain size, density, residual porosity, grain-boundary structure, secondary-phase distribution, and interfacial bonding. These features influence both the propagation of blue excitation light and emitted light inside the ceramic, as well as the ability of heat to diffuse away from the emitting region [155]. Moderate scattering, for instance, can increase the effective optical path of blue light in

the ceramic and raise the probability of exciting the luminescent phase. Excessive scattering, however, reduces light-extraction efficiency by causing repeated internal reflection and optical loss [156]. Similarly, secondary phases such as Al_2O_3 and AlN can provide heat-diffusion pathways, but poor interfacial bonding or discontinuous distribution can introduce additional thermal resistance [157, 158]. The objective of microstructure regulation is therefore not simply to maximize density or transparency, but to bring photon-transport and heat-conduction pathways into a balanced state.

At the device scale, these coupling effects are further amplified. Ceramic thickness, surface state, laser spot size, incidence geometry, heat-sink material, interfacial contact, and cooling configuration can all alter the final output [159]. A ceramic sample may show high emission intensity in conventional spectroscopic tests yet still undergo rapid saturation at high power if heat-sink contact is poor or if a small laser spot causes severe local heating [160]. Conversely, some materials may not exhibit the strongest emission under low-power excitation but can maintain more stable luminous-flux output in the high-power regime because they possess better scattering architectures and more efficient heat-diffusion channels. This is why phosphor ceramic research must move from material-level performance toward device-level performance.

Figure 4 provides an integrated illustration of this cross-scale relationship. Figure 4a shows a testing platform that approximates device-operating conditions, emphasizing that high-power phosphor ceramics should be evaluated under environments as close as possible to real service conditions, rather than relying solely on conventional spectroscopic measurements. Figure 4b,c presents phase composition, microstructure, and elemental distribution, showing how YAG: Ce and secondary phases such as Al_2O_3 form composite structures inside the ceramic. The transmittance variation in Figure 4d reflects the internal scattering and absorption state of the ceramic, whereas Figure 4e directly captures the evolution of output intensity with increasing laser power [38]. Figure 4f shows that Al_2O_3 content affects luminous exitance and conversion efficiency [161], and Figure 4g further reveals the relationship between AlN content and surface temperature rise [162].

Taken together, these results show that composition and sintering conditions first determine microstructure; microstructure then governs absorption, scattering and heat diffusion; and these processes ultimately manifest as luminous flux, LE, saturation threshold and stability. The design of phosphor ceramics should therefore be built on a clear cross-scale chain: compositional design defines the luminescent centers and host structure; processing controls grains, pores, grain boundaries, and secondary-phase distribution; microstructure dictates photon and heat transport; and device boundary conditions determine the final output capability. Only by connecting this chain can one explain why some materials perform well as powders or under low-power testing but become limited in laser lighting, and why multiphase ceramics, layered ceramics, ceramic-metal composites, and glassy-interface composite structures have become important directions for high-flux light-conversion materials. In this sense, phosphor

ceramics are no longer simply “luminescent ceramics,” but multiscale functional architectures for high-power solid-state light sources. Research should therefore shift from comparing emission intensity alone to establishing systematic correlations among composition, processing, microstructure, photothermal transport and device output. The following sections on YAG: Ce, LuAG: Ce, GAGG: Ce, Al_2O_3 /YAG: Ce, AlN /YAG: Ce, multicolor ceramics, near-infrared ceramics, glassy interfaces, and machine-learning-based design are organized around this central logic.

3 | Garnet-Based Phosphor Ceramics

Garnet-based phosphor ceramics are among the most extensively studied and systematically device-validated systems in high-flux inorganic light-conversion materials. Representative examples include YAG: Ce, LuAG: Ce, and GAGG: Ce, as well as multicomponent garnet and garnet-like ceramics regulated by cations such as Y, Lu, Gd, Ga, Sc, Mg, and Si [163, 164]. The garnet structure offers high chemical stability, thermal stability, and mechanical strength, enabling a stable lattice under high-temperature sintering and high-power blue-light or laser excitation. At the same time, the ceramic form allows photon propagation and heat diffusion to be regulated through grains, grain boundaries, pores, thickness, secondary phases, and surface morphology. Garnet-based ceramics are therefore not only central light-conversion platforms for white LEDs, laser lighting, and laser displays, but also model systems for understanding the “composition-microstructure-photothermal coupling-device output” relationship in phosphor ceramics.

From the perspective of luminescence regulation, the 5d energy levels of Ce^{3+} in garnet lattices are highly sensitive to the local crystal field, leading YAG: Ce, LuAG: Ce and GAGG: Ce to exhibit yellow, green, and broad-band yellow-orange emission, respectively. Cr^{3+} -doped garnet ceramics such as GAGG can further extend emission into the near-infrared region. From the perspective of device design, however, the performance of garnet ceramics is determined not only by the luminescent centers, but also by blue-light absorption, emitted-light extraction, scattering uniformity, heat-diffusion pathways, and packaging interfaces. Accordingly, the development trajectory of garnet-based phosphor ceramics has shifted from obtaining efficient luminescent phases to constructing photothermally coupled architectures capable of sustaining high-flux excitation.

3.1 | YAG: Ce Transparent Ceramics: Benchmark Yellow Emitters and Defect Regulation

YAG: Ce is the most representative yellow-converting system among garnet-based phosphor ceramics. When Ce^{3+} is incorporated into the YAG lattice, its 5d–4f transition produces broad-band yellow emission under blue-light excitation, which combines with residual blue light to generate white output. Compared with conventional phosphor/organic resin encapsulation, YAG: Ce transparent ceramics offer an all-inorganic composition, higher thermal conductivity, good chemical stability, and strong resistance to photothermal ageing, making them better suited to high-power LED and blue-LD excitation.

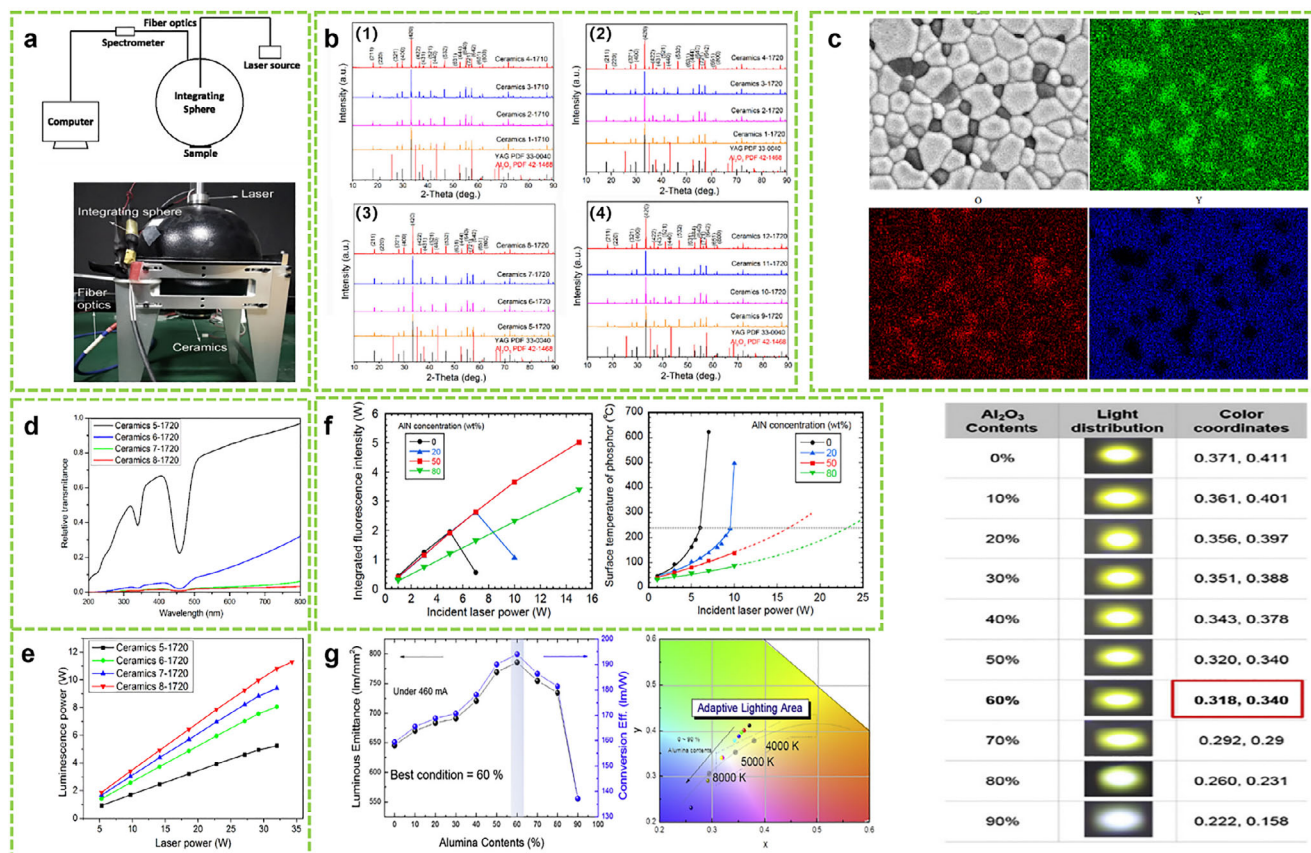


FIGURE 4 | Cross-scale correlation between microstructure regulation and device-level output in phosphor ceramics. (a) Testing platform for evaluating Al₂O₃/YAG: Ce composite phosphor ceramics under high-power excitation. (b) Phase composition of Al₂O₃/YAG: Ce composite phosphor ceramics revealed by x-ray diffraction (XRD) analysis. (c) Scanning electron microscopy (SEM) images and EDS elemental mapping of Al₂O₃/YAG: Ce composite phosphor ceramics, showing the microstructural distribution of different phases. (d) Variation in optical transmittance of Al₂O₃/YAG: Ce composite phosphor ceramics. (e) Luminescence output of Al₂O₃/YAG: Ce composite phosphor ceramics under different laser powers. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [38]. Copyright 2019, The Author(s). Optical Society of America. (f) Effects of Al₂O₃ content on the luminous emittance and conversion efficiency of Al₂O₃/YAG: Ce composite phosphor ceramics. Reproduced with permission from literature [161]. Copyright 2021, Elsevier B.V. (g) Effects of AlN content on fluorescence intensity and surface temperature in AlN/YAG: Ce composite phosphor ceramics. Reproduced with permission from literature [162]. Copyright 2017, Elsevier B.V.

Nishiura et al. reported early evidence for the potential of transparent YAG: Ce ceramics in white LEDs [165]. Their ceramic microstructure and polished sample appearance showed that YAG: Ce ceramics can achieve yellow conversion while preserving bulk transparency (Figure 5a). This work established the materials basis for YAG: Ce ceramics as all-inorganic white-light conversion layers. In YAG: Ce ceramics, thickness is a fundamental variable for regulating blue-light absorption, yellow emission output and chromaticity coordinates. As the ceramic thickness increases from 0.156 mm to 0.632 mm, residual blue light gradually decreases, whereas the yellow emission band becomes markedly stronger (Figure 5b). Correspondingly, the chromaticity coordinates shift from the blue region toward the white and yellow regions (Figure 5c) [165]. These results show that white-light output from YAG: Ce transparent ceramics can be tuned through geometric thickness, but they also reveal the intrinsic limitations of thickness control: excessively thin samples suffer from insufficient blue-light absorption, whereas overly thick samples may reduce forward light extraction, lower the color temperature and limit color-rendering performance

[166]. The design objective for YAG: Ce ceramics is therefore not simply to maximize absorption, but to balance blue-light transmission, yellow-light conversion, light-extraction efficiency, and color quality.

With the development of blue-LD lighting, research on YAG: Ce ceramics has gradually shifted from thickness regulation to defect engineering and high-power photothermal stability. Yao et al. reported Mg, Si co-regulated YAG: Ce transparent ceramics in which annealing was used to modulate grain-boundary defects, oxygen vacancies, and the local crystal-field environment [29]. Sample photographs showed that Mg, Si content and annealing state markedly influence ceramic transparency and color depth (Figure 5d). Further SEM results revealed obvious grain-boundary pores in samples with low Mg, Si content, whereas higher Mg, Si content helped reduce porosity and improve grain-boundary densification (Figure 5e). These results indicate that the transparency of YAG: Ce ceramics is governed not only by phase composition, but also by grain-boundary pores, amorphous residues, and local defects.

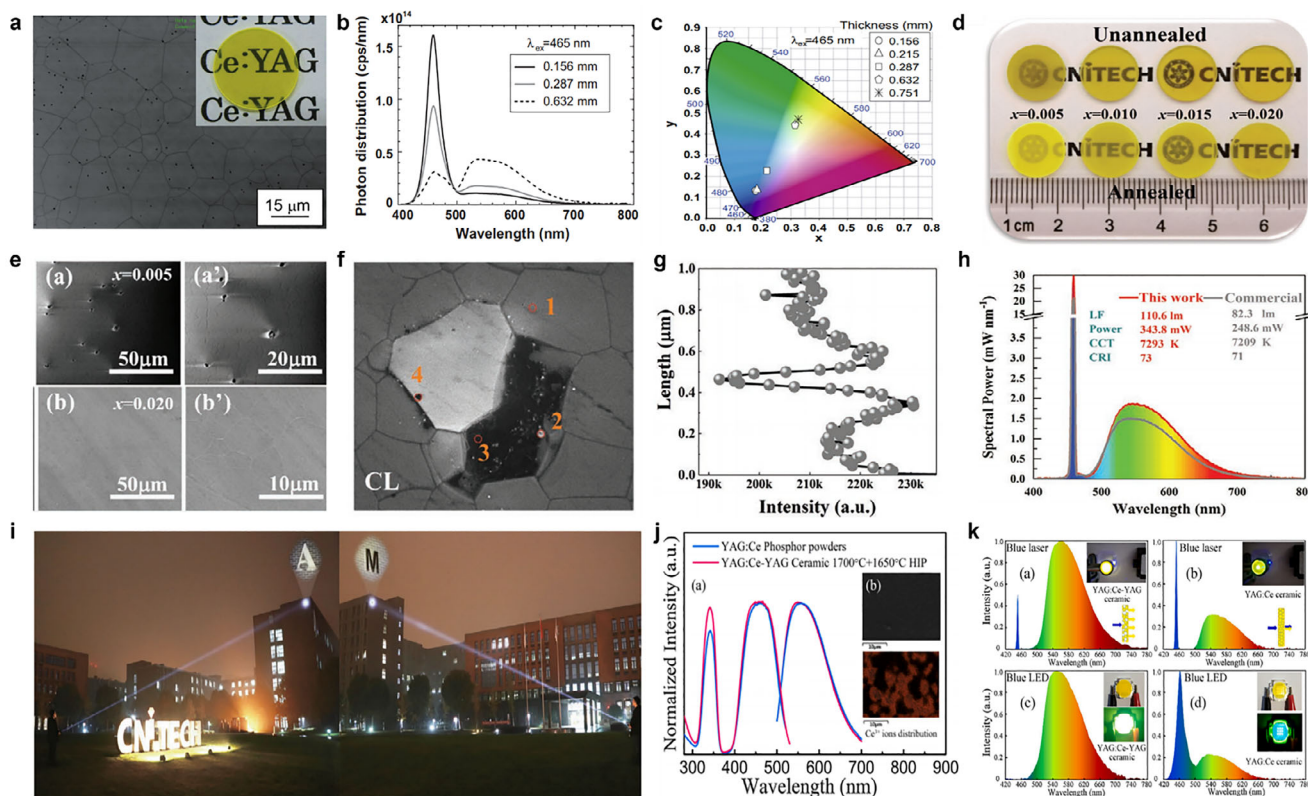


FIGURE 5 | YAG: Ce ceramic phosphors: from thickness regulation and defect engineering to laser-driven lighting output. (a) Microstructure and appearance of transparent YAG: Ce ceramics. (b) Photon distribution spectra of YAG: Ce ceramics with different thicknesses under 465 nm LED excitation. (c) CIE chromaticity coordinates of YAG: Ce ceramics with different thicknesses under 465 nm LED excitation. Reproduced with permission from literature [165]. Copyright 2010, Elsevier B.V. (d) Photographs of unannealed and annealed YAG: Ce transparent ceramic phosphors under daylight. (e) SEM images of annealed YAG: Ce transparent ceramic phosphors with different Mg, Si contents. (f) Cathodoluminescence image of annealed YAG: Ce transparent ceramic phosphor. (g) Line-scanned cathodoluminescence peak intensity of annealed YAG: Ce transparent ceramic phosphor. (h) Electroluminescence spectra and device performance of optimized and commercial YAG: Ce ceramic phosphors in an LD lighting device. (i) Outdoor laser-driven lighting demonstration based on YAG: Ce transparent ceramic phosphors. Reproduced with permission from literature [29]. Copyright 2020, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (j) Normalized excitation/emission spectra and Ce element distribution of YAG: Ce-YAG composite ceramics. (k) Luminescence performances of YAG: Ce-YAG composite ceramics and single-phase YAG: Ce transparent ceramics under blue LED and blue LD excitation. Reproduced with permission from literature [167]. Copyright 2020, Elsevier B.V.

Another key issue in YAG: Ce ceramics is the spatial relationship between Ce^{3+} luminescent centers and grain-boundary defects. Scanning electron microscopy-cathodoluminescence (SEM-CL) characterization showed that grain interiors generally exhibit stronger CL signals, whereas grain boundaries and defect-rich regions often form weak-emission zones (Figure 5f). Variations in CL peak intensity along selected line profiles further confirmed pronounced microscale emission fluctuations between grains and grain boundaries (Figure 5g). Grain boundaries are therefore not inert interfaces, but important structural units that influence microscale luminescence uniformity, non-radiative recombination, and local heat accumulation. High-quality YAG: Ce transparent ceramics must therefore achieve effective Ce activation within grains, suppression of grain-boundary defects and controlled optical scattering.

For laser lighting, materials regulation must ultimately be validated by LD device output. The optimized YAG: Ce transparent ceramics reported by Yao et al. [29] delivered higher luminous flux and optical power than commercial YAG: Ce ceramics in LD lighting devices, while maintaining comparable CCT and

CRI values (Figure 5h). Outdoor illumination demonstrations further showed that YAG: Ce transparent ceramics can generate directional, high-brightness white output under blue-LD excitation (Figure 5i). These results indicate that defect control and annealing regulation not only improve the intrinsic luminescence performance of YAG: Ce ceramics, but also enhance their device compatibility in realistic laser-lighting scenarios.

Beyond defect control, composite architectures and scattering regulation are also important directions for YAG: Ce ceramics. Zhu et al. [167] constructed YAG: Ce-YAG composite ceramics, in which the Ce-free YAG phase was used to modulate photon-propagation pathways while preserving the stability of the garnet phase and introducing moderate scattering. Excitation/emission spectra and Ce elemental-distribution results showed that the YAG: Ce emitting phase retained effective luminescence in the composite ceramic and formed a relatively uniform spatial distribution of Ce (Figure 5j). Further comparison under LED and LD excitation revealed distinct differences in residual blue light and yellow-conversion behavior between YAG: Ce-YAG composite ceramics and single-phase YAG: Ce transparent

ceramics (Figure 5k). Composite ceramics therefore do not aim to eliminate scattering completely; instead, scattering is used as a structural parameter to regulate excitation-light path length, blue-light absorption, and emitted-light extraction.

Overall, the development of YAG: Ce ceramics illustrates the transition of garnet-based phosphor ceramics from “materials that can emit” to “devices that can withstand high-power operation.” Thickness determines blue-light absorption depth and initial chromaticity coordinates; defect engineering governs transparency, microscale luminescence, and thermal stability; composite scattering architectures control optical-field uniformity and light-extraction efficiency; and LD device testing ultimately verifies usability under realistic high-power conditions. YAG: Ce is therefore not only the representative yellow ceramic converter, but also a reference system for the design of LuAG: Ce, GAGG: Ce and multiphase garnet ceramics.

3.2 | LuAG: Ce Ceramics: High-Brightness Green Emission and Spatial Thermal Management

LuAG: Ce is an important garnet ceramic for high-brightness green emission and laser displays [168]. Compared with YAG: Ce, the LuAG host modifies the local crystal field around Ce^{3+} , shifting the emission toward the green region [169]. Because green light is a key channel in laser displays, projection systems and multicolor light-source reconstruction, LuAG: Ce should not be regarded as a simple compositional substitute for YAG: Ce, but as an important materials platform that extends garnet ceramics from white lighting to high-brightness display applications.

Chen et al. reported highly transparent LuAG: Ce ceramics with high LE and high saturation threshold under blue-LD excitation [72]. The fabrication process involved powder mixing, forming, vacuum sintering, hot isostatic pressing (HIP), annealing and polishing (Figure 6a), indicating that highly transparent LuAG: Ce ceramics are highly sensitive to powder homogeneity, sintering densification and post-treatment conditions. Different MgO/tetraethyl orthosilicate (TEOS) sintering-aid combinations substantially affected grain size, grain-boundary state and residual porosity (Figure 6b), which in turn modified the in-line transmittance and visual transparency of the ceramics (Figure 6c). The high transparency of LuAG: Ce ceramics is therefore not merely an optical appearance, but an integrated outcome of low porosity, weak scattering, reduced non-radiative defects and improved grain-boundary continuity. At the device level, LuAG: Ce-based green LD devices were constructed and their electroluminescence (EL) spectra, CIE chromaticity coordinates, luminous flux and LE were systematically measured as functions of laser power density (Figure 6d). The results show that highly transparent LuAG: Ce ceramics can deliver stable green emission under 460 nm blue-LD excitation, while maintaining high LE and strong power-handling capability. For laser display and projection applications, the advantages of LuAG: Ce lie in high green brightness, good thermal stability and a high saturation threshold. Its limitation is that the emission is strongly green-shifted, making it difficult to achieve high color rendering when used alone for white lighting. LuAG: Ce is therefore better suited as a green conversion module in multichannel light-source architectures.

Beyond single-phase transparent ceramics, Zhou et al. developed hydroxyapatite-LuAG phosphor-in-ceramic (HA-LuAG PiC) structures by embedding LuAG: Ce particles into a transparent hydroxyapatite (HA) ceramic matrix [170]. Transmission electron microscopy/high-resolution transmission electron microscopy (TEM/HRTEM) and elemental mapping revealed clear interfaces between LuAG: Ce particles and the HA matrix, with well-defined elemental distributions in the two phases (Figure 6e). In this architecture, LuAG: Ce particles provide green light conversion, whereas the transparent HA ceramic matrix offers inorganic support, a thermally stable environment and encapsulation protection. Blue-laser testing, irradiation photographs, surface-temperature measurements and luminous-flux data further demonstrated that HA-LuAG PiC can maintain effective green output under relatively high-power excitation (Figure 6f). Compared with single-phase transparent ceramics, the PiC architecture offers advantages in sintering temperature, compositional compatibility and retention of the phosphor-particle structure.

To address even higher power densities, Zhang et al. proposed layered Al_2O_3 -LuAG: Ce composite ceramics in which the LuAG: Ce emitting layer and Al_2O_3 heat-conduction layer are spatially separated (Figure 6g) [171]. This layered architecture differs from conventional homogeneously mixed multiphase ceramics: the LuAG: Ce layer mainly performs light conversion, whereas the Al_2O_3 layer primarily provides heat spreading. This design partly avoids the dilution of the emitting phase by a high fraction of inert secondary phase. Thermal simulations showed that an appropriately designed layered structure can reduce local hot-spot temperature and improve the uniformity of heat diffusion (Figure 6h). These studies show that the development of LuAG: Ce ceramics has progressed from single-phase transparency toward PiC interfacial composites and layered thermal-management architectures.

3.3 | CAGG/GAGG: Ce Broad-Band Garnet Ceramics: Ga Regulation, Multiphase Construction and Defect Response

CAGG/GAGG: Ce is one of the most promising garnet-based phosphor ceramic systems for broad-band spectral regulation. Compared with YAG: Ce and LuAG: Ce, the garnet lattice composed of multiple cations, including Gd, Al, and Ga, provides a more flexible local coordination environment for Ce^{3+} . As a result, the 5d energy-level position, emission peak, spectral bandwidth, and thermal-quenching behavior of Ce^{3+} can be continuously optimized through compositional regulation. The focus of CAGG/GAGG: Ce research is therefore not simply to obtain yellow-green emission, but to achieve broad-band white-light output under blue-LD excitation through lattice regulation, multiphase construction, and defect management [172, 173].

Kosyanov et al. systematically investigated the effect of Ga^{3+} substitution on the structure and laser-lighting performance of Ce: GAGG and Al_2O_3 -Ce: GAGG ceramics [174]. As shown in Figure 7a, when the Ga content increases from $x = 0.5$ to $x = 3.0$, the appearance of Ce: GAGG and Al_2O_3 -Ce: GAGG ceramics changes from deep yellow-orange to pale yellow, directly reflecting the regulation of the Ce^{3+} luminescent environment

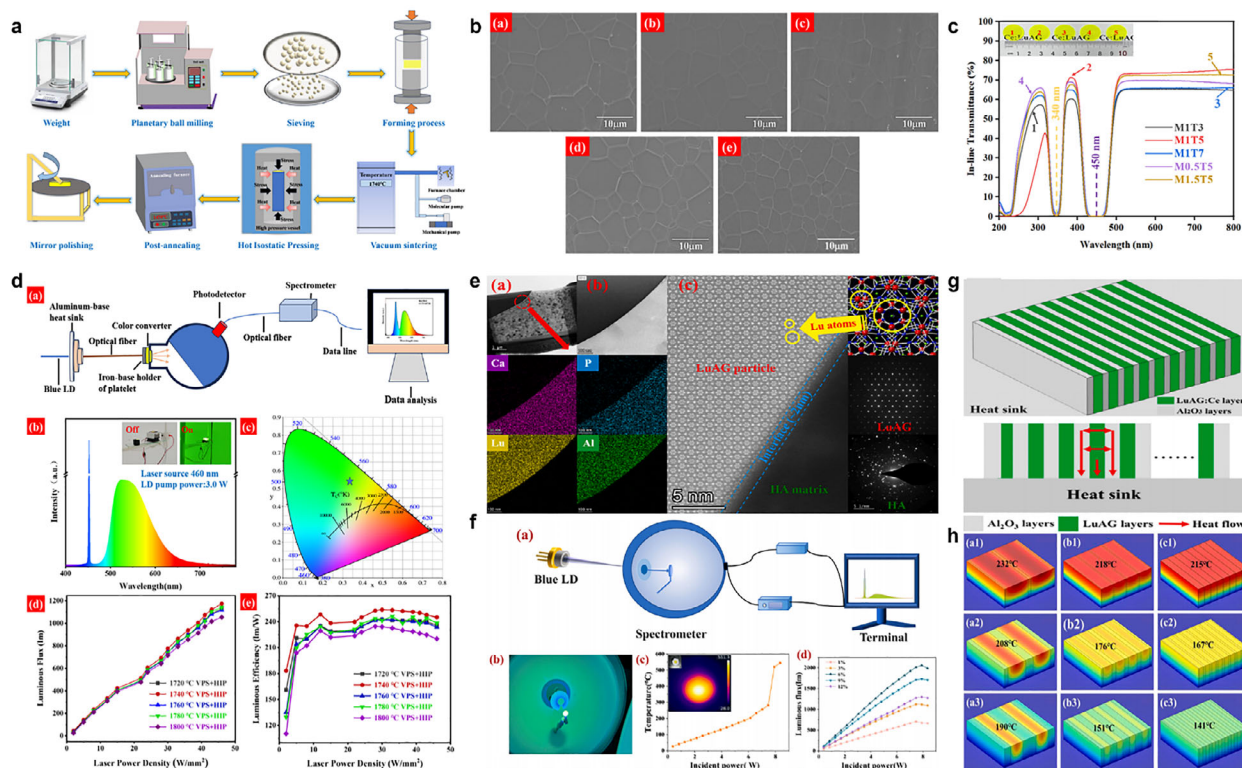


FIGURE 6 | LuAG:Ce ceramic phosphors: transparency enhancement, PiC integration, and layered thermal management. (a) Fabrication process of LuAG:Ce ceramic phosphors. (b) FESEM images of LuAG:Ce ceramic phosphors prepared with different MgO/TEOS sintering-aid combinations. (c) In-line transmittance spectra and appearances of LuAG:Ce ceramic phosphors. (d) Green LD device configuration, EL spectrum, CIE chromaticity coordinates, luminous flux, and LE of LuAG:Ce ceramic phosphors. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [72]. Copyright 2024, The Author(s). Optica Publishing Group. (e) TEM, HRTEM, and elemental mapping images of the interface between LuAG:Ce particles and the HA ceramic matrix in HA-LuAGPiC. (f) Blue-laser testing configuration, laser-irradiated photographs, surface temperature, and luminous flux of HA-LuAGPiC. Reproduced with permission from literature [170]. Copyright 2023, Elsevier Ltd. (g) Structural model and heat-flow schematic of layered Al₂O₃-LuAG:Ce composite ceramic phosphors. (h) Simulated heat distributions of layered Al₂O₃-LuAG:Ce composite ceramic phosphors. Reproduced with permission from literature [171]. Copyright 2022, Elsevier Ltd.

by Ga substitution. Figure 7b shows that the lattice constant of the garnet phase increases with Ga content, indicating that Ga³⁺ enters Al³⁺ sites, induces lattice expansion and further modifies the crystal-field strength around Ce³⁺. The evolution of lattice parameters differs between single-phase and multiphase ceramics, suggesting that Ga partitioning among different phases influences the actual luminescence response. The multiphase architecture provides a route for photothermal co-regulation in CAGG/GAGG:Ce ceramics. Figure 7c shows that the garnet emitting phase and the Al₂O₃ phase form continuous interfaces in Al₂O₃-Ce:GAGG. The introduction of Al₂O₃ can suppress abnormal grain growth and improve heat diffusion, while also modifying blue-light propagation and interfacial scattering. The key to multiphase design is therefore not to simply increase the inert phase content, but to balance emitting-phase continuity, scattering strength and heat-diffusion capability.

Spectral results further confirm the effectiveness of Ga substitution. As shown in Figure 7d, increasing Ga content induces a blue shift of Ce³⁺ emission in both Ce:GAGG and Al₂O₃-Ce:GAGG, with shifts of about 26 nm in the single-phase ceramic and about 18 nm in the multiphase ceramic. This indicates that the emission color of CAGG/GAGG:Ce is governed not only by the nominal Ga content, but also by Ga partitioning, crystal-field variation,

and microstructural effects. Device output reflects the combined outcome of compositional and structural regulation. Figure 7e,f shows that, under blue-LD excitation, changes in Ga content simultaneously alter CIE chromaticity coordinates, LE, CCT, and CRI. The emission blue shift can increase the color temperature but may also weaken spectral coverage and compromise color rendering. CAGG/GAGG:Ce ceramics should therefore not be evaluated solely by room-temperature photoluminescence (PL) intensity; instead, their performance must be assessed by integrating spectral behavior, scattering, thermal stability, and LD device output.

Beyond Ga regulation and multiphase design, energy transfer and defect behavior in GAGG-based materials also deserve attention. Zhang et al. reported the energy-transfer process between Ce³⁺ and Mn²⁺ dual luminescent centers in GAGG:Ce, Mn [175]. Figure 7g,h show that Mn co-activation introduces additional de-excitation pathways, while Figure 7i further indicates that Mn doping accelerates the decay of Ce³⁺ centers. Although this study was conducted in the context of scintillator crystals, the revealed energy-migration mechanism provides useful insight into the luminescence dynamics of CAGG/GAGG:Ce ceramics. Defect traps are directly related to the stability of GAGG-based materials. Figure 7j,k shows that Mn co-activation

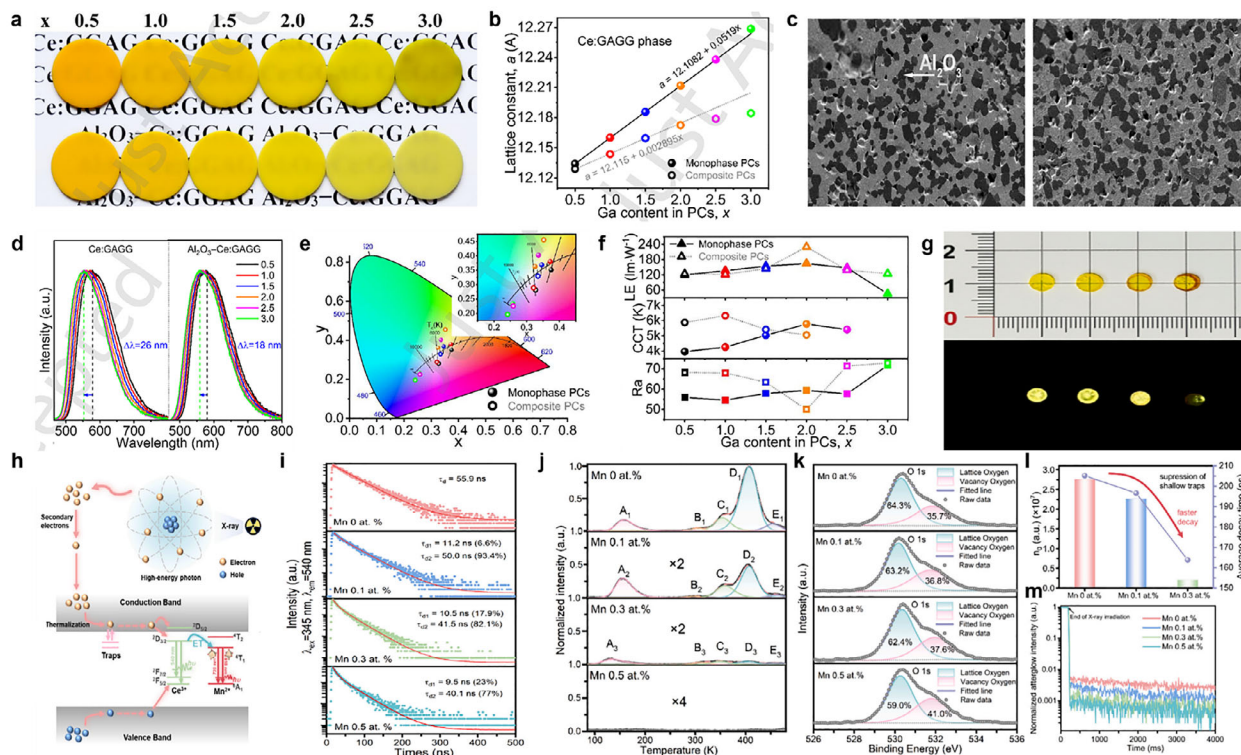


FIGURE 7 | Ga-regulated lattice structure, composite microstructure, laser-lighting output, and defect response of CAGG/GAGG: Ce-based garnet materials. (a) Optical appearance of Ce: GAGG and Al_2O_3 -Ce: GAGG ceramics with different Ga contents. (b) Lattice constant of the Ce: GAGG phase as a function of Ga content. (c) Microstructures of Al_2O_3 -Ce: GAGG composite ceramics. (d) Photoluminescence spectra of Ce: GAGG and Al_2O_3 -Ce: GAGG ceramics with different Ga contents. (e) CIE chromaticity coordinates under blue-LD excitation. (f) LE, correlated color temperature, and color rendering index as a function of Ga content. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [174]. Copyright 2026, The Author(s). Published by Tsinghua University Press. (g) Optical appearance and luminescence photographs of GAGG: Ce, Mn crystals. (h) Energy-transfer mechanism between Ce^{3+} and Mn^{2+} centers in GAGG. (i) Photoluminescence decay curves of Ce^{3+} centers in GAGG: Ce, Mn. (j) Thermoluminescence trap response of GAGG: Ce, Mn. (k) O 1s XPS spectra related to lattice oxygen and oxygen-vacancy components. (l) Average scintillation decay time. (m) X-ray-induced afterglow behavior. Reproduced with permission from literature [175]. Copyright 2026, Published by Elsevier B.V.

modifies thermoluminescence (TL) traps and oxygen-vacancy-related components, and Figure 7l,m further demonstrates that trap regulation can suppress induced afterglow and shorten the average decay time. For laser-lighting ceramics, similar defect states may cause energy retention, thermally activated non-radiative losses and chromaticity drift. Defect regulation should therefore be considered together with Ga substitution and multiphase construction.

Overall, the strength of CAGG/GAGG: Ce ceramics lies in the broad spectral tunability and high color-rendering potential enabled by their multi-cation garnet lattices. Their main challenge arises from the coupling among Ga partitioning, multiphase interfaces and defect traps. Future development should precisely tune the local crystal field of Ce^{3+} through Ga^{3+} substitution, optimize scattering and heat diffusion through Al_2O_3 -based multiphase architectures, and suppress thermal quenching and color drift by regulating trap states and oxygen vacancies. Such integrated control is essential for achieving broad-band, high-efficacy and stable white-light output required for high-power laser lighting.

Recent studies have further expanded garnet design through non-stoichiometric and multi-cation engineering. Non-stoichiometric

Ga regulation in terbium gallium garnet ceramics has been shown to modify phase formation, microstructural evolution, and optical transparency, demonstrating that deviations from the ideal cation ratio can directly affect the fabrication and optical propagation of garnet ceramics [176]. A multi-cation-engineered Cr^{3+} -activated garnet phosphor with the composition $\text{Gd}_{1.02}\text{Ca}_{1.98}\text{Al}_{3-y}\text{Ga}_y\text{Sn}_{1.98}\text{O}_{12}$: Cr^{3+} was recently developed by using Ca^{2+} - Sn^{4+} pairs to stabilize the garnet framework and Ga^{3+} incorporation to regulate the local coordination environment of Cr^{3+} . The optimized composition exhibited broadband NIR emission and improved thermal stability, illustrating how non-stoichiometric cation balance can simultaneously influence lattice stability and luminescence [177]. Related cation-substitution engineering in $\text{Y}_3\text{Al}_5\text{O}_{12}$: Cr^{3+} has also been used to regulate the garnet structure and achieve broadband NIR emission [178]. These studies indicate that non-stoichiometric garnets should be regarded as compositionally and defect-engineered platforms rather than as simple deviations from ideal stoichiometry. Their performance is determined by the coupled effects of cation balance, phase stability, local coordination, defect chemistry, optical transport, and thermal behavior, all of which should be considered when evaluating their potential for ceramic light-conversion devices.

3.4 | Design Logic and Performance Boundaries of Garnet-Based Phosphor Ceramics

Garnet-based phosphor ceramics constitute the most mature and representative foundation among high-flux light-conversion materials [163, 179]. YAG: Ce, LuAG: Ce and GAGG: Ce should not be regarded as isolated material examples; rather, they represent a continuous development trajectory of garnet ceramics from stable yellow conversion to high-brightness green output, and further to broad-band, high-color-rendering spectral regulation [180, 181]. YAG: Ce provides the classical yellow-conversion model for high-power white lighting and laser lighting. LuAG: Ce, enabled by stronger crystal-field regulation and higher transparency, is more suited to laser displays and high-brightness green emission. GAGG: Ce broadens the emission spectrum through Gd/Ga compositional regulation, offering an important route to improved white-light quality and color-rendering performance. The core value of garnet-based ceramics therefore lies not only in their chemical and thermal stability, but also in their ability to coordinate spectral and photothermal behavior through host composition, activator environment and ceramic microstructure [182, 183].

From the perspective of materials design, the performance of garnet-based ceramics is mainly governed by four coupled factors. First, host cations such as Y/Lu/Gd and Al/Ga/Sc/Mg/Si determine the local crystal field around Ce^{3+} , thereby regulating the 5d energy-level position, emission peak, and emission bandwidth [184, 185]. Second, Ce^{3+} concentration and ceramic thickness control blue-light absorption depth and emission intensity, but excessive doping or overly thick samples can induce reabsorption, concentration quenching and heat accumulation. Third, grain size, residual pores, grain-boundary phases, and surface texture govern light scattering and extraction inside the ceramic, determining whether the material behaves more like a transparent optical window or an effective light-conversion medium with sufficient absorption. Finally, secondary phases such as Al_2O_3 and AlN, or layered architectures, can further reshape heat-conduction and photon-propagation pathways, driving garnet ceramics from single emitting phases toward the co-design of luminescent phases, thermally conductive phases and scattering structures. It should be emphasized that optimization of garnet-based ceramics does not mean maximizing a single performance parameter, but balancing multiple interdependent metrics. High transparency reduces scattering losses but may lead to insufficient blue-light absorption. Enhanced scattering can increase optical path length and absorption efficiency but may reduce forward light extraction. Increasing Ce^{3+} concentration can strengthen emission but may also introduce additional non-radiative losses. Incorporating secondary phases can improve thermal management but may dilute the emitting phase or introduce interfacial thermal resistance. These trade-offs show that the true design core of garnet-based phosphor ceramics is the simultaneous optimization of light absorption, light extraction, heat diffusion, and spectral quality, rather than the isolated enhancement of quantum efficiency or thermal conductivity [186].

From the perspective of application boundaries, YAG: Ce is suitable for highly stable, high-flux yellow conversion, but

its insufficient red component limits its independent use in high-color-rendering warm-white lighting. LuAG: Ce is well suited to high-brightness green emission and laser displays but cannot by itself meet the demands of full-spectrum white light. GAGG: Ce and other broad-band Ce^{3+} -activated garnet ceramics can improve color-rendering performance, yet their multicomponent structures increase the difficulty of sintering densification, grain-boundary segregation, and defect control. Garnet-based ceramics are therefore the most important foundational platform in phosphor ceramics, but they cannot cover all requirements of high-power light sources. The subsequent development of red ceramics, multiphase ceramics, near-infrared ceramics and glassy composite interfaces can be understood as further supplementation and expansion beyond the spectral limitations, thermal-management boundaries, and device-integration constraints of garnet-based systems [187].

4 | Multiphase Phosphor Ceramics and Photothermal Co-Regulation

4.1 | From Single-Phase to Multiphase Ceramics: Structural Requirements for High-Flux Output

The preceding section shows that garnet-based ceramics such as YAG: Ce, LuAG: Ce, and GAGG: Ce have established a mature all-inorganic materials platform for high-power light conversion. However, in laser lighting, projection displays and high-brightness white light sources, the conversion layer must not only maintain high luminescence efficiency, but also withstand heat accumulation, luminance saturation, and long-term photothermal stress under high-power-density excitation. Under these conditions, the limitations of single-phase ceramics become increasingly apparent: luminescence conversion, photon propagation, and heat diffusion are often carried by the same material phase, making it difficult to optimize absorption, light extraction, heat dissipation, and spectral quality simultaneously [188].

Multiphase phosphor ceramics have emerged to address this functional coupling. Their core concept is not the simple addition of inert secondary phases, but the redistribution of functions within the light converter through the co-design of luminescent phases, thermally conductive phases, scattering phases, and interfacial structures [189, 190]. The luminescent phase is responsible for excitation-light absorption and target emission. Secondary phases such as Al_2O_3 and AlN can construct heat-diffusion pathways and reduce local temperature rise [146]. Phase interfaces and refractive-index contrast can regulate light scattering and the effective optical path of blue light. Layered, graded, or multilayered structures further enable spatial separation among the light-conversion layer, thermal-management layer and mechanical-support layer [191].

Multiphase ceramics therefore represent a transition in phosphor ceramics from “material ceramicization” to “structural functionalization.” The representative Al_2O_3 /YAG: Ce system demonstrates that secondary phases can simultaneously

influence scattering pathways and heat-conduction pathways [149]. High-thermal-conductivity systems such as AlN/YAG: Ce further emphasize the importance of continuous thermal-transport networks for improving the saturation threshold. Layered and graded architectures show that multiphase design can evolve from random mixing toward spatially programmed structures [192]. Importantly, however, multiphase construction does not necessarily lead to performance improvement. Excessive secondary-phase content can dilute the emitting phase, poor interfacial bonding can introduce thermal resistance and defect-assisted quenching, and overly strong scattering can reduce forward light-extraction efficiency [193, 194]. The key to multiphase phosphor ceramics is therefore to balance emitting-phase volume fraction, secondary-phase connectivity, interfacial quality, scattering strength, and ceramic thickness.

Following this logic, this section focuses on Al₂O₃/YAG: Ce, AlN/YAG: Ce, multiphase composites and layered/graded architectures, with emphasis on how multiphase ceramics co-regulate light absorption, heat diffusion, and device output under high-power excitation, thereby overcoming the performance boundaries of single-phase ceramics in high-flux applications.

4.2 | Al₂O₃/YAG: Ce Multiphase Ceramics: Compositional Windows and White-Light Quality Regulation

Al₂O₃/YAG: Ce multiphase ceramics are among the most representative model systems in oxide-based high-power light-conversion ceramics [195, 196]. Their significance lies in revealing how a non-emitting oxide secondary phase can reshape optical transport, heat diffusion, and the white-light output boundaries of YAG: Ce ceramics. Compared with single-phase YAG: Ce transparent ceramics, Al₂O₃ does not directly provide luminescent centers; instead, it regulates blue-light absorption, yellow-light extraction, and device color quality by modifying phase composition, two-phase interfacial density, scattering strength, and the effective volume fraction of the emitting phase. The key scientific question in this system is therefore not whether Al₂O₃ should be introduced, but how to establish a matched relationship among Al₂O₃ content, Ce³⁺ concentration, and ceramic microstructure, so that the multiphase ceramic can simultaneously achieve high luminescence efficiency, suitable CCT, and acceptable CRI under high-power LD excitation [197, 198].

In addition to conventional powder-based processing, glass crystallization has been explored as an alternative route for fabricating transparent YAG/Al₂O₃ ceramics. Ma et al. reported the pressure less nano crystallization of Y₂O₃-Al₂O₃ bulk glasses, producing transparent Ce³⁺-doped YAG-Al₂O₃ nanoceramics [199]. TEM observations reveal a homogeneous nanostructure composed of YAG nanocrystals and Al₂O₃ crystalline domains (Figure 8a), while XRD analysis confirms the coexistence of YAG and γ -Al₂O₃ phases (Figure 8b). HRTEM further shows that thin Al₂O₃ regions surround the YAG nanograins and form well-defined interphase boundaries (Figure 8c). Despite this biphasic structure, the ceramic retains broad optical transparency

from the visible to the mid-infrared region (Figure 8d). Subsequent crystallization-kinetics studies further demonstrated that transparent YAG-based nanoceramics can be obtained through controlled thermal treatment. These findings suggest that careful control of glass composition and crystallization conditions is essential for balancing phase formation, transparency, scattering, and luminescence output.

Jiang et al. systematically investigated the effects of Al₂O₃ content and Ce³⁺ concentration on the performance of Al₂O₃/YAG: Ce ceramics, providing direct evidence for this compositional window [200]. As shown in Figure 8e,f, samples with different Al₂O₃ contents exhibit clear differences in appearance and XRD patterns, while the main phases remain YAG and Al₂O₃. This indicates that a stable oxide secondary phase can be introduced while preserving the YAG: Ce emitting phase. Further SEM results show that Al₂O₃ content and Ce³⁺ concentration modify grain morphology, densification state, and phase distribution in the ceramics (Figure 8g). These structural differences form the basis for subsequent changes in LE, color temperature, and color-rendering performance. Under LD excitation, the effect of Al₂O₃ content on luminescence efficiency is not simply monotonic. The results of Jiang et al. show pronounced differences in excitation spectra, emission spectra, and luminescence efficiency among samples with different Al₂O₃ contents (Figure 8h,i) [200]. An appropriate amount of Al₂O₃ helps regulate optical scattering and thermal stability, whereas excessive Al₂O₃ reduces the effective fraction of the YAG: Ce emitting phase and weakens yellow-light conversion. Similarly, Ce³⁺ concentration also has an optimal range (Figure 8j,k), insufficient Ce³⁺ leads to inadequate blue-light absorption, whereas excessive Ce³⁺ may induce concentration quenching, reabsorption, and heat accumulation. The performance of Al₂O₃/YAG: Ce therefore depends on the synergistic matching between Al₂O₃ content and Ce³⁺ concentration. More importantly, the application evaluation of Al₂O₃/YAG: Ce cannot rely on luminescence efficiency alone. Figure 8l-o shows that Al₂O₃ content and Ce³⁺ concentration also strongly affect CCT and CRI. Excessive residual blue light increases the color temperature, whereas overly strong yellow conversion can limit spectral balance. Moreover, because YAG: Ce itself lacks sufficient red emission, its high-color-rendering capability remains limited even when high brightness is achieved through Al₂O₃ and Ce³⁺ regulation. This indicates that Al₂O₃/YAG: Ce is better suited as a foundational multiphase platform for high-brightness white-light conversion, rather than as a final solution for full-spectrum, high-color-rendering lighting.

The central lesson from Al₂O₃/YAG: Ce multiphase ceramics is therefore that oxide secondary phases can extend the high-power output capability of YAG: Ce ceramics, but their effects are constrained by clear compositional boundaries. Too little Al₂O₃ provides insufficient scattering and thermal-management regulation, whereas excessive Al₂O₃ dilutes the emitting phase. Likewise, Ce³⁺ concentrations that are either too low or too high restrict the final output. This leads naturally to the question addressed in the next section: if heat diffusion under high-power excitation needs to be further improved, relying on Al₂O₃ alone is insufficient. High-thermal-conductivity secondary phases such as AlN, together with their interfacial compatibility with YAG: Ce, become a more critical design direction.

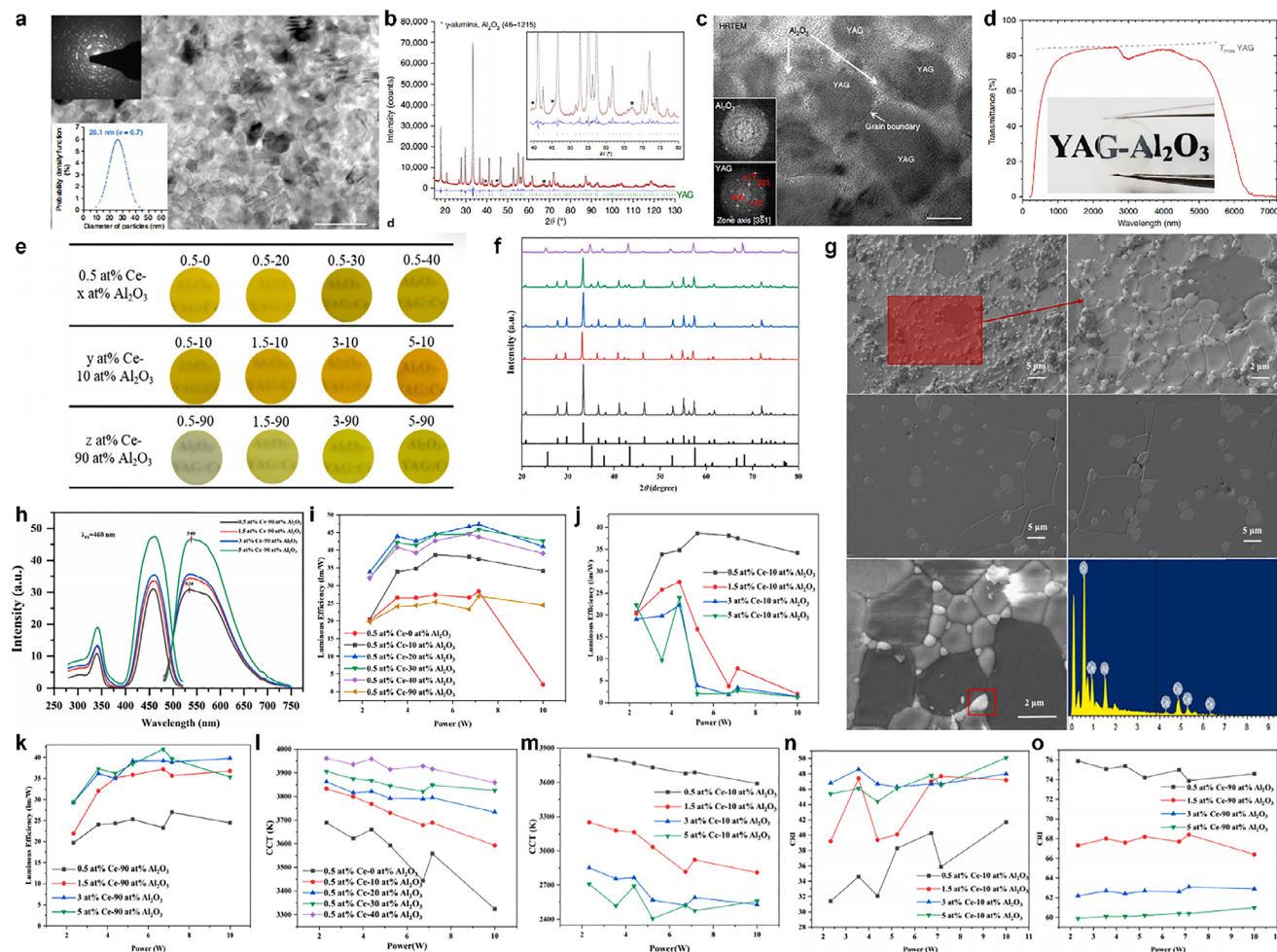


FIGURE 8 | Composition-window optimization and white-light output of $\text{Al}_2\text{O}_3/\text{YAG}:\text{Ce}$ composite ceramics under blue laser diode excitation. (a) Bright-field TEM image and selected-area electron diffraction pattern of the fully crystallized nanoceramic. (b) XRD pattern and Rietveld refinement confirming the coexistence of YAG and $\gamma\text{-Al}_2\text{O}_3$ phases. (c) HRTEM image showing thin Al_2O_3 crystalline regions surrounding the YAG nanograins. (d) Optical transmission spectra of the YAG- Al_2O_3 nanoceramic from the ultraviolet-visible-near-infrared to the mid-infrared region. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [199]. Copyright 2018, The Author(s). Published by Springer Nature. (e) Photographs of samples with different Al_2O_3 and Ce^{3+} contents. (f) XRD patterns of the corresponding ceramics. (g) Representative SEM images and EDS analysis of composite ceramics. (h) PL spectra of samples with 90 at% Al_2O_3 and different Ce^{3+} concentrations under 460 nm excitation. (i) Laser-driven luminous efficiency of samples with different Al_2O_3 contents at 0.5 at% Ce^{3+} . (j) Laser-driven luminous efficiency of samples with different Ce^{3+} concentrations at 10 at% Al_2O_3 . (k) Laser-driven luminous efficiency of samples with different Ce^{3+} concentrations at 90 at% Al_2O_3 . (l) CCT of samples with different Al_2O_3 contents at 0.5 at% Ce^{3+} . (m) CCT of samples with different Ce^{3+} concentrations at 10 at% Al_2O_3 . (n) CRI of samples with different Ce^{3+} concentrations at 90 at% Al_2O_3 . (o) CRI of samples with different Ce^{3+} concentrations at 10 at% Al_2O_3 . Reproduced with permission from literature [200]. Copyright 2022, Published by Elsevier B.V.

4.3 | AlN/YAG: Ce Multiphase Ceramics: High-Thermal-Conductivity Secondary Phases and Photothermal Coupling

In the $\text{Al}_2\text{O}_3/\text{YAG}:\text{Ce}$ system, oxide secondary phases can improve scattering and thermal stability, but their ability to enhance thermal conductivity remains limited [201, 202]. As the power density of blue LD excitation further increases, local heat accumulation in the light-conversion layer rapidly amplifies luminescence quenching and luminance saturation. Introducing secondary phases with higher thermal conductivity has therefore become an important direction in the development of multiphase ceramics [203]. AlN, which combines high thermal conductivity, a wide bandgap, and good thermal stability, is a representative candidate for

constructing high-thermal-conductivity light-conversion ceramics. However, AlN is a non-oxide ceramic, whereas YAG: Ce is an oxide luminescent phase; their substantial differences in sintering atmosphere, interfacial reactions, and phase stability introduce additional materials challenges [204]. The central challenge in AlN/YAG: Ce is therefore not simply to maximize thermal conductivity, but to establish effective heat-diffusion pathways and control oxide-non-oxide interfacial reactions while preserving the luminescence capability of YAG: Ce. In addition, the incorporation and distribution of AlN can modify the optical scattering, light-extraction efficiency, and spatial thermal distribution of the composite. Moderate scattering may improve emission uniformity and light extraction, whereas excessive scattering can increase the optical path length, promote reabsorption,

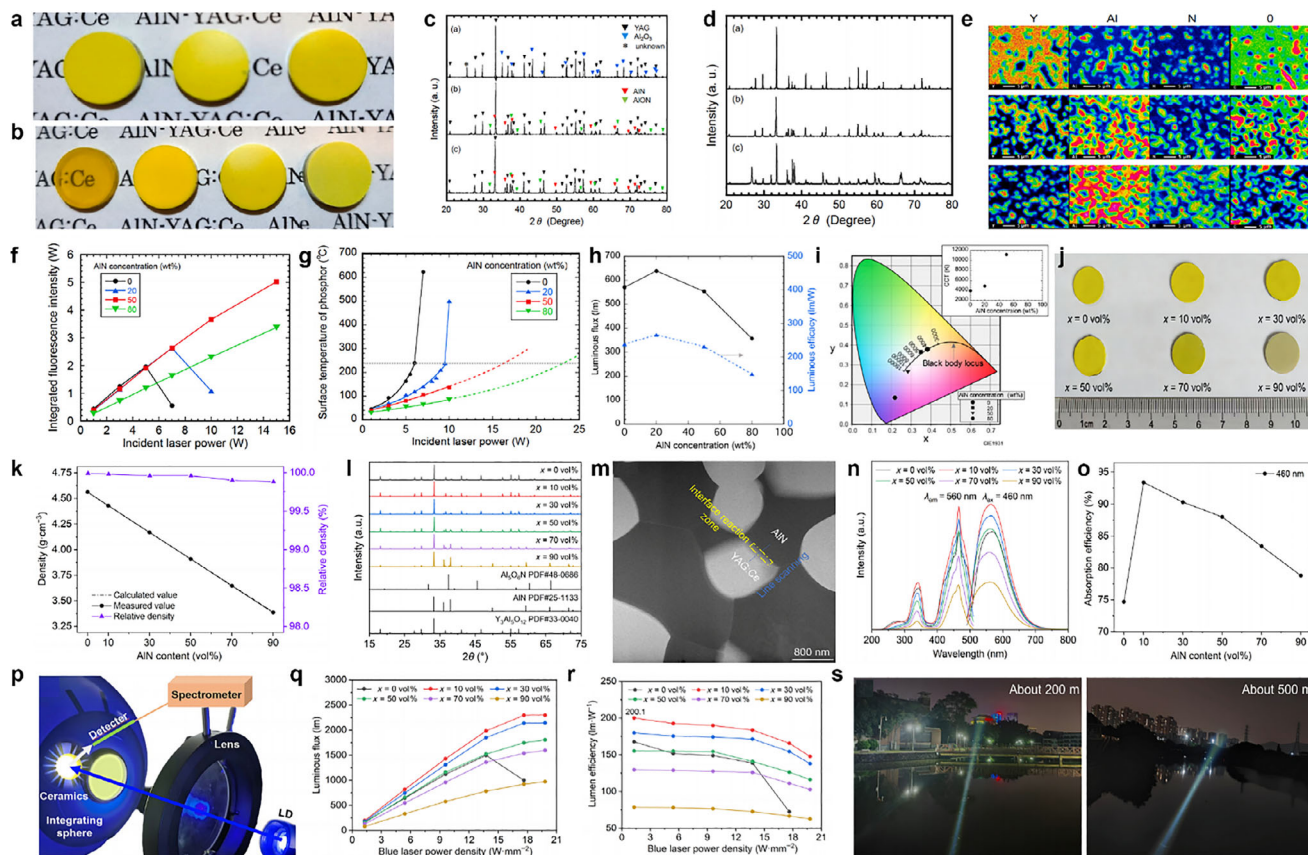


FIGURE 9 | AIN/YAG:Ce composite ceramics for high-thermal-conductivity laser-driven white lighting. (a and b) Photographs of AIN-YAG:Ce composite ceramics with different AIN contents. (c and d) XRD patterns showing the phase evolution of AIN-YAG:Ce ceramics and the formation of oxynitride-related secondary phases. (e) Elemental mapping images revealing the spatial distribution of Y, Al, N, and O in the composite ceramics. (f and g) Fluorescence intensity and surface temperature as functions of incident laser power for samples with different AIN contents. (h and i) Luminous flux, LE, CIE chromaticity coordinates, and CCT as functions of AIN content. Reproduced with permission from literature [161]. Copyright 2021, Published by Elsevier B.V. (j and k) Photographs, density, and relative density of x AIN-YAG:Ce ceramics with different AIN volume fractions. (l) XRD patterns of x AIN-YAG:Ce ceramics, confirming YAG, AIN, and $\text{Al}_5\text{O}_6\text{N}$ phases. (m) TEM-EDS line-scan analysis of the YAG:Ce/AIN interface. (n and o) PLE/PL spectra and absorption efficiency of x AIN-YAG:Ce ceramics. (p) Schematic illustration of the LD-driven lighting test configuration. (q and r) Luminous flux and LE under different blue laser power densities. (s) Long-distance white-light illumination demonstrations at about 200 and 500 m. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [205]. Copyright 2026, The Author(s). Published by Tsinghua University Press.

and reduce forward transmittance. The optimum AIN/YAG:Ce architecture should consequently be determined by balancing thermal transport, interfacial stability, optical output, and chromaticity stability rather than by maximizing thermal conductivity alone.

Fujioka et al. provided early evidence for the feasibility of AIN-YAG:Ce multiphase ceramics in laser lighting [161]. By comparing the phase composition and appearance of 50 wt% AIN-YAG:Ce samples processed in air, N_2 , and modified vapor transport equilibration (m-VTE) atmospheres, they found that the sintering atmosphere strongly affects AIN retention and oxidation degree (Figure 9a). This indicates that AIN/YAG:Ce differs from oxide-oxide composite systems such as Al_2O_3 /YAG:Ce, because its preparation is first constrained by AIN oxidation and aluminum oxynitride (AlON) formation. Subsequent regulation of AIN content showed systematic changes in AIN characteristic peaks, phase distribution, and microstructure with composition (Figure 9b–e), demonstrating that AIN can enter YAG:Ce

ceramics as a secondary phase and participate in microstructure construction. The advantage of AIN is mainly reflected in thermal management under high-power excitation. Laser tests show that increasing AIN content can reduce the surface temperature rise of the ceramic, but fluorescence intensity, luminous flux, and luminescence efficiency do not increase monotonically with AIN content (Figure 9f–i). Although high-thermal-conductivity secondary phases facilitate heat dissipation, excessive AIN reduces the fraction of the YAG:Ce emitting phase and alters optical scattering and blue-light absorption. AIN/YAG:Ce therefore also has a compositional window; its central trade-off shifts from “color-quality regulation” in Al_2O_3 /YAG:Ce to the balance between “thermal-conductivity enhancement and preservation of the emitting phase.”

Cheng et al. recently further advanced the photothermal co-design of AIN-YAG:Ce ceramics [205]. In this work, multiphase ceramics with different AIN volume fractions were prepared by powder-embedded sintering under a nitrogen atmosphere, and

their densification, interfacial structure, thermal conductivity, and device output were systematically analyzed. The sample density and relative density varied with AlN content, indicating that AlN is not merely a high-thermal-conductivity filler, but also affects the ceramic sintering behavior (Figure 9j,k). XRD results showed that the characteristic peaks of AlN became stronger with increasing AlN content, whereas the $\text{Al}_5\text{O}_6\text{N}$ secondary phase appeared at high AlN contents (Figure 9l), further confirming the risk of interfacial reactions between AlN and YAG: Ce. Transmission electron microscopy-energy-dispersive x-ray spectroscopy (TEM-EDS) analysis directly revealed elemental distribution and local diffusion at the AlN/YAG: Ce interface (Figure 9m), indicating that the interface serves not only as a heat-transfer pathway, but also as a potential region for side reactions and defect formation. From the performance perspective, the results of Cheng et al. further demonstrate that the “highest thermal conductivity” does not necessarily correspond to the “best device output.” An appropriate amount of AlN can enhance blue-light absorption and EQE, whereas excessive AlN reduces the fraction of the YAG: Ce emitting phase and increases the influence of secondary phases (Figure 9n,o). The thermal conductivity of the 50 vol% AlN-YAG: Ce sample reached $27.2 \text{ W m}^{-1} \text{ K}^{-1}$, markedly higher than that of YAG: Ce ceramics. However, better luminescence efficiency and a suitable CCT were obtained in the 10 vol% AlN-YAG: Ce sample (Figure 9p-r). A further 10 W blue-laser device demonstration showed that the optimized AlN-YAG: Ce ceramic enabled long-distance white-light illumination (Figure 9s). These results indicate that the true value of AlN/YAG: Ce lies not merely in increasing material thermal conductivity, but in improving the power-handling capability of laser lighting through the combined control of high-thermal-conductivity phases, scattering effects, emitting-phase fraction, and interfaces.

Taken together, the work of Fujioka et al. established a feasible preparation route for AlN/YAG: Ce multiphase ceramics and clarified the effect of AlN content, whereas the work of Cheng et al. further revealed interfacial reactions, photothermal coupling and device-application potential in AlN/YAG: Ce [205]. These studies collectively show that high-thermal-conductivity secondary phases can overcome the heat-dissipation limitations of conventional oxide-based multiphase ceramics but also introduce more complex issues of phase stability and interfacial chemistry. Future development of AlN/YAG: Ce should focus on suppressing AlN oxidation and the formation of $\text{Al}_5\text{O}_6\text{N}$ /AlON secondary phases, constructing continuous low-thermal-resistance heat-diffusion pathways, and maintaining a sufficient fraction of the YAG: Ce emitting phase together with stable white-light color quality. This logic also lays the foundation for the subsequent development of multiphase composites, layered architectures, and spatial thermal-management ceramics.

4.4 | ZrO_2 , MgAl_2O_4 , and Multiphase Composite Systems: Interfaces, Scattering, and Mechanical Stability

In Al_2O_3 /YAG: Ce and AlN/YAG: Ce multiphase ceramics, secondary phases are mainly used to regulate scattering or enhance heat diffusion. However, ceramic converters for high-power LD lighting must also withstand local temperature rise, thermal cycling and packaging stress. Interfacial stability, thermal-

expansion matching and mechanical reliability are therefore equally critical. The significance of ZrO_2 , MgAl_2O_4 , and other multiphase composite systems lies in their ability to introduce functional phases with different refractive indices, thermal-expansion coefficients, and mechanical properties, thereby enabling further co-regulation of photon propagation, interfacial structure and service stability [206, 207].

The ZrO_2 - Al_2O_3 -YAG: Ce ternary ceramics reported by Chen et al. demonstrate the role of a third phase in spectral and interfacial regulation [41]. As shown in Figure 10a,b, YAG, Al_2O_3 , and ZrO_2 can coexist stably in the ceramic. SEM and EDS results further show that Zr, Al, and Y elements form relatively independent spatial distributions (Figure 10c). Such multiphase interfaces not only modify the scattering pathways of blue and yellow light but may also influence the local environment around Ce^{3+} . With increasing ZrO_2 content, the Ce^{3+} emission peak redshifts from approximately 535 nm to 560–570 nm (Figure 10d), partially compensating for the insufficient red component of conventional YAG: Ce. Device results show that white LEDs packaged with ZrO_2 - Al_2O_3 -YAG: Ce (ZA-YAG: Ce) achieve a higher CRI and warmer white-light output (Figure 10e,f), indicating that ZrO_2 functions more as a spectral-modification and interface-regulation phase than as a simple inert filler.

MgAl_2O_4 -based multiphase ceramics place greater emphasis on scattering regulation and structural stability. MgAl_2O_4 has a wide bandgap, good chemical stability, and high mechanical strength, and its refractive index and thermal-expansion behavior differ from those of garnet phases. It can therefore serve as an interfacial regulation phase and mechanical-support phase in YAG: Ce-based ceramics. When MgAl_2O_4 is uniformly distributed and well bonded at the interface, it can form moderate scattering centers, increase the effective optical path of blue light and improve luminescence uniformity [208, 209]. However, excessive interfacial defects or thermal-expansion mismatch can introduce additional scattering losses and thermal-stress concentration. The key to MgAl_2O_4 /YAG: Ce-type systems is therefore not to increase the secondary-phase fraction, but to control interfacial quality, grain size, and phase continuity [210, 211].

Multiphase compositing can also improve photothermal distribution in laser lighting through functional regional integration. Sang et al. designed Al_2O_3 -YAG: Ce/YAG composite ceramics by combining a luminescent conversion region with a transparent YAG support region for transmissive blue-LD lighting (Figure 10g-i) [212]. In this architecture, Al_2O_3 -YAG: Ce is responsible for blue-light absorption and yellow-light conversion, whereas transparent YAG provides optical transmission, heat diffusion, and mechanical support. Compared with randomly mixed multiphase ceramics, this structure more closely matches device requirements and reflects a development trend from multiphase coexistence toward functional zoning.

Overall, ZrO_2 , MgAl_2O_4 , and related multiphase composite systems advance multiphase ceramic design from “secondary-phase content optimization” to “interfacial function regulation.” ZrO_2 mainly contributes to spectral modification and warm-white tuning, MgAl_2O_4 emphasizes scattering regulation and mechanical stability, and multiregion composite structures further separate the functions of luminescence, scattering, heat conduction, and

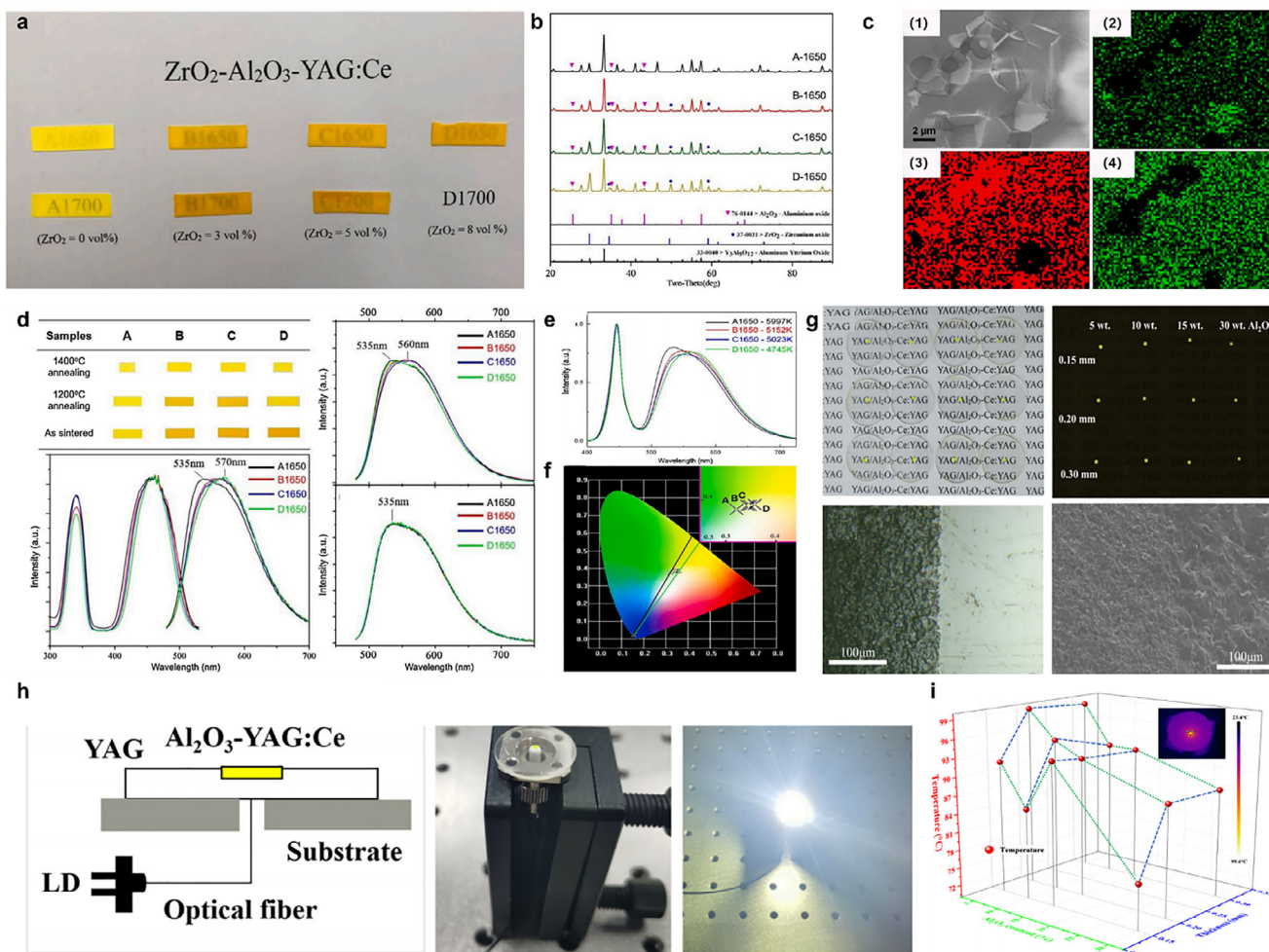


FIGURE 10 | Interface regulation, spectral reconstruction, and device-level design in ternary and multiphase YAG: Ce-based composite ceramics. (a) Photographs of $\text{ZrO}_2\text{-Al}_2\text{O}_3\text{-YAG:Ce}$ ceramics with different ZrO_2 contents sintered at 1650°C and 1700°C. (b) XRD patterns of ZA-YAG: Ce ceramics, confirming the coexistence of YAG, Al_2O_3 , and ZrO_2 phases. (c) SEM image and corresponding EDS elemental mappings of ZA-YAG: Ce ceramics. (d) Photographs and normalized PL/PLE spectra of ZA-YAG: Ce ceramics before and after air annealing, showing the ZrO_2 -induced red-shift of Ce^{3+} emission. (e) Electroluminescence spectra of white LEDs fabricated with ZA-YAG: Ce ceramic converters. (f) CIE chromaticity coordinates of the corresponding white LED devices. Reproduced with permission from literature [41]. Copyright 2020, Published by Elsevier Ltd. (g) Photographs, optical transmission micrograph, and SEM image of $\text{Al}_2\text{O}_3\text{-YAG:Ce/YAG}$ composite ceramic phosphors. (h) Schematic and photographs of the transmissive LD lighting device based on $\text{Al}_2\text{O}_3\text{-YAG:Ce/YAG}$ composite ceramics. (i) Temperature distribution and laser-spot temperature of $\text{Al}_2\text{O}_3\text{-YAG:Ce/YAG}$ composite ceramics under high-power blue LD excitation. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [212]. Copyright 2022, The Author(s). Optica Publishing Group.

mechanical support. Future systems of this type must simultaneously optimize optical scattering, interfacial thermal resistance and thermomechanical reliability to meet the requirements of high-power laser lighting for high LE, stable color quality, and long-term operation.

4.5 | Layered, Graded, and Spatially Architected Ceramics: From Material Composites to Structural Design

In high-power LD lighting, blue-light incidence, luminescence conversion, heat generation, and light-extraction direction, all exhibit pronounced spatial characteristics. If the luminescent, scattering, and thermally conductive phases are only randomly mixed, it is difficult to simultaneously achieve strong blue-light

absorption, high forward light extraction, low temperature rise, and a uniform color field. The core concept of layered, graded, and spatially architected ceramics is therefore to deliberately arrange different functional regions within the ceramic, enabling the co-design of photon-propagation and heat-diffusion pathways.

The layered $\text{Al}_2\text{O}_3\text{/YAG:Ce}$ composite ceramics reported by Wang et al. exemplify the transition from randomly mixed multiphase systems to structurally organized composites [136]. Figure 11a shows that layered interfaces can regulate the propagation pathways of blue and yellow light and reduce lateral losses caused by total internal reflection. Figure 11b further reveals a well-defined layered structure and a closely bonded $\text{Al}_2\text{O}_3\text{/YAG:Ce}$ interface. For transmissive laser lighting, this interface functions both as a scattering-regulation unit and as a heat-transfer pathway; thus, layer thickness, interfacial

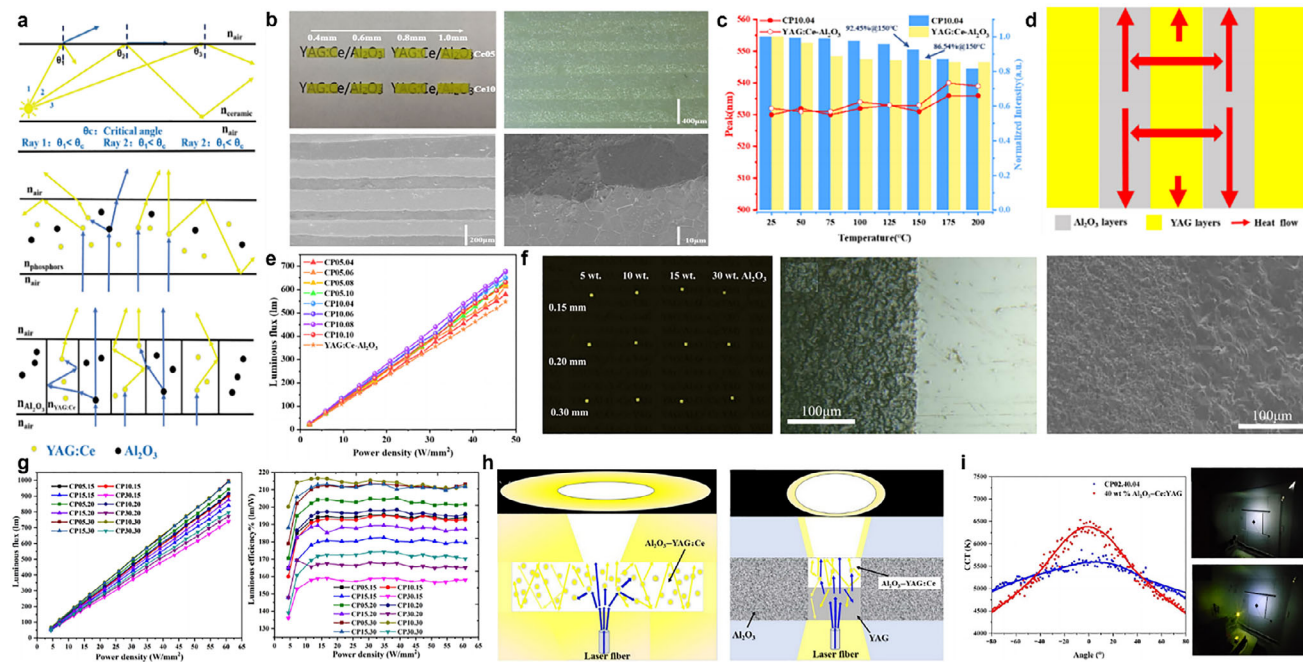


FIGURE 11 | Layered and spatially partitioned composite ceramic phosphors for optical-path regulation, thermal management, and color-field homogenization. (a) Total internal reflection and internal light-propagation pathways in laminated $\text{Al}_2\text{O}_3/\text{YAG:Ce}$ composite ceramic phosphors. (b) Optical appearance, transmission micrograph, laminated cross-section, and interfacial SEM images of laminated $\text{Al}_2\text{O}_3/\text{YAG:Ce}$ ceramics. (c) Temperature-dependent emission peak position and normalized PL intensity of laminated $\text{Al}_2\text{O}_3/\text{YAG:Ce}$ ceramic and conventional $\text{YAG:Ce}-\text{Al}_2\text{O}_3$ composite ceramic. (d) Heat-flow model of the laminated $\text{Al}_2\text{O}_3/\text{YAG:Ce}$ structure. (e) Forward luminous flux of laminated $\text{Al}_2\text{O}_3/\text{YAG:Ce}$ ceramics under different laser power densities. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [136]. Copyright 2023, The Author(s). Optica Publishing Group. (f) Optical appearance, blue-light-excited emission regions, transmission micrograph, and interfacial SEM image of $\text{Al}_2\text{O}_3-\text{YAG:Ce}/\text{YAG}$ composite ceramic phosphors. (g) Luminous flux and LE of $\text{Al}_2\text{O}_3-\text{YAG:Ce}/\text{YAG}$ composite ceramic phosphors under different laser power densities. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [212]. Copyright 2022, The Author(s). Optica Publishing Group. (h) Light-path comparison between a conventional parallel ceramic phosphor and an optimized $\text{Al}_2\text{O}_3/\text{Al}_2\text{O}_3-\text{YAG:Ce}/\text{YAG}$ composite-structured ceramic. (i) Spatial CCT distribution and irradiation patterns of $\text{Al}_2\text{O}_3/\text{Al}_2\text{O}_3-\text{YAG:Ce}/\text{YAG}$ composite-structured ceramic and conventional $\text{Al}_2\text{O}_3/\text{YAG:Ce}$ ceramic. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [45]. Copyright 2024, The Author(s). Published by Tsinghua University Press.

quality, and phase-region continuity are key determinants of performance. The photothermal advantages of layered structures are further illustrated in Figure 11c–e. Figure 11c shows that layered $\text{Al}_2\text{O}_3/\text{YAG:Ce}$ maintains relatively high PL intensity during heating. The heat-flow model in Figure 11d indicates that the Al_2O_3 layer facilitates both lateral and vertical heat diffusion, reducing local heat accumulation in the emitting layer. Figure 11e further shows that the forward luminous flux of this layered ceramic continues to increase under different laser power densities. These results demonstrate that layered architectures can mitigate the common trade-off in conventional multiphase ceramics, namely enhancing scattering at the expense of forward light extraction.

Separation of the emitting region from the transparent support region represents another important spatial architecture. Sang et al. designed $\text{Al}_2\text{O}_3-\text{YAG:Ce}/\text{YAG}$ composite ceramics by integrating an $\text{Al}_2\text{O}_3-\text{YAG:Ce}$ luminescent conversion region with a transparent YAG region [212]. Figure 11f shows a clear and tightly bonded interface between the two regions: $\text{Al}_2\text{O}_3-\text{YAG:Ce}$ is responsible for blue-light absorption and yellow-light conversion, whereas transparent YAG provides optical transmis-

sion, heat diffusion and mechanical support. Figure 11g further shows that this architecture delivers high luminous flux and LE under different laser power densities, indicating that transparent YAG is not merely an inert phase, but a functional region that participates in device-level photothermal management. Furthermore, $\text{Al}_2\text{O}_3/\text{Al}_2\text{O}_3-\text{YAG:Ce}/\text{YAG}$ composite ceramics advance spatial design toward color-field homogenization [45]. Figure 11h compares the laser interaction pathways in conventional parallel ceramic converters and optimized composite-structured ceramics, showing that multiregion integration can redistribute blue-light propagation and yellow-emission pathways. Figure 11i shows that the optimized structure provides a smoother spatial CCT distribution and a more uniform illumination spot. These results indicate that spatially architected ceramics should not be evaluated only by luminous flux and LE; angularly dependent color temperature and practical illumination patterns should also be considered.

Overall, layered, graded, and spatially architected ceramics represent the transition of multiphase phosphor ceramics from “phase-composition optimization” to “device-scale structural design.” Future work in this direction should focus on controlling layer

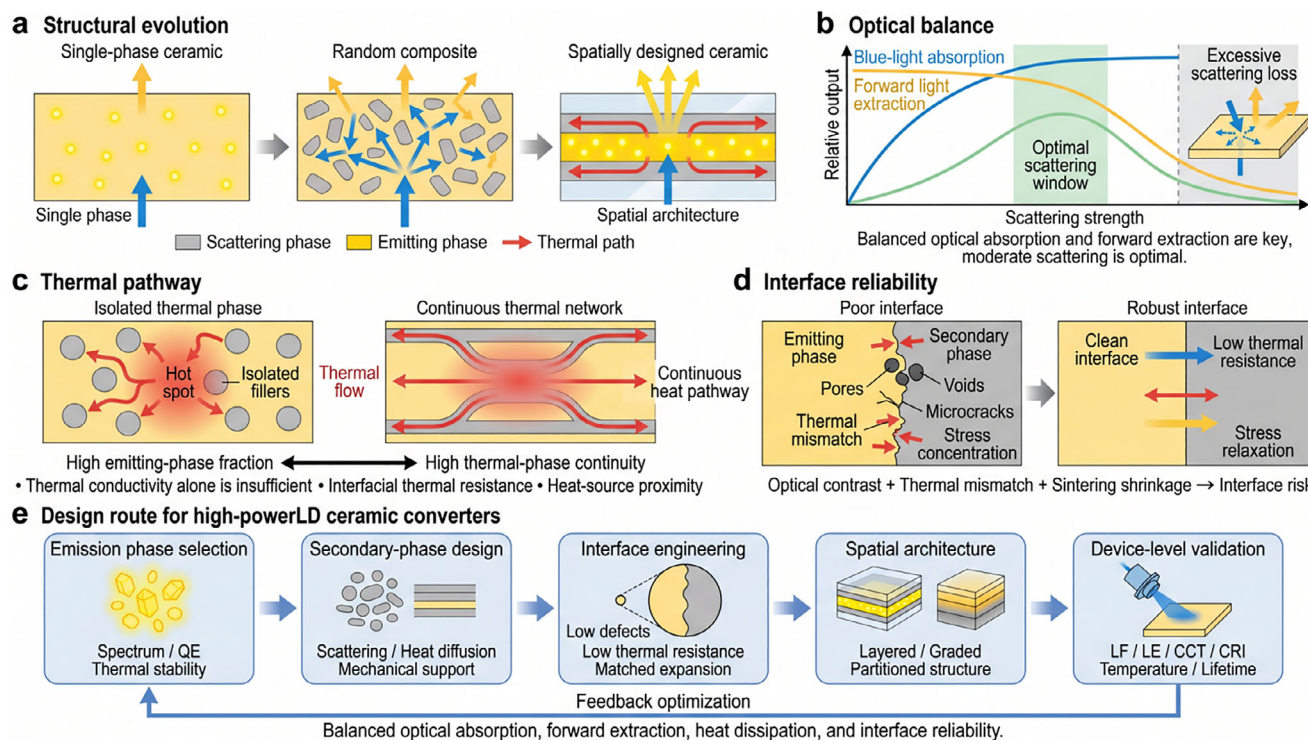


FIGURE 12 | Design principles and performance boundaries of multiphase phosphor ceramics under high-power LD excitation. (a) Structural evolution of multiphase phosphor ceramics. (b) Optical balance among scattering, absorption, and forward light extraction. (c) Thermal pathway design in composite ceramics. (d) Interface reliability and thermomechanical stability. (e) Integrated design route for high-power LD ceramic converters.

thickness, phase-region position, interfacial thermal resistance, refractive-index matching, and thermal-expansion matching, so that blue-light absorption, luminescence conversion, forward light extraction, heat diffusion, and mechanical support can operate cooperatively within a single ceramic architecture.

4.6 | Performance Boundaries and Design Principles of Multiphase Ceramics

The value of multiphase phosphor ceramics lies in their ability to overcome the photothermal performance limits of single-phase ceramics under high-power LD excitation. Single-phase YAG: Ce, LuAG: Ce and GAGG: Ce ceramics provide good chemical stability and reliable luminescence, but offer limited freedom in regulating photon propagation, heat diffusion, and color quality. After introducing secondary or tertiary phases such as Al_2O_3 , AlN, ZrO_2 , and MgAl_2O_4 , scattering, heat conduction, interfacial structure, and mechanical response inside the ceramic can all be reconfigured. Multiphase ceramics are therefore not simple mixtures of “emitting phase plus inert phase,” but materials platforms for coupled optical–thermal–mechanical regulation through phase composition and spatial architecture (Figure 12a).

The core of optical regulation is the moderation of scattering strength. Moderate scattering can extend the propagation path of blue light inside the ceramic, thereby improving excitation-light absorption and luminescence uniformity. Excessive scattering, however, reduces forward light extraction, causing optical-extraction loss and reduced brightness (Figure 12b). High transparency does not necessarily guarantee high output, and strong

scattering does not necessarily lead to high LE. For transmissive LD lighting, the ideal architecture should balance blue-light absorption, yellow-light conversion, and forward light extraction, rather than pursuing transmittance or room-temperature emission intensity alone.

Thermal management determines whether multiphase ceramics can maintain stable output under high-power excitation. Al_2O_3 can improve thermal stability and scattering distribution, AlN can markedly enhance thermal conductivity, and support phases such as transparent YAG or sapphire can provide heat-diffusion pathways. However, the introduction of high-thermal-conductivity phases can also dilute the emitting phase, and excessive secondary-phase content may reduce blue-light absorption and luminescence efficiency (Figure 12c). Thermal design in multiphase ceramics should therefore not be based solely on numerical thermal conductivity values; it should also consider whether the thermally conductive phase forms effective pathways, whether the heat source is close to the heat-dissipation route, and whether interfacial thermal resistance is controllable.

Interfacial stability determines whether multiphase ceramics can operate reliably over long periods. Different phases usually differ in refractive index, coefficient of thermal expansion, and sintering shrinkage. These differences can help regulate scattering, but may also generate residual stress, microcracks, and interfacial thermal resistance (Figure 12d). Under cyclic high-power LD excitation, local temperature rise can amplify the mechanical risks associated with interfacial mismatch. The evaluation of multiphase ceramics should therefore extend beyond luminous flux and LE to include thermal-shock resistance, interfacial bonding strength,

long-term photothermal stability, and chromaticity-coordinate drift.

The development of multiphase ceramics is moving from “compositional optimization” toward “structural design.” Randomly mixed multiphase ceramics mainly regulate scattering and heat diffusion through secondary-phase content. Ternary ceramics further introduce spectral modification and interfacial regulation. Layered, graded, and spatially architected ceramics then enable functional partitioning among emitting regions, scattering regions, heat-conduction regions, and support regions. Figure 12e summarizes the design route for high-performance multiphase phosphor ceramics: the luminescent phase defines the spectral basis, secondary phases regulate scattering and heat diffusion, interface control reduces losses and failure risks, and device testing validates luminous flux, LE, CCT, CRI, temperature, rise and long-term stability.

Overall, the performance boundaries of multiphase phosphor ceramics are not determined by any single parameter, but are jointly defined by light absorption, light extraction, heat diffusion, interfacial reliability, and device architecture. Future design of high-power light-conversion ceramics should avoid a one-sided pursuit of high transmittance, high thermal conductivity or high emission intensity, and should instead establish an integrated evaluation framework oriented toward realistic LD operating conditions. Only by co-designing emitting, scattering, thermally conductive, and supporting phases across both materials and device scales can multiphase phosphor ceramics achieve high LE, high brightness, stable color quality, and long-term reliable output.

5 | Multicolor Visible Phosphor Ceramics and Full-Spectrum Reconstruction

5.1 | Spectral Compensation for High Color Rendering and Warm White Light

Chapter 4 focuses on scattering regulation, heat diffusion, interfacial stability, and spatial architecture in multiphase ceramics, with the central question of how phosphor ceramics can maintain stable output under high-power LD excitation. With the development of Al_2O_3 , AlN , ZrO_2 , MgAl_2O_4 , and layered composite architectures, ceramic converters are no longer merely luminescent materials; they are evolving into inorganic light-conversion platforms capable of sustaining high heat flux, high luminous flux, and complex optical pathways. Building on this foundation, Chapter 5 addresses a second key question: once ceramics can withstand high-power excitation, how can spectral compensation be used to achieve higher color rendering, lower color temperature, and white-light output closer to natural light. Figure 13a summarizes this conceptual transition from “photothermal structural design” to “multicolor spectral reconstruction.”

Conventional YAG: Ce ceramics generate broad-band yellow emission under blue LED/LD excitation, which mixes with residual blue light to produce white output. This system has long served as a central platform for white ceramic converters because of its high efficiency, high stability, and mature processing basis.

However, the spectral distribution of YAG: Ce-based white light is not continuous, often showing pronounced deficiencies in the cyan region at 480–500 nm and the red region at 600–650 nm. As illustrated in Figure 13b, these spectral gaps limit high CRI, strong R₉ value and warm-white output, and also create a mismatch between the resulting illumination and sunlight or blackbody radiation targets. The further development of visible phosphor ceramics should therefore not focus solely on strengthening yellow-emitting YAG: Ce but should instead pursue more complete visible-spectrum coverage through red, cyan, and green compensation.

Different compensation bands serve distinct functions. Red ceramics mainly compensate for the 600–650 nm region, lowering CCT, increasing R₉, and improving warm-white quality. Cyan ceramics compensate for the 470–500 nm region, filling the cyan gap in conventional blue/YAG: Ce white light and improving spectral continuity and visual fidelity. Green ceramics, located in the 520–550 nm region, help regulate the spectral center of gravity and color saturation in laser displays, projection systems, and multichannel white-light reconstruction. As shown in Figure 13c, the design of high-quality white-light ceramics should move beyond the simple “blue + yellow” scheme toward a multi-band cooperative system consisting of blue excitation, yellow main conversion, and red/cyan/green compensation. Spectral compensation does not mean simply increasing a single color component. Excessive red emission causes large Stokes losses and reduces LE; insufficient cyan compensation weakens solar-like spectral continuity; and green emission that is too narrow or too intense may shift chromaticity coordinates and visual hue. High-color-rendering warm-white ceramics therefore require a balance among CCT, CRI, R₉, distance from the Planckian locus (DUV) and LE. As shown in Figure 13d, ideal spectral design should not maximize a single metric, but should achieve a practical optimum among color quality, energy efficiency, and thermal stability for real devices.

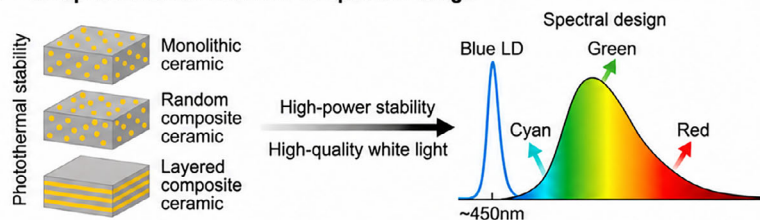
From the perspective of material architecture, multicolor compensation ceramics can be integrated through different structural formats. Monolithic composite ceramics are compact, but reabsorption and thermal coupling may occur among different luminescent centers. Stacked ceramics enable spatially separated control of absorption and emission, but interfacial reflection and thermal resistance must be minimized. Patterned ceramics can reconstruct spectra by adjusting the area ratio of different color regions. Rotating ceramic color wheels are more suitable for high-power laser displays and projection applications (Figure 13e). These structural strategies connect naturally with the multiphase and spatially architected ceramics discussed in Chapter 4, showing that multicolor visible ceramics are not merely a luminescent-material issue, but a problem of integrated spectral, structural, and device design.

5.2 | Eu^{2+} -Activated Red Ceramics: Oxide, Nitride, and Aluminosilicate Systems

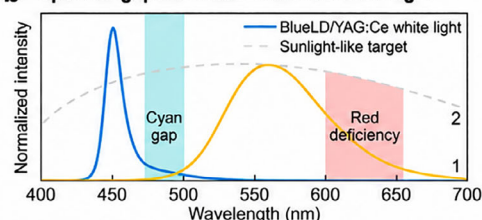
Eu^{2+} -activated red ceramics are among the most critical compensation materials for high-color-rendering warm-white LD lighting. Compared with YAG: Ce yellow ceramics, the 4f–5d transition of Eu^{2+} is more sensitive to the local crystal field,

Spectral-compensation logic for high-color-rendering and warm-white phosphor ceramics

a From photothermal structure to spectral design



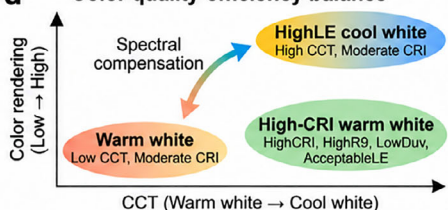
b Spectral gaps in blueLD/YAG:Ce white light



c Multiband compensation channels



d Color quality-efficiency balance



e Integration modes of multicolor ceramic converters

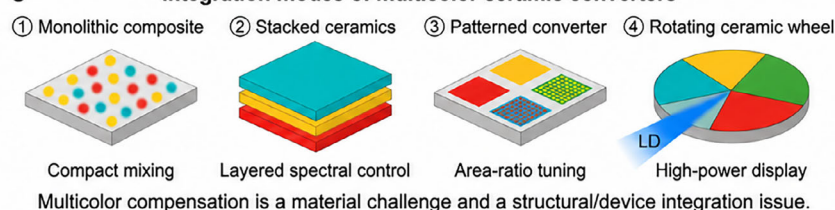


FIGURE 13 | Spectral-compensation logic for high-color-rendering and warm-white phosphor ceramics. (a) Transition from photothermal structural design to multiband spectral design. (b) Spectral gaps of conventional blue-LD/YAG: Ce white light relative to a sunlight-like target. (c) Cyan, green, yellow, and red compensation channels across the visible spectrum. (d) Color-quality and luminous-efficacy balance for high-CRI warm-white emission. (e) Integration modes of multicolor ceramic converters, including monolithic composites, stacked ceramics, patterned converters, and rotating ceramic wheels.

coordination environment, and structural rigidity, enabling the emission peak, bandwidth, and thermal stability to be tuned through host-structure design [213, 214]. The role of red ceramics is not merely to fill the 600–650 nm spectral region; it is also directly linked to enhanced R_9 , reduced CCT, and improved visual quality of warm white light.

The $\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}:\text{Eu}^{2+}$ (MAS: Eu^{2+}) ceramics reported by Ali et al. demonstrate the potential of channel-type aluminosilicate structures to stabilize Eu^{2+} red emission [215]. As shown in Figure 14a–c, the hollow channels and T_1/T_2 sites in the MAS host provide multiple local luminescent environments for Eu^{2+} , and the vitrification-crystallization process can drive Eu^{2+} from blue/green-emitting sites toward red-dominant sites. Further LD device tests show that MAS: Eu^{2+} ceramics can deliver stable red output under 445 nm laser excitation, together with high luminous flux, luminous efficacy, and output power (Figure 14d–h). These results indicate that the key to oxide/aluminosilicate red ceramics is not simply increasing Eu^{2+} concentration but enhancing red conversion through the combined control of structural channels, valence stability, and site reconstruction.

Yang et al. further extended Eu^{2+} red ceramics to a double-perovskite oxide system [52]. $\text{Sr}_3\text{TaO}_{5.5}:\text{Eu}^{2+}$ (STOE) possesses an ordered double-perovskite framework that provides a stable coordination environment for Eu^{2+} and produces red emission near 620 nm under blue-light excitation (Figure 14i–k). Temperature-dependent results show that the ordered structure exhibits better thermal stability than the disordered structure (Figure 14l), high-

lighting the importance of local structural order in suppressing thermal quenching of Eu^{2+} red emission. White LD devices based on STOE and LuAG: Ce further achieve warm-white output and a relatively high CRI (Figure 14m–p), demonstrating that stable oxide red ceramics can serve as effective red-compensation units in high-color-rendering LD lighting.

Eu^{2+} -activated nitride red ceramics generally provide stronger crystal fields and higher covalency, making them important systems for deep-red and red compensation. The $\text{Sr}_{0.5}\text{Ca}_{0.5}\text{AlSiN}_3:\text{Eu}^{2+}$ (SCASN: Eu^{2+}) ceramics reported by Tian et al. exhibit strong red output under high-power excitation [216]. Figure 15a–c shows that SCASN: Eu^{2+} ceramics produce broad-band red emission under blue-light excitation, with luminous flux and luminance increasing as the laser power density rises, demonstrating their potential as high-power red-conversion ceramics. Compared with oxide red ceramics, SCASN: Eu^{2+} offers stronger red-compensation capability, but its ceramic processing requires stricter control of surface oxidation, phase stability, and sintering-induced damage.

The cordierite-type $\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}:\text{Eu}^{2+}$ (MAS: Eu^{2+}) ceramics reported by Chen et al. provide a materials platform closer to device-level application for red ceramics [56]. Photoluminescence excitation/photoluminescence (PLE/PL) spectra and temperature-dependent emission results indicate that the rigid cordierite framework can stabilize Eu^{2+} luminescent centers and maintain strong red output at elevated temperatures (Figure 15d,e). For high-power LD applications, this ceramic

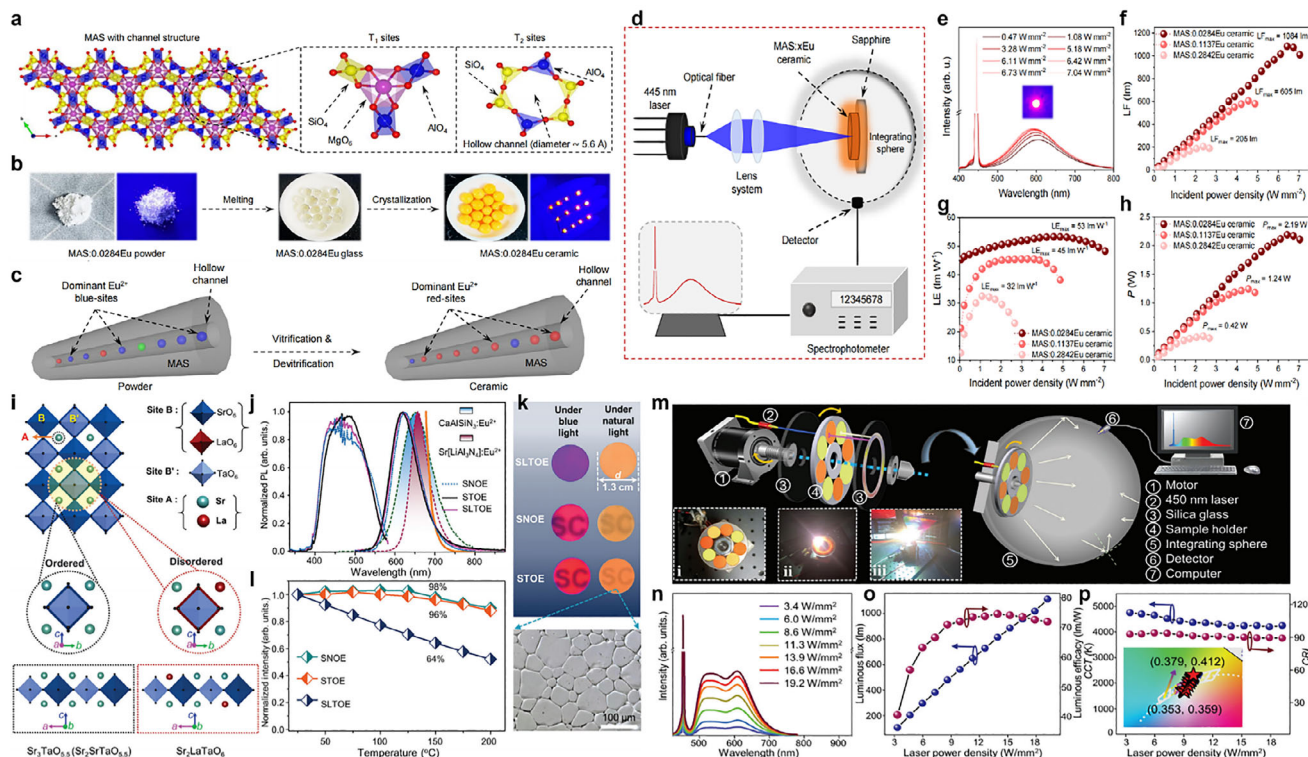


FIGURE 14 | Eu^{2+} -activated oxide red-emitting ceramics for laser-driven warm-white lighting. (a) Channel structure of MAS and local T_1/T_2 coordination environments. (b) Powder, glass, and ceramic states of MAS: Eu^{2+} under daylight and UV excitation. (c) Redistribution of Eu^{2+} emission sites during vitrification and devitrification. (d) LD-driven red-emitting device configuration based on MAS: Eu^{2+} ceramic. (e) Power density-dependent emission spectra of MAS: Eu^{2+} ceramic. (f) Luminous flux, (g) luminous efficacy, and (h) output power of MAS: Eu^{2+} ceramic under 445 nm laser excitation. Reproduced with permission. Reproduced under the terms of the CC-BY-NC-ND Creative Commons Attribution 4.0 International license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>) [315]. Copyright 2026, The Author(s). Published by Springer Nature. (i) Ordered and disordered double-perovskite structures for Eu^{2+} -activated oxide ceramics. (j) PLE/PL spectra, (k) ceramic appearance, and microstructure, and (l) temperature-dependent PL stability of Eu^{2+} -activated double-perovskite ceramics. (m) White LD device configuration using MAS: Eu^{2+} or STO: Eu^{2+} red ceramic and LuAG: Ce ceramic converters. (n) Power-density-dependent emission spectra, (o) luminous flux and luminous efficacy, and (p) CCT, CRI, and CIE chromaticity coordinates of the white LD device. Reproduced with permission from literature [52]. Copyright 2023, Wiley-VCH GmbH.

was further integrated with an AlN substrate to reduce the temperature rise of the emitting layer, while luminous flux, luminous efficacy, and lumen density were tuned by varying film thickness (Figure 15f–j). Further white-LD architectures show that MAS: Eu^{2+} ceramics, when combined with LuAG: Ce green converters, can effectively tune chromaticity coordinates, enhance CRI, and reduce CCT (Figure 15k–n).

Overall, the development of Eu^{2+} -activated red ceramics is shifting from the search for red-emitting hosts to the co-design of valence stabilization, site regulation, and device integration. Channel-type MAS: Eu^{2+} highlights the role of vitrification–crystallization in reconstructing red-emitting sites; STO emphasizes the support of ordered oxide frameworks for thermally stable red emission; SCASN: Eu^{2+} represents the nitride route for strong red compensation; and cordierite-type MAS: Eu^{2+} demonstrates device compatibility in high-power warm-white LDs. Future progress in this direction requires balancing red-emission efficiency, thermal stability, R_0 enhancement, and long-term reliability, while integrating red ceramics with yellow, cyan, and green ceramics to construct high-quality full-spectrum white-light output.

5.3 | Mn^{4+} -Activated Red Light-Conversion Materials: Narrow-Band Emission Advantages and High-Power Stability Limits

The Eu^{2+} -activated red ceramics discussed in the previous section mainly rely on broad-band emission to compensate for the red deficit in white light, making them suitable for improving the CRI and constructing warm-white spectra. However, broad-band red emission often extends into the deep-red region beyond 650 nm, where the contribution to human visual brightness is low and LE is easily penalized. Therefore, in addition to Eu^{2+} -based broad-band red ceramics, red-compensation strategies also require Mn^{4+} -activated red light-conversion materials with narrower emission and higher color purity in order to achieve more precise spectral regulation [217, 218].

Mn^{4+} is typically located in an octahedral coordination environment. Its d3 electronic configuration gives rise to narrow-band red emission through the ${}^2\text{E}_g \rightarrow {}^4\text{A}_2$ transition, with emission maxima usually concentrated in the 620–660 nm range. Because the luminescent energy levels of Mn^{4+} are closely related to the local crystal field and ligand bond length, different fluoride

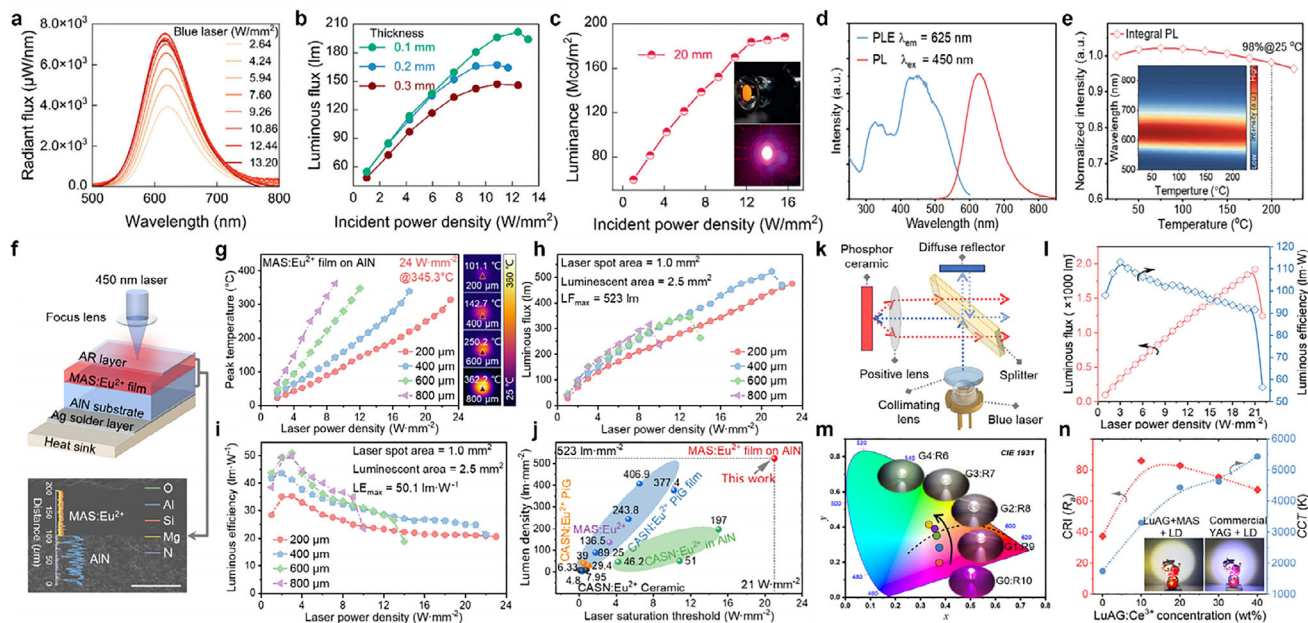


FIGURE 15 | Eu^{2+} -activated nitride and cordierite red-emitting ceramics for high-power laser-driven lighting. (a) Power-density-dependent red emission spectra, (b) luminous flux, and (c) luminance of SCASN: Eu^{2+} ceramics under blue-laser excitation. Reproduced with permission from literature [216]. Copyright 2025, Elsevier Ltd. (d) PLE/PL spectra and (e) temperature-dependent PL stability of MAS: Eu^{2+} cordierite ceramic. (f) Thermal-management structure of MAS: Eu^{2+} film on AlN substrate and corresponding interfacial elemental distribution. (g) Peak temperature, (h) luminous flux, and (i) luminous efficacy of MAS: Eu^{2+} films with different thicknesses under blue-laser excitation. (j) Lumen density and laser-saturation threshold comparison of red-emitting ceramic converters. (k) White laser device configuration based on MAS: Eu^{2+} and LuAG: Ce ceramic converters. (l) Luminous flux and luminous efficacy, (m) CIE chromaticity coordinates, and (n) CRI and CCT of the white laser device. Reproduced with permission from literature [56]. Copyright 2023, Wiley-VCH GmbH.

hosts exhibit similar but not identical red spectral signatures (Figure 16a–c) [219]. Typical materials include K_2SiF_6 : Mn^{4+} , K_2GeF_6 : Mn^{4+} , K_2TiF_6 : Mn^{4+} and Rb_2SiF_6 : Mn^{4+} , among which K_2SiF_6 : Mn^{4+} is one of the most representative narrow-band red materials (Figure 16d–i) [220–222]. Compared with Eu^{2+} -based materials, the greatest advantage of Mn^{4+} red emission is not broad spectral coverage, but the ability to precisely supplement the red component with a much narrower band, thereby achieving a better balance between color quality and luminous efficiency.

However, Mn^{4+} -based systems also face clear limitations in high-power applications. Because the Mn^{4+} transition lifetime is typically on the millisecond scale, optical saturation can easily occur under intense blue-light or laser excitation. In addition, common Mn^{4+} -activated fluoride materials generally exhibit weak hygrothermal stability and are difficult to convert directly into stable ceramic bodies through high-temperature sintering. A comparison of saturation thresholds for representative red materials also shows that, although Mn^{4+} -activated fluorides offer narrow-band red emission, their power-handling capability is usually weaker than that of Eu^{2+} - and Ce^{3+} -based red materials (Table 1).

Accordingly, the role of Mn^{4+} red materials in this chapter can be viewed as complementary to Eu^{2+} -activated red ceramics. The Eu^{2+} systems provide broad-band red emission and stronger ceramic-processability, whereas the Mn^{4+} systems provide highly color-pure narrow-band red emission and fine spectral correction

capability. Together, they constitute the two major routes for red compensation. After concluding the discussion of the red spectral region, the next section turns to cyan and green ceramics, because the 500–560 nm region not only determines the spectral continuity of white light, but also directly affects brightness, color gamut, and visual efficiency in laser displays and full-spectrum lighting.

5.4 | Cyan/Green Ceramics: Key Compensation Bands for Laser Displays and Full-Spectrum Lighting

Beyond red compensation, the cyan and green spectral regions are equally critical for high-quality white lighting and laser displays. Conventional blue LD/YAG: Ce or blue-LD/yellow-red phosphor combinations often show a cyan gap in the 480–500 nm region, weakening solar-like spectral continuity and the faithful rendering of cyan-green objects. In the 520–550 nm green region, continued reliance on broad-band Ce^{3+} emission is insufficient to meet the requirements of narrow-band green primaries for high-color-gamut displays. This section therefore focuses on the distinct roles of cyan/green ceramics as spectral compensation components and display-primary units.

Cyan ceramics mainly target full-spectrum lighting. Hu et al. reported $\text{Li}_2\text{CaSiO}_4$: Eu^{2+} ceramics that produce narrow-band cyan emission at approximately 482 nm under 400–405 nm violet excitation, effectively filling the cyan gap in conventional white

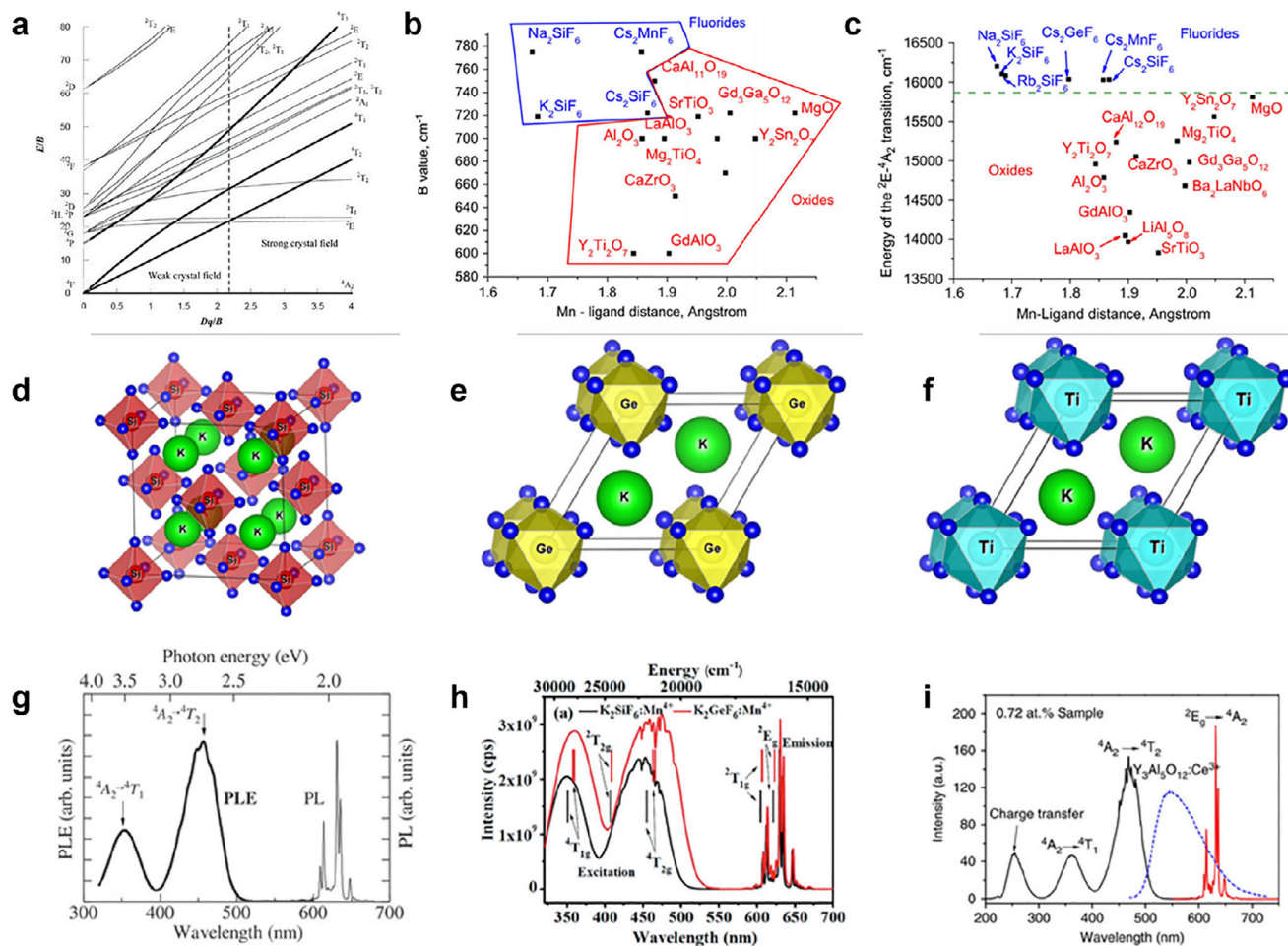


FIGURE 16 | Luminescence mechanism and representative fluoride hosts of Mn^{4+} -activated narrow-band red phosphors. (a) Tanabe-Sugano diagram for a d_3 electronic configuration, showing the crystal-field-dependent energy levels of Mn^{4+} . (b) Relationship between the Racah parameter B and Mn-ligand distance in Mn^{4+} -doped fluorides and oxides. (c) Dependence of the ${}^2\text{E} \rightarrow {}^4\text{A}_2$ transition energy on Mn-ligand distance, comparing fluoride and oxide hosts. Reproduced with permission from literature [219]. Copyright 2013, Elsevier Ltd. (d–f) Crystal structures of K_2SiF_6 , K_2GeF_6 , and K_2TiF_6 , respectively. (g) Photoluminescence excitation and emission spectra of $\text{K}_2\text{SiF}_6:\text{Mn}^{4+}$ at room temperature [220]. Copyright 2008, Electrochemical Society. (h) Excitation and emission spectra of $\text{K}_2\text{SiF}_6:\text{Mn}^{4+}$ and $\text{K}_2\text{GeF}_6:\text{Mn}^{4+}$, compared with calculated Mn^{4+} energy-level positions. Reproduced with permission from literature [221]. Copyright 2016, Royal Society of Chemistry. (i) Excitation and emission spectra of $\text{K}_2\text{TiF}_6:\text{Mn}^{4+}$, with the emission spectrum of commercial YAG: Ce^{3+} shown for comparison. Reproduced with permission from literature [222]. Copyright 2014, Nature Publishing Group.

TABLE 1 | Output luminous flux and luminance saturation threshold of some typical red phosphors.

Phosphors	Activator	Emission peak (nm)	Luminous flux (lm)	Saturation threshold (W/mm^2)
Cs_2TiF_6 single crystal [223]	Mn^{4+}	630		0.1
K_2SiF_6 PiG [224]	Mn^{4+}	630	33	0.56
Rb_2SiF_6 single crystal [225]	Mn^{4+}	630	60	0.04
K_2SiF_6 single crystal [226]	Mn^{4+}	630		0.2985
$\text{CaAlSi}_3\text{N}_3$ PiG [227]	Eu^{2+}	635	29.4	1
$\text{CaAlSi}_3\text{N}_3$ PiG [228]	Eu^{2+}	620	49.3	1.90
$\text{CaAlSi}_3\text{N}_3$ ceramics [153]	Eu^{2+}	655	210	1.5
$\text{AlN}/\text{CaAlSi}_3\text{N}_3$ ceramics [54]	Eu^{2+}	638	32	
$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$ glass [55]	Eu^{2+}	620	273	3.25
HP- CaSiN_2 phosphor film [229]	Ce^{3+}	610	1087	10.89

light (Figure 17a,b) [230]. Under violet-LD driving, these ceramic exhibits stable optical output, small chromaticity-coordinate drift, and good thermal stability. After continuous irradiation for 120 min, the emission intensity shows almost no noticeable degradation (Figure 17c–h). Hu et al. further incorporated this ceramic into multicolor patterned light-conversion structures. The resulting full-spectrum prototype light source achieved a general R_a of 96.5, with R_5 and R_6 values of 98 and 97, respectively, demonstrating that cyan ceramics not only fill the spectral gap but also substantially improve color rendering in the cyan-green region (Figure 17i–k).

Green ceramics are more closely associated with high-color-gamut construction in laser displays. Hu et al. also reported $\text{Al}_2\text{O}_3\text{-LaMgAl}_{11}\text{O}_{19}\text{: Mn}^{2+}$ ($\text{Al}_2\text{O}_3\text{-LMA: Mn}^{2+}$) transparent composite ceramics, which emit green light at 517 nm under 450 nm blue-light excitation with a full width at half maximum (FWHM) of only 24 nm, much narrower than conventional Ce^{3+} broad-band green emission and commercial $\beta\text{-SiAlON: Eu}^{2+}$ green phosphors (Figure 17l) [231]. In this system, the rigid LMA lattice and isolated Mn^{2+} sites help suppress spectral broadening, while the Al_2O_3 secondary phase simultaneously enhances blue-light absorption and heat diffusion. The optimized composite ceramic delivers high green luminous flux, stable chromaticity coordinates, and reduced heat accumulation under high-power blue-LD excitation (Figure 17m–s). A laser display system based on this ceramic achieves 100.8% coverage of Rec. 2020 and exhibits higher green saturation (Figure 17t).

Cyan and green ceramics therefore represent two distinct visible-light compensation strategies. The former improves spectral continuity and color fidelity in full-spectrum lighting by filling the 480–500 nm gap, whereas the latter expands the color gamut of laser displays through narrow-band, high-purity green emission. Together, they drive phosphor ceramics beyond conventional white-light converters toward multicolor light-conversion systems with wavelength-specific functional division.

5.5 | Multicenter Coupling and Energy Transfer: From Single-Band Conversion to Full-Spectrum Reconstruction

The previous section showed that cyan and green ceramics can be used for spectral-gap compensation and high-color-gamut displays, respectively. Practical white lighting, however, does not rely on a single compensation band, but requires multiple luminescent centers or multiple conversion layers to operate cooperatively. The design logic of visible ceramics must therefore move from “single-band compensation” toward “multicenter spectral reconstruction.” The central challenge is how to regulate energy transfer, reabsorption, and spectral ratios simultaneously under high-flux operation.

The $\text{Ca}_3\text{Sc}_2\text{Si}_3\text{O}_{12}\text{: Ce}^{3+}, \text{Mn}^{2+}$ (CSS: $\text{Ce}^{3+}, \text{Mn}^{2+}$) ceramics reported by Wu et al. provide a representative route for spectral tuning through co-doping. Ce^{3+} generates cyan-green emission under blue-light excitation, whereas Mn^{2+} introduces yellow and red emission [232]. Because the Ce^{3+} emission overlaps spectrally with the Mn^{2+} excitation, $\text{Ce}^{3+} \rightarrow \text{Mn}^{2+}$ energy transfer occurs

in this system (Figure 18a,b). As the Mn^{2+} content increases, the Ce^{3+} lifetime gradually decreases and the energy-transfer efficiency increases, shifting the ceramic emission from cyan green toward the white-light region and improving the general R_a (Figure 18c–f). Under blue-LD excitation, this co-doped ceramic can produce broad-band white output, although it remains limited by thermal quenching and luminous-flux saturation at high power (Figure 18g,h).

Another route is spatially partitioned compositing. Liao et al. constructed a composite converter combining $\text{CaAlSiN}_3\text{: Eu}^{2+}$ (CASN: Eu) PiGF with YAG: Ce transparent ceramics, integrating the efficient yellow conversion of YAG: Ce with red compensation from CASN: Eu [48]. By adjusting the composition of the red PiGF layer, the spectral ratio, luminous flux, LE, CCT, CRI, and chromaticity coordinates of the composite converter can be continuously tuned (Figure 18i–l). However, multicomponent compositing also introduces new energy-loss pathways. Differences in conversion efficiency between static and rotating modes, changes in absorption efficiency, transient absorption, and time-resolved luminescence results indicate that luminescence saturation under high-power blue-light excitation is not governed solely by thermal quenching, but is also related to excited-state absorption, reabsorption, and optically induced nonlinear quenching (Figure 18m–p).

The key to multicenter ceramics is therefore not simply adding more luminescent components but controlling the direction and distribution of energy flow. Effective full-spectrum reconstruction requires a balance among luminescent-center concentration, energy-transfer efficiency, spatially partitioned architecture, reabsorption pathways and heat-diffusion capability. Energy transfer that is too weak cannot sufficiently compensate the long-wavelength spectrum, whereas excessive energy migration may introduce non-radiative losses. Spatial partitioning can reduce interference among different components, but interfacial thermal resistance and optical losses may become new limiting factors. These issues led directly to the following discussion of bottlenecks and future directions in multicolor visible ceramics.

5.6 | Bottlenecks and Future Directions of Multicolor Visible Ceramics

The red, cyan/green, and multicenter ceramics discussed above show that visible phosphor ceramics have evolved from conventional YAG: Ce yellow converters into all-inorganic spectral-reconstruction platforms spanning multiple wavelength bands [233, 234]. Multicolor design, however, does not mean simply stacking different luminescent components. For high-power LED/LD applications, multicolor visible ceramics still face multiple trade-offs among spectral quality, energy efficiency, and photothermal stability [153, 235]. First, spectral compensation is often accompanied by efficiency loss. Red components can improve CRI and R_g and reduce CCT, but long-wavelength emission introduces larger Stokes losses [236]. Cyan compensation improves solar-like spectral continuity but must be matched with violet- or blue-excitation systems. Narrow-band green emission helps expand display color gamut, but may be limited by absorption strength, quantum efficiency, and ceramic processability. Second, multicomponent compositing can introduce

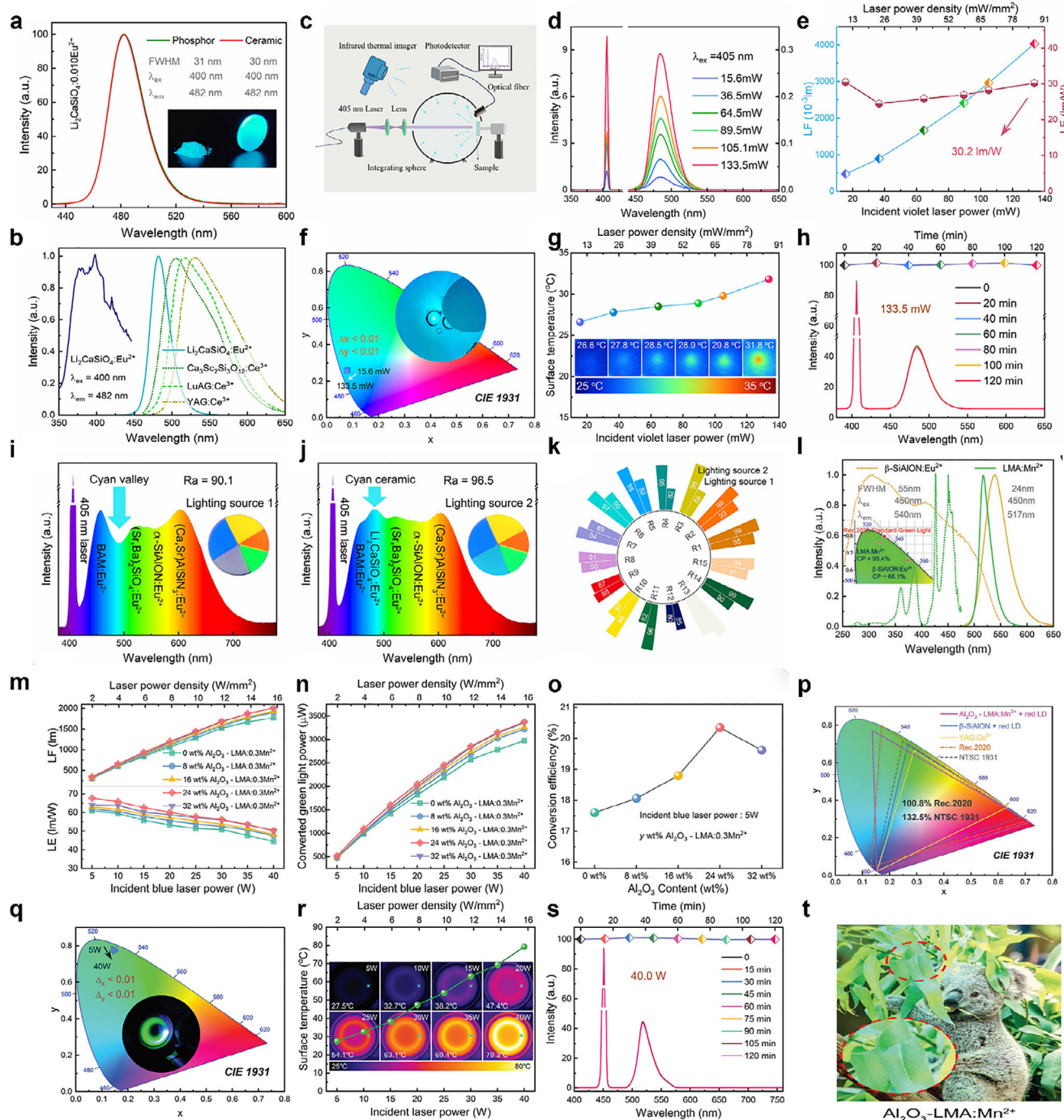


FIGURE 17 | Cyan- and green-emitting ceramic converters for full-spectrum lighting and laser-driven wide-color-gamut display. (a) Photoluminescence spectra and photographs of $\text{Li}_2\text{CaSiO}_4:\text{Eu}^{2+}$ phosphor and ceramic, showing the preservation of narrow cyan emission after ceramic densification. (b) Spectral comparison between $\text{Li}_2\text{CaSiO}_4:\text{Eu}^{2+}$ ceramic and representative Ce^{3+} -activated cyan/green/yellow ceramic phosphors, highlighting its suitability for filling the cyan gap. (c) Schematic configuration for violet-laser-driven optical characterization. (d–h) Laser-power-dependent emission spectra, luminous output, chromaticity coordinates, thermal response, and long-term irradiation stability of $\text{Li}_2\text{CaSiO}_4:\text{Eu}^{2+}$ cyan ceramic under 405 nm excitation. (i–k) Emission spectra, spectral composition, and color-rendering indices of prototype full-spectrum lighting sources with and without cyan-ceramic compensation. Reproduced with permission from literature [230]. Copyright 2025, Wiley-VCH GmbH. (l) Excitation/emission spectra and color coordinates of $\text{Al}_2\text{O}_3\text{-LaMgAl}_{11}\text{O}_{19}:\text{Mn}^{2+}$ transparent composite ceramic compared with commercial $\beta\text{-SiAlON}:\text{Eu}^{2+}$, showing ultra-narrowband green emission. (m–o) Laser-power-dependent luminous flux, luminous efficacy, converted green-light power, and conversion efficiency of $\text{Al}_2\text{O}_3\text{-LMA}:\text{Mn}^{2+}$ ceramics with different Al_2O_3 contents. (p and q) Chromaticity coordinates and color-gamut comparison of laser-driven display systems based on different green converters. (r and s) Thermal images, local temperature evolution, and irradiation stability of $\text{Al}_2\text{O}_3\text{-LMA}:\text{Mn}^{2+}$ ceramic under high-power blue-laser excitation. (t) Demonstration image of the $\text{Al}_2\text{O}_3\text{-LMA}:\text{Mn}^{2+}$ -based laser display, showing enhanced green saturation. Reproduced with permission from literature [231]. Copyright 2024, Wiley-VCH GmbH.

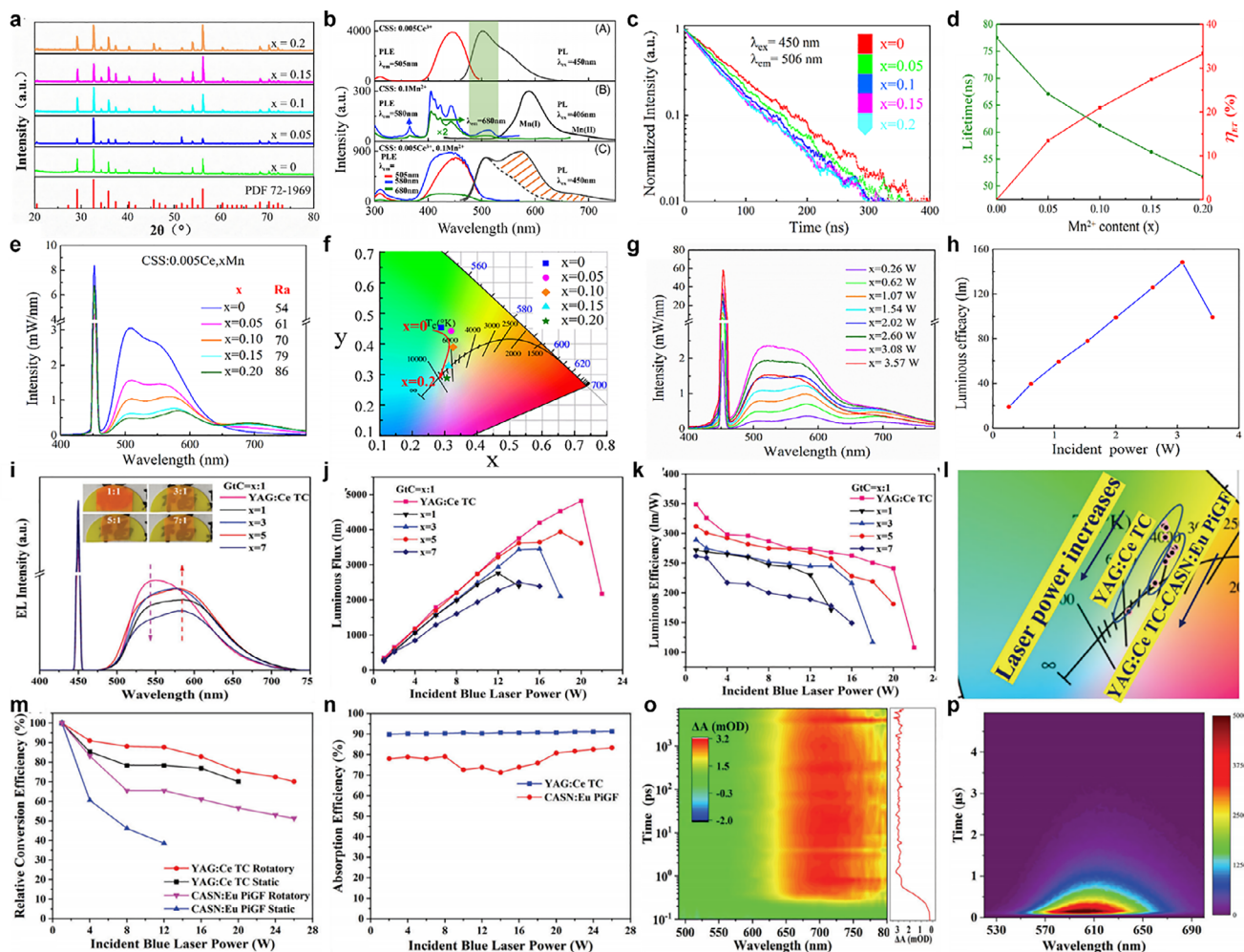


FIGURE 18 | Multicenter coupling, spectral reconstruction, and saturation mechanisms in visible phosphor ceramics and composite converters. (a) XRD patterns of CSS: 0.005Ce³⁺, xMn²⁺ ceramics with different Mn²⁺ contents. (b) PLE and PL spectra of CSS: Ce³⁺, CSS: Mn²⁺, and CSS: Ce³⁺, Mn²⁺ ceramics, showing spectral overlap between Ce³⁺ emission and Mn²⁺ excitation. (c) Decay curves of Ce³⁺ emission monitored at 506 nm under 450 nm excitation. (d) Ce³⁺ lifetime and Ce³⁺→Mn²⁺ energy-transfer efficiency as a function of Mn²⁺ content. (e) Laser-driven electroluminescence spectra of CSS: Ce³⁺, xMn²⁺ ceramics, showing color-tunable emission and improved color rendering. (f) Corresponding CIE chromaticity coordinates. (g) Power-dependent electroluminescence spectra of CSS: 0.005Ce³⁺, 0.2Mn²⁺ ceramic under blue-laser excitation. (h) Luminous flux of CSS: 0.005Ce³⁺, 0.2Mn²⁺ ceramic as a function of incident laser power. Reproduced with permission from literature [232]. Copyright 2024, The American Ceramic Society. (i) Electroluminescence spectra of CASN: Eu PiGF-YAG: Ce transparent ceramic composites with different glass-to-CASN: Eu ratios under blue-laser excitation. (j and k) Laser-power-dependent luminous flux and luminous efficacy of the composite converters. (l) CIE chromaticity coordinates of YAG: Ce transparent ceramic and CASN: Eu PiGF-YAG: Ce transparent ceramic composites. (m) Relative conversion efficiency of YAG: Ce transparent ceramic and CASN: Eu PiGF in static and rotating excitation modes. (n) Absorption efficiency of YAG: Ce transparent ceramic and CASN: Eu PiGF under blue-laser excitation. (o) Femtosecond transient absorption map of YAG: Ce transparent ceramic under 450 nm excitation. (p) Time-resolved photoluminescence map of CASN: Eu PiGF under laser excitation. Reproduced with permission from literature [48]. Copyright 2023, Wiley-VCH GmbH.

reabsorption, interfacial reflection, thermal resistance, and local heat accumulation, making device output no longer determined by a single luminescent center. Under high-power blue-light excitation in particular, luminescence saturation often arises from the combined effects of thermal quenching, optically induced saturation, excited-state absorption, and nonlinear energy loss [237].

Future development of multicolor visible ceramics should proceed in three directions. First, high-stability single-band ceramics should be developed, including efficient Eu²⁺-activated red ceramics, narrow-band Mn⁴⁺/Mn²⁺ emitters, cyan compensation ceramics, and high-color-purity green ceramics, with thermal

quenching suppressed through rigid lattices, isolated luminescent sites, and weak electron-phonon coupling [238]. Second, spatially partitioned and graded composite architectures should be constructed, arranging red, yellow, cyan, and green emitting units according to optical paths and heat-flow distribution to reduce reabsorption and interfacial losses [238, 239]. Third, integrated evaluation frameworks oriented toward real devices should be established, simultaneously comparing luminous flux, luminous efficacy, CRI, R₉, CCT, distance from the DUV, chromaticity-coordinate stability, saturation threshold, and long-term photothermal reliability [240]. Only through simultaneous optimization of spectral design, ceramic microstructure, and device architecture can multicolor visible ceramics move from

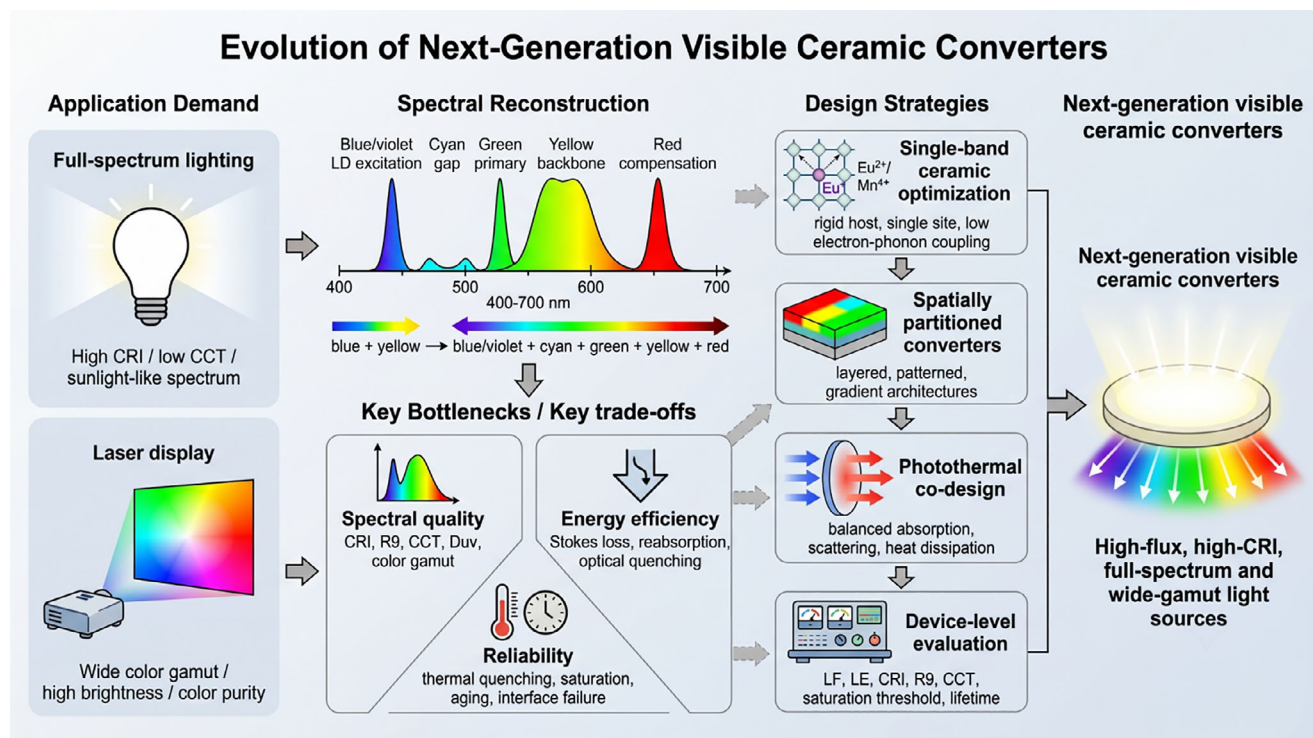


FIGURE 19 | Bottlenecks and future design roadmap of visible multicolor phosphor ceramics.

“high-brightness white light” toward “high-quality full-spectrum and high-color-gamut light sources” (Figure 19).

This development logic also lays the foundation for the next chapter on near-infrared phosphor ceramics. Multicolor visible ceramics mainly serve human-vision-oriented lighting and display, whereas near-infrared ceramics further target non-visual applications such as night vision, bioimaging, food inspection, and intelligent spectral recognition, driving phosphor ceramics from lighting materials toward intelligent light-conversion materials.

6 | Near-Infrared Phosphor Ceramics and Intelligent Light-Source Applications

The preceding chapter discussed how visible phosphor ceramics enable full-spectrum lighting and high-color-gamut displays through red, cyan/green, and multicenter spectral coordination. As application scenarios extend from human vision to machine vision, spectral recognition and biological detection, the functional boundaries of light-conversion materials are further expanding into the NIR region. NIR light offers strong penetration capability, low scattering loss, and rich material fingerprint responses, making it useful for night-vision imaging, biological tissue detection, food analysis, medical diagnostics, and intelligent spectral recognition. Compared with conventional NIR phosphor powders, ceramic forms can withstand higher-power blue-light or laser excitation and improve output power and long-term stability through thermally conductive matrices, controllable scattering, and dense structures [187, 241, 242]. This chapter therefore focuses on NIR luminescent centers such as Cr^{3+} and Ni^{2+} , with emphasis on crystal-field regulation,

broad-band emission mechanisms, photothermal stability, and applications in intelligent NIR light sources based on garnet, spinel, and Ga/Sc-based oxide ceramics.

6.1 | Application Demands and Ceramic Integration of Near-Infrared Converters

Near-infrared light sources represent an important direction for extending phosphor ceramics from visible lighting toward intelligent light conversion. Unlike visible light, which primarily serves human vision, NIR light is more closely associated with non-visual applications such as machine vision, spectral recognition, and biological detection. NIR-I emission in the 700–1000 nm range is relevant to night-vision imaging, security monitoring, food inspection, and portable spectroscopic analysis. NIR-II emission in the 1000–1700 nm range generally experiences lower tissue scattering and can provide deeper penetration in biological media, supporting applications such as bioimaging and deep-tissue optical diagnostics. The broader NIR-II spectral range is also valuable for nondestructive testing and spectroscopic analysis [243, 244]. NIR light-conversion materials therefore require not only broad-band and tunable emission, but also high output power, good thermal stability, and efficient spectral matching with blue LEDs/LDs.

Although conventional NIR phosphor powders have developed rapidly in materials screening and spectral tuning, they are readily limited under high-power excitation by resin ageing, heat accumulation, optical scattering losses, and luminescence saturation. Ceramic integration provides materials better suited to device-level NIR light sources. On the one hand, dense ceramics offer higher thermal conductivity and stronger resistance to

photothermal shock, enabling sustained excitation by blue LDs or high-power LEDs. On the other hand, grains, pores, phase interfaces, and thickness in ceramics can regulate excitation-light absorption, NIR light extraction, and heat-diffusion pathways. In particular, for crystal-field-sensitive luminescent centers such as Cr^{3+} and Ni^{2+} , ceramic matrices can further tune emission peak position, bandwidth, and thermal-quenching behavior through local coordination environments [245–247].

The research focus of NIR phosphor ceramics is therefore not merely the discovery of new NIR-emitting centers, but the establishment of correlations among crystal-field regulation, ceramic microstructure, photothermal stability, and device output. The following sections discuss Cr^{3+} -activated broad-band NIR ceramics, garnet/spinel/gallate systems, Ni^{2+} -activated, and NIR-II emission, and applications in night vision, bioimaging, and spectral recognition.

6.2 | Cr^{3+} -Activated Near-Infrared Ceramics: Crystal-Field Regulation and Broad-Band Emission Mechanisms

Near-infrared light sources require broad emission bands, high output power, and the ability to withstand prolonged high-power excitation from blue LEDs/LDs. Cr^{3+} is currently one of the most widely used activators in NIR phosphor ceramics, owing to its efficient excitation by 450–470 nm blue light and tunable NIR emission across the 650–1200 nm range. Compared with phosphor powders, ceramic forms provide higher thermal conductivity, stronger resistance to photothermal shock and more stable inorganic architectures, making them better suited for high-brightness NIR LED/LD sources [247, 248].

The NIR emission of Cr^{3+} originates from energy-level splitting of its 3d_3 configuration in an octahedral crystal field. Cr^{3+} typically occupies $[\text{MO}_6]$ octahedral sites and forms $[\text{CrO}_6]$ luminescent centers [249, 250]. Its emission type is mainly governed by the D_q/B ratio. When D_q/B is large, the 2E excited state lies lower in energy and the emission is dominated by the narrow-band $^2E \rightarrow ^4A_2$ R line. When the crystal field weakens, the 4T_2 state decreases in energy and the spin-allowed $^4T_2 \rightarrow ^4A_2$ transition is enhanced, producing broad-band NIR emission [251, 252]. Therefore, the broad-band design of Cr^{3+} ceramics is not achieved simply by increasing the Cr^{3+} concentration, but by regulating the crystal-field strength, local distortion, and electron–phonon coupling around $[\text{CrO}_6]$ centers.

The $\text{MgO}:\text{Cr}^{3+}$ translucent ceramics reported by Liu et al. provide a representative mechanism of defect-induced broad-band emission [253]. $\text{MgO}:0.2\%\text{Cr}^{3+}$ produces broad-band NIR emission centered at 810 nm under 460 nm excitation, indicating its direct compatibility with blue-light excitation for NIR light-source construction (Figure 20a). As the Cr^{3+} concentration increases, the emission of $\text{MgO}:\text{Cr}^{3+}$ gradually evolves from a relatively narrow band to broad-band emission (Figure 20b). Further analysis shows that substitution of Cr^{3+} for Mg^{2+} introduces Mg vacancies and forms local defect structures such as $\text{Cr}_{\text{Mg}}^{\bullet}-\text{V}_{\text{Mg}}^{\bullet}-\text{Cr}_{\text{Mg}}^{\bullet}$, distorting the $[\text{CrO}_6]$ octahedra and lowering local symmetry (Figure 20c–f). Thus, the broad-band emission of $\text{MgO}:$

Cr^{3+} does not arise solely from an average weakening of the crystal field, but from the combined effects of vacancy-induced multiple Cr^{3+} local centers, lattice distortion and intercenter energy transfer.

This local-structure regulation can be fully translated into high-power device advantages only in ceramic form. The $\text{MgO}:\text{Cr}^{3+}$ ceramics prepared by Liu et al. exhibit an EQE of 81% and a high thermal conductivity of $52 \text{ W m}^{-1} \text{ K}^{-1}$, far superior to conventional low-thermal-conductivity encapsulation systems (Figure 20g,h) [253]. Under 450 nm blue-laser pumping, the ceramic delivers NIR output power exceeding 6 W, with a light-conversion efficiency of approximately 29%, while maintaining good continuous-operation stability and angular emission uniformity (Figure 20i–l). These results show that NIR ceramics must not only regulate luminescent centers but also rely on high-thermal-conductivity matrices to increase laser saturation thresholds.

Beyond vacancies and local distortion, crystal-field engineering is a general strategy for regulating broad-band Cr^{3+} emission. In $\text{Gd}_3\text{Al}_{2-x}\text{Sc}_x\text{Ga}_3\text{O}_{12}:\text{Cr}^{3+}$ (GASGO: Cr^{3+}) ceramics, Wu et al. weakened the crystal field around Cr^{3+} by substituting Sc^{3+} for Al^{3+} , reducing D_q/B from 2.35 to 1.97, red-shifting the emission peak and increasing the FWHM from 84 nm to 117 nm (Figure 20m,n) [254]. Xiong et al. further demonstrated in $\text{Ga}_{1.98-x}\text{Sc}_x\text{O}_3:0.02\text{Cr}^{3+}$ ceramics that Sc^{3+} incorporation can continuously red-shift the emission peak from 710 nm to 820 nm [63], accompanied by pronounced changes in crystal-field strength and luminescence lifetime (Figure 20o–q). Their temperature-dependent emission, thermal-quenching fitting, and laser-output results show that broad-band red-shifting can expand NIR spectral coverage but may also strengthen electron–phonon coupling and introduce thermal-quenching risks (Figure 20r–t).

The design logic of Cr^{3+} -activated NIR ceramics can therefore be summarized at three levels. First, weakening the crystal field drives the emission transition from narrow-band 2E emission to broad-band 4T_2 emission. Second, vacancies, antisite defects and local distortions can create multiple Cr^{3+} luminescent centers. Third, dense ceramic structures with high thermal conductivity enhance output stability under high-power blue-light or laser excitation. Building on these mechanisms, the next section compares different Cr^{3+} -activated NIR ceramic systems, including garnet, spinel, and Ga/Sc-based oxides, and analyzes their differences in emission bandwidth, thermal stability, output power, and application scenarios.

6.3 | Garnet, Spinel, and Gallate Near-Infrared Ceramics

In Cr^{3+} -activated NIR ceramics, the host structure directly determines the local coordination, crystal-field strength, emission peak, bandwidth, and high-power stability of Cr^{3+} . Garnets, spinels, and gallates are currently three of the most representative ceramic matrices. Garnet systems provide a mature ceramic-processing foundation and relatively high luminescence efficiency. Spinel systems allow the local environment of Cr^{3+} to be tuned through antisite defects and vacancies. Gallate systems

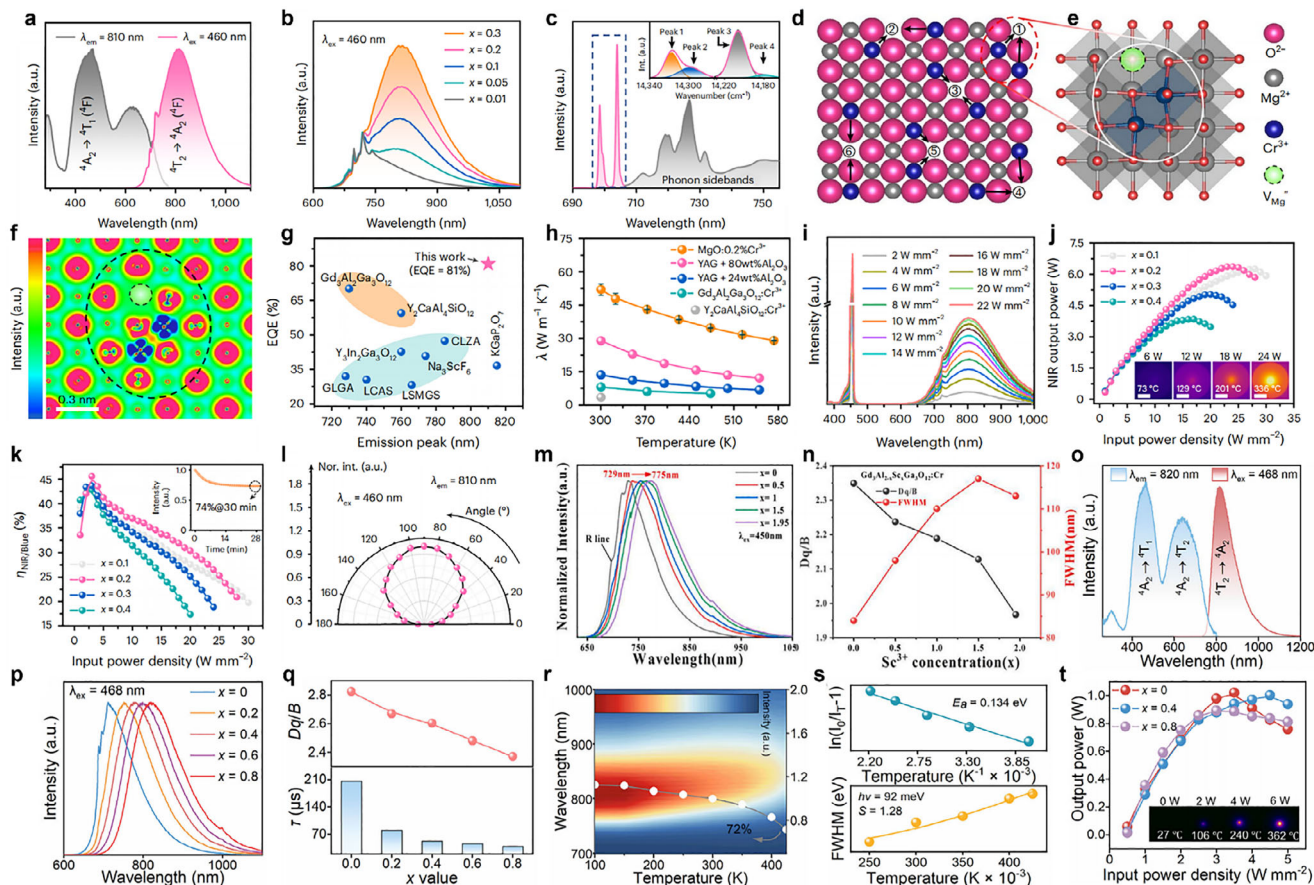


FIGURE 20 | Crystal-field regulation, defect-assisted broadband emission, and laser-driven NIR output of Cr^{3+} -activated phosphor ceramics. (a) Room-temperature PLE and PL spectra of $\text{MgO}:0.2\%\text{Cr}^{3+}$ translucent ceramic monitored at 810 nm and excited at 460 nm. (b) PL spectra of $\text{MgO}:x\%\text{Cr}^{3+}$ ceramics with different Cr^{3+} concentrations under 460 nm excitation. (c) High-resolution PL spectrum of $\text{MgO}:0.2\%\text{Cr}^{3+}$ ceramic measured at 77 K, showing sharp-line emission and phonon sidebands. (d) Possible distributions of $\text{Cr}_{\text{Mg}}^{\cdot-}\text{V}_{\text{Mg}}^{\cdot-}\text{Cr}_{\text{Mg}}^{\cdot-}$ defect dimers in MgO . (e) Enlarged local structure showing Mg-vacancy-induced distorted $[\text{CrO}_6]$ octahedra. (f) Two-dimensional charge-density distribution of the defect model. (g) Comparison of EQE and emission peak position between $\text{MgO}:\text{Cr}^{3+}$ and representative Cr^{3+} -activated NIR phosphors. (h) Temperature-dependent thermal conductivity of $\text{MgO}:\text{Cr}^{3+}$ ceramic and reference ceramic converters. (i) Emission spectra of the $\text{MgO}:\text{Cr}^{3+}$ ceramic-converted NIR light source under different blue-laser power densities. (j) NIR output power as a function of input power density, with thermal images shown in the inset. (k) Blue-to-NIR conversion efficiency as a function of input power density, with the inset showing output stability under continuous laser irradiation. (l) Angular distribution of NIR emission from $\text{MgO}:\text{Cr}^{3+}$ ceramic. Reproduced with permission from literature [253]. Copyright 2024, Published by Springer Nature. (m) Normalized PL spectra of $\text{GASGO}:\text{Cr}^{3+}$ ceramics showing Sc-induced spectral redshift and bandwidth broadening. (n) Dq/B and FWHM variation of $\text{GASGO}:\text{Cr}^{3+}$ ceramics as a function of Sc^{3+} concentration. Reproduced with permission from literature [254]. Copyright 2023, Elsevier Ltd. (o) PLE and PL spectra of $\text{Ga}_{1.18}\text{Sc}_{0.8}\text{O}_3:0.02\text{Cr}^{3+}$ ceramic. (p) Normalized PL spectra of $\text{Ga}_{1.98-x}\text{Sc}_x\text{O}_3:0.02\text{Cr}^{3+}$ ceramics under 468 nm excitation. (q) Crystal-field strength Dq/B and fluorescence lifetime as a function of Sc content. (r) Temperature-dependent PL contour map of $\text{Ga}_{1.98-x}\text{Sc}_x\text{O}_3:0.02\text{Cr}^{3+}$ ceramic. (s) Thermal-quenching activation energy and Huang-Rhys factor fitting. (t) NIR output power of $\text{Ga}_{1.98-x}\text{Sc}_x\text{O}_3:0.02\text{Cr}^{3+}$ ceramics as a function of laser input power density, with thermal images shown in the inset. Reproduced with permission from literature [63]. Copyright 2024, Wiley-VCH GmbH.

show strong broad-band NIR output capability under blue-laser excitation. These three material families therefore support the development of high-power NIR ceramic light sources from complementary perspectives.

Cr^{3+} -activated garnet ceramics first demonstrate advantages in high efficiency and device integration. The $\text{Gd}_3\text{Al}_2\text{Ga}_3\text{O}_{12}:\text{Cr}^{3+}$ (GAGG: Cr^{3+}) ceramics reported by Jiang et al. produce NIR emission over 650–950 nm under 445 nm blue-light excitation [61], with the R lines and broad-band emission originating from the ${}^2\text{E} \rightarrow {}^4\text{A}_2$ and ${}^4\text{T}_2 \rightarrow {}^4\text{A}_2$ transitions of Cr^{3+} , respectively. As the Cr^{3+} concentration increases, blue-light absorption is enhanced, but excessive concentration induces energy migration and con-

centration quenching. A balance must therefore be established among absorption efficiency, quantum efficiency, and output power. The optimized GAGG: Cr^{3+} ceramics show high EQE and deliver NIR output exceeding 1.6 W under blue LD driving, demonstrating the suitability of garnet ceramics for compact high-power NIR converters (Figure 21a–d).

Further cation regulation within the garnet structure can improve thermal stability and device reliability. The $(\text{Lu},\text{Y})_3(\text{Al},\text{Sc},\text{Cr})_2\text{Al}_3\text{O}_{12}$ NIR phosphor ceramics (LuYScCr NIR-PCs) prepared by Ma et al. use Lu/Y and Sc/Al radius matching to tune lattice rigidity, placing Cr^{3+} in a more stable octahedral luminescent environment and reducing non-radiative

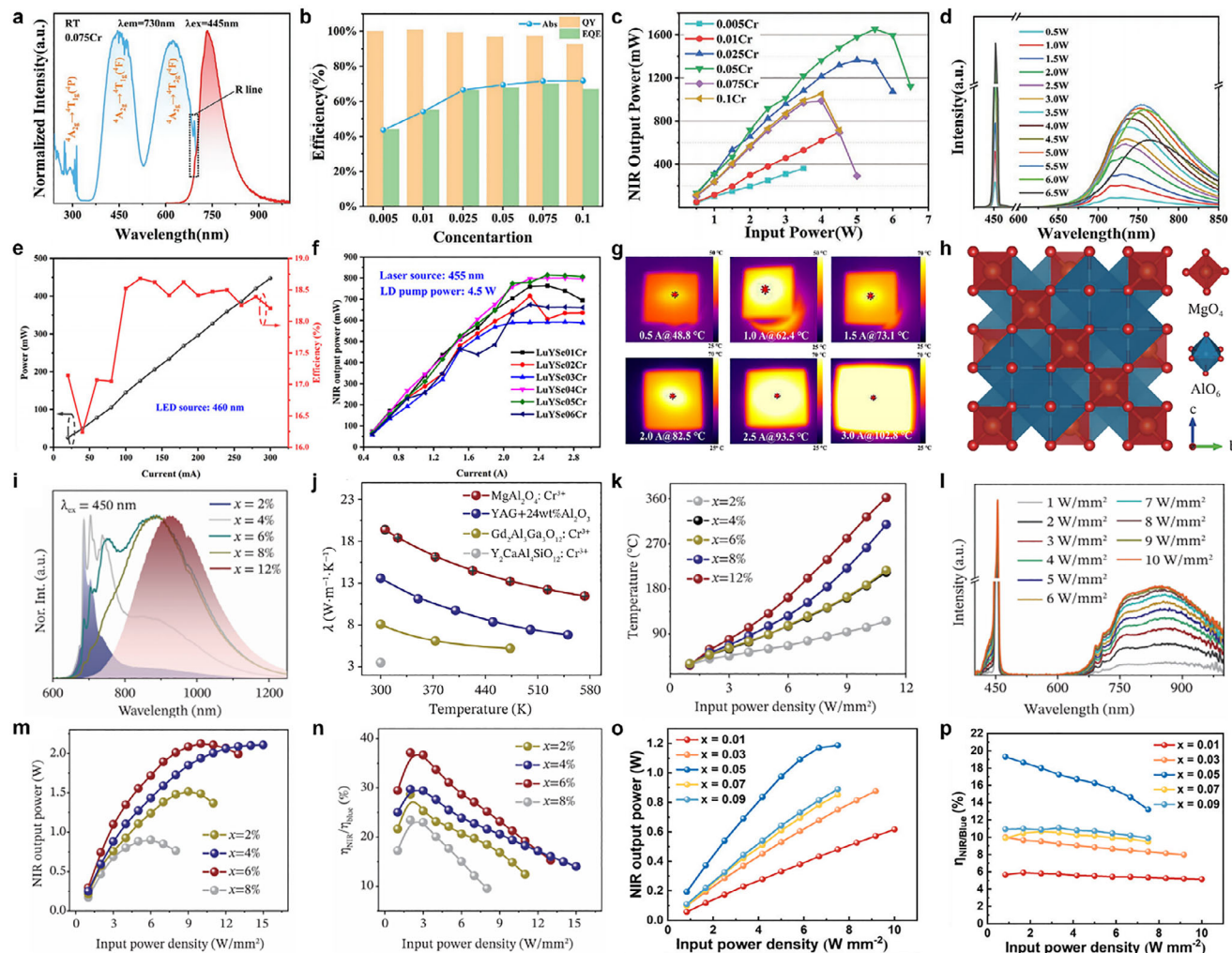


FIGURE 21 | Representative Cr^{3+} -activated NIR phosphor ceramics based on garnet, spinel, and gallate hosts. (a) PLE and PL spectra of GAGG: 0.075Cr^{3+} ceramic under 445 nm excitation and monitored at 730 nm. (b) Absorbance, quantum yield, and external quantum efficiency of GAGG: $x\text{Cr}^{3+}$ ceramics as a function of Cr^{3+} concentration. (c) NIR output power of GAGG: $x\text{Cr}^{3+}$ ceramic-converted LD devices under different input powers. (d) Emission spectra of the GAGG: Cr^{3+} ceramic-converted LD device with increasing laser input power. (e) NIR output power and photoelectric conversion efficiency of the LuYScCr NIR-PC-based LED prototype as a function of driving current. (f) NIR output power of LuYScCr NIR-PCs under 455 nm LD excitation. Reproduced with permission from literature [61]. Copyright 2022, Wiley-VCH GmbH. (g) Thermal images of LuYScCr NIR-PC-based LD devices at different driving currents. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [256]. Copyright 2024, The Author(s). Published by Tsinghua University Press. (h) Crystal structure of MgAl_2O_4 spinel. (i) Normalized PL spectra of $\text{MgAl}_2\text{O}_4: x\text{Cr}^{3+}$ translucent ceramics under 450 nm excitation. (j) Temperature-dependent thermal conductivity of $\text{MgAl}_2\text{O}_4: \text{Cr}^{3+}$ ceramic compared with representative NIR ceramic converters. (k) Irradiation-spot temperature of $\text{MgAl}_2\text{O}_4: x\text{Cr}^{3+}$ ceramics as a function of laser input power density. (l) Input power density-dependent emission spectra of $\text{MgAl}_2\text{O}_4: 6\%\text{Cr}^{3+}$ ceramic under 450 nm laser excitation. (m and n) NIR output power and blue-to-NIR conversion efficiency of $\text{MgAl}_2\text{O}_4: x\text{Cr}^{3+}$ ceramics under laser excitation. Reproduced with permission from literature [62]. Copyright 2025, UESTC and John Wiley & Sons Australia, Ltd. (o and p) NIR output power and blue-to-NIR conversion efficiency of $\text{LaMgGa}_{11-x}\text{O}_{19}: x\text{Cr}^{3+}$ ceramics as a function of laser input power density. Reproduced with permission from literature [255]. Copyright 2025, Elsevier Ltd.

losses at elevated temperatures. This system achieves 447 mW NIR output under LED driving and approximately 814 mW under 455 nm LD excitation. Thermal-imaging results show that the device temperature rise increases with driving current, but overall heat diffusion remains favorable (Figure 21e–g). These findings indicate that garnet ceramics should not focus only on luminescence efficiency; structural rigidity and thermal management are also essential for improving high-power applicability.

6.4 | Garnet, Spinel, and Gallate Near-Infrared Ceramics

The spinel magnesium aluminate $\text{MgAl}_2\text{O}_4: \text{Cr}^{3+}$ system provides a design route toward longer-wavelength, broad-band NIR emission. MgAl_2O_4 consists of $[\text{MgO}_4]$ tetrahedra and $[\text{AlO}_6]$ octahedra, with Cr^{3+} mainly occupying octahedral sites. Because Mg/Al antisite defects, Mg vacancies and Al vacancies are readily formed in spinel lattices, Cr^{3+} experiences local distortions

of varying degrees, giving rise to multiple Cr^{3+} luminescent centers. The translucent $\text{MgAl}_2\text{O}_4: x\text{Cr}^{3+}$ ceramics reported by Liu et al. produce broad-band emission spanning 650–1200 nm under 450 nm excitation, with the emission peak extending to approximately 890 nm [62]. Under laser driving, this ceramic delivers output power exceeding 2 W, demonstrating the clear advantage of spinel ceramics in long-wavelength broad-band NIR sources (Figure 21h–n).

The lanthanum magnesium gallate ($\text{LaMgGa}_{11}\text{O}_{19}$): Cr^{3+} (LMG: Cr^{3+}) ceramics represent another high-brightness NIR conversion platform. The LMG: Cr^{3+} ceramics prepared by He et al. generate broad-band NIR emission centered at approximately 730 nm under blue-light excitation [255]. The optimized sample reaches an EQE of 55.4% and an output power of about 1.2 W under 7.5 W mm^{-2} blue-laser excitation (Figure 21o,p). Compared with garnet systems, gallate hosts provide a different structural environment for Cr^{3+} , offering a moderate crystal field and good thermal stability. Compared with spinel systems, their emission peak is relatively shorter in wavelength, but they remain highly competitive in high-brightness laser output.

Overall, garnet, spinel and gallate Cr^{3+} ceramics each have distinct strengths. Garnet systems are more suitable for high-efficiency NIR conversion and stable device packaging, spinel systems are better for constructing long-wavelength broad-band emission, and gallate systems combine relatively high output power with strong laser adaptability.

6.5 | Ni^{2+} and Other Near-Infrared Luminescent Centers: NIR-II Emission and Deep-Penetration Applications

Unlike Cr^{3+} , which mainly covers the NIR-I region, Ni^{2+} is more suitable for constructing broad-band NIR-II emission over 900–1700 nm. Ni^{2+} usually occupies octahedral sites, and its ${}^3\text{T}_2 \rightarrow {}^3\text{A}_2$ transition can generate long-wavelength near-infrared emission [257, 258]. However, the d–d transition absorption of Ni^{2+} is intrinsically weak, and its emission efficiency is readily limited by local symmetry and non-radiative relaxation [259, 260]. The core design strategy for Ni^{2+} -based NIR-II ceramics is therefore to enhance blue-light absorption, increase transition probability, and suppress thermal quenching [252, 261].

$\text{Cr}^{3+}/\text{Ni}^{2+}$ co-doping is an effective strategy for improving Ni^{2+} luminescence efficiency. In the $\text{MgO}: \text{Ni}^{2+}$, Cr^{3+} translucent ceramics reported by Gu et al., Cr^{3+} shows strong absorption in the blue region and can transfer energy to Ni^{2+} , thereby enhancing NIR-II emission near 1330 nm (Figure 22a–c) [57]. Meanwhile, Cr^{3+} co-doping induces distortion of $[\text{NiO}_6]$ octahedra around Ni^{2+} , weakening the parity-forbidden character of d–d transitions and further strengthening Ni^{2+} emission (Figure 22d,e). This ceramic achieves an IQE of 61.06% and an EQE of 39.69%, while retaining 92.11% of its emission intensity at 478 K, markedly outperforming the corresponding powder (Figure 22f,g). At the device level, the ceramic form provides better thermal management and laser-bearing capability for NIR-II light sources. $\text{MgO}: \text{Ni}^{2+}$, Cr^{3+} ceramics possess relatively high thermal conductivity and can deliver 214 mW NIR-II output under blue-laser driving. As power density increases, the emission intensity first rises

and then saturates and decreases because of heat accumulation (Figure 22h–j). Continuous irradiation results also indicate that high-power NIR-II ceramics still require further optimization of heat dissipation and long-term stability (Figure 22k).

Spinel $\text{MgGa}_2\text{O}_4: \text{Cr}^{3+}$, Ni^{2+} ceramics further demonstrate the expansion potential of NIR-II ceramics. Li et al. prepared $\text{MgGa}_2\text{O}_4: \text{Cr}^{3+}$, Ni^{2+} translucent ceramics by spark plasma sintering (SPS) [262], using $\text{Cr}^{3+} \rightarrow \text{Ni}^{2+}$ energy transfer to achieve broad-band NIR-II emission centered at 1280 nm, with an EQE of up to 81.4% (Figure 22l–o). Under dynamic laser-driving conditions, this ceramic delivers broad-band NIR-II output exceeding 1.86 W, highlighting the advantages of spinel ceramics for high-power long-wavelength NIR sources (Figure 22p,q).

Overall, the development of Ni^{2+} -based NIR-II ceramics depends on the synergy among Cr^{3+} sensitization, local-distortion enhancement, and ceramic thermal management. Other long-wavelength NIR luminescent centers are still being explored, but $\text{Cr}^{3+}/\text{Ni}^{2+}$ co-doped oxides currently remain the most representative ceramic systems for high-power laser-driven NIR-II emission. From a comparative perspective, Cr^{3+} - and Ni^{2+} -activated ceramics fulfil different spectral and application requirements. Cr^{3+} -activated materials generally provide stronger broadband emission in the short-wavelength NIR region and are more readily excited by commercial blue or red light sources, whereas Ni^{2+} -activated systems can extend emission into the NIR-II region but often require stricter control of crystal field, site occupation, and non-radiative relaxation. For both systems, broad spectral coverage alone is insufficient to establish practical superiority. Their application potential must also be evaluated in terms of excitation compatibility, quantum efficiency, thermal quenching, saturation behavior, optical output power, and device-level stability.

6.6 | Applications of Near-Infrared Ceramics in Night Vision, Bioimaging, Food Inspection, and Spectral Recognition

The application value of NIR phosphor ceramics depends not only on emission peak position and quantum efficiency, but also on whether they can deliver high brightness, low thermal decay, and stable broad-band output in real devices. Compared with powder/resin encapsulation systems, ceramic converters can withstand higher-power-density blue LED/LD excitation and improve continuous-operation stability through high thermal conductivity and all-inorganic architectures. As a result, NIR ceramics have moved beyond simple demonstrations of material performance and are increasingly entering applications such as night-vision illumination, transmission imaging, nondestructive testing, spectral recognition, and sensing in complex environments (Figure 23).

Night vision and penetration imaging are currently the most direct application directions. The $\text{MgO}: \text{Cr}^{3+}$ translucent ceramics reported by Liu et al. achieve watt-level broad-band NIR output under blue-laser driving, enabling long-distance night vision and transmission imaging of arm veins and objects behind cardboard (Figure 23a–c) [253]. Chen et al. further developed a laser-driven NIR light source based on $\text{Ca}_3\text{MgHfGe}_3\text{O}_{12}: \text{Cr}^{3+}$

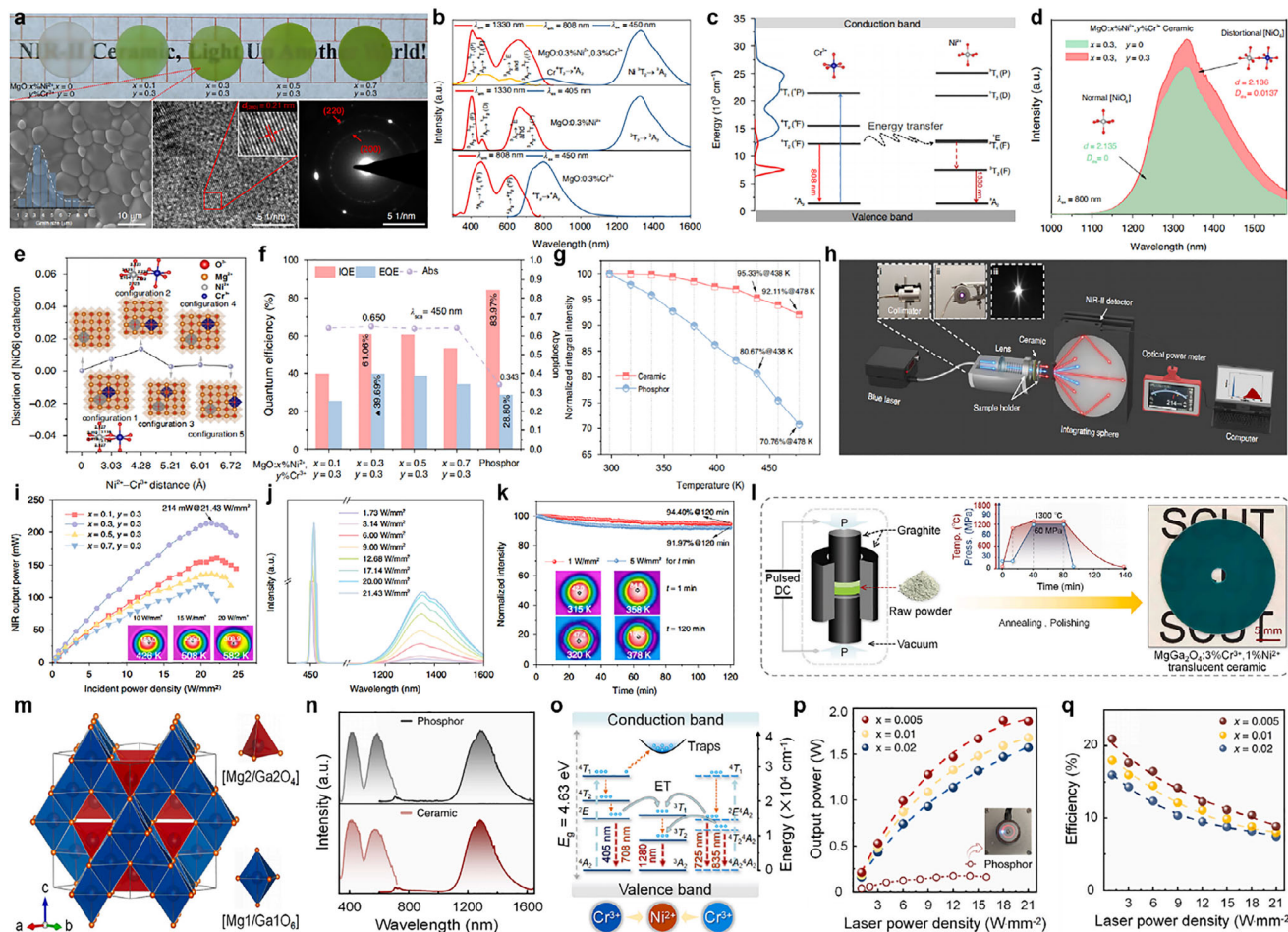


FIGURE 22 | $\text{Cr}^{3+}/\text{Ni}^{2+}$ co-activated NIR-II luminescent ceramics and laser-driven broadband NIR-II output. (a) Photographs, SEM image, grain-size distribution, TEM image, and SAED pattern of $\text{MgO}: x\%\text{Ni}^{2+}, y\%\text{Cr}^{3+}$ translucent ceramics. (b) PLE and PL spectra of $\text{MgO}: 0.3\%\text{Ni}^{2+}, 0.3\%\text{Cr}^{3+}$, $\text{MgO}: 0.3\%\text{Ni}^{2+}$, and $\text{MgO}: 0.3\%\text{Cr}^{3+}$ ceramics. (c) Energy-level diagram of $\text{Cr}^{3+}/\text{Ni}^{2+}$ in $\text{MgO}: 0.3\%\text{Ni}^{2+}, 0.3\%\text{Cr}^{3+}$ ceramic, showing blue-light excitation of Cr^{3+} and energy transfer from Cr^{3+} to Ni^{2+} . (d) NIR-II PL spectra of Ni^{2+} in normal and distorted $[\text{NiO}_6]$ octahedra under 800 nm excitation. (e) Calculated distortion of $[\text{NiO}_6]$ octahedra as a function of Ni^{2+} – Cr^{3+} distance. (f) Absorption efficiency, IQE, and EQE of $\text{MgO}: x\%\text{Ni}^{2+}, 0.3\%\text{Cr}^{3+}$ ceramics, and the corresponding phosphor. (g) Temperature-dependent integrated emission intensities of $\text{MgO}: 0.3\%\text{Ni}^{2+}, 0.3\%\text{Cr}^{3+}$ ceramic and phosphor. (h) Schematic configuration of the laser-driven NIR-II device and optical measurement system. (i) NIR-II output power of $\text{MgO}: x\%\text{Ni}^{2+}, 0.3\%\text{Cr}^{3+}$ ceramic-converted laser-driven devices as a function of incident power density, with thermal images shown in the inset. (j) Power density-dependent emission spectra of $\text{MgO}: 0.3\%\text{Ni}^{2+}, 0.3\%\text{Cr}^{3+}$ ceramic under blue-laser excitation. (k) Continuous-irradiation stability of $\text{MgO}: 0.3\%\text{Ni}^{2+}, 0.3\%\text{Cr}^{3+}$ ceramic under 1 and 5 W mm^{-2} laser excitation. Reproduced with permission from literature [57]. Copyright 2025, Published by Springer Nature. (l) SPS fabrication process and photograph of $\text{MgGa}_2\text{O}_4: 3\%\text{Cr}^{3+}, 1\%\text{Ni}^{2+}$ translucent ceramic. (m) Crystal structure of MgGa_2O_4 spinel. (n) PLE and PL spectra of $\text{MgGa}_2\text{O}_4: 3\%\text{Cr}^{3+}, \text{Ni}^{2+}$ phosphor, and ceramic. (o) Energy-transfer mechanism from Cr^{3+} to Ni^{2+} in $\text{MgGa}_2\text{O}_4: \text{Cr}^{3+}, \text{Ni}^{2+}$ translucent ceramic. (p and q) NIR-II output power and conversion efficiency of $\text{MgGa}_2\text{O}_4: 3\%\text{Cr}^{3+}, x\%\text{Ni}^{2+}$ ceramic-converted laser-driven devices as a function of laser power density. Reproduced with permission from literature [262]. Copyright 2025, Elsevier Ltd.

phosphor ceramics [58]. By combining an AlN high-thermal-conductivity substrate, rotational heat dissipation and a reflective optical path, they obtained a high-output near-infrared phosphor-converted laser diode (NIR pc-LD). This device can not only reveal stamp information in ancient paintings and calligraphy that is difficult to distinguish under visible light but also enable night imaging over distances of 50–200 m (Figure 23d–g). These results demonstrate that high-power NIR ceramic light sources have practical potential in cultural relic inspection, security monitoring, and long-range assisted vision.

NIR ceramics can also be used for nondestructive detection of physiological signals and everyday objects. The high-brightness

NIR light generated by $\text{MgAl}_2\text{O}_4: \text{Cr}^{3+}$ translucent ceramics can penetrate a finger and be received by a detector, enabling photoplethysmography (PPG) signals and heart-rate information to be obtained [62]. The same light source can also be used for observing the air cell of an egg and evaluating line-pair resolution (Figure 23h,i). The $\text{Ga}_{1.18}\text{Sc}_{0.8}\text{O}_3: 0.02\text{Cr}^{3+}$ ceramics reported by Xiong et al. demonstrate a broader range of applications: their laser-driven NIR light source enables fruit imaging, palm-vessel imaging, and ethanol concentration detection based on the different NIR absorption characteristics of water and ethanol (Figure 23j–m) [63]. These applications highlight the advantages of broad-band NIR ceramic light sources in food safety, vital-sign monitoring, and liquid-composition analysis.

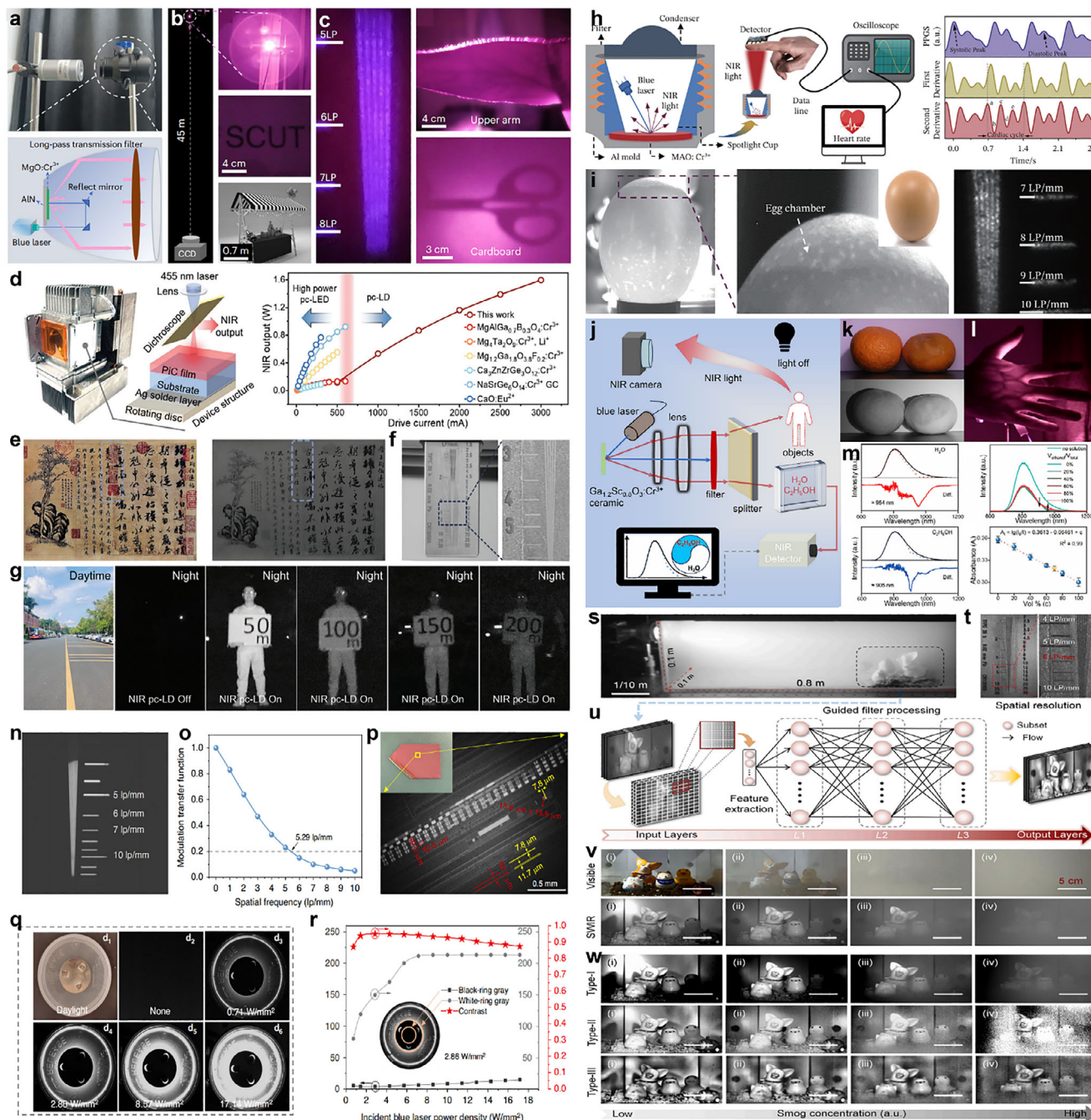


FIGURE 23 | Application demonstrations of laser-driven broadband NIR and NIR-II ceramic light sources. (a) Packaged $\text{MgO}:\text{Cr}^{3+}$ ceramic-converted NIR light source. (b) Long-distance NIR illumination and imaging using the $\text{MgO}:\text{Cr}^{3+}$ ceramic-converted light source. (c) Transillumination imaging of blood vessels in an upper arm and scissors behind cardboard. Reproduced with permission from literature [253]. Copyright 2024, Published by Springer Nature. (d) Device configuration of the $\text{Ca}_3\text{MgHfGe}_3\text{O}_{12}:\text{Cr}^{3+}$ phosphor-in-ceramic-converted laser-driven NIR source. (e) NIR output comparison of the laser-driven NIR source. (f) Calligraphy inspection and imaging-resolution evaluation. (g) Long-distance night-vision imaging. Reproduced with permission from literature [58]. Copyright 2024, Wiley-VCH GmbH. (h) $\text{MgAl}_2\text{O}_4:\text{Cr}^{3+}$ translucent-ceramic NIR source for photoplethysmography and egg air-chamber inspection. (i) Line-pair imaging-resolution test using the $\text{MgAl}_2\text{O}_4:\text{Cr}^{3+}$ translucent-ceramic NIR source. Reproduced with permission from literature [62]. Copyright 2025, UESTC and John Wiley & Sons Australia, Ltd. (j) Fruit imaging using the $\text{Ga}_{1.18}\text{Sc}_{0.8}\text{O}_3:0.02\text{Cr}^{3+}$ ceramic-based NIR source. (k) Palm blood-vessel imaging. (l) Ethanol-concentration analysis. (m) Quantitative evaluation of ethanol-concentration detection. Reproduced with permission from literature [63]. Copyright 2024, Wiley-VCH GmbH. (n) $\text{MgGa}_2\text{O}_4:\text{Cr}^{3+}, \text{Ni}^{2+}$ NIR-II luminescent ceramic source for spatial-resolution evaluation. (o) Spatial-resolution imaging result. (p) Silicon-wafer microstructure imaging. (q) Imaging-contrast comparison. (r) Imaging-contrast analysis. Reproduced with permission from literature [57]. Copyright 2025, Nature Publishing Group. (s) Dynamic $\text{MgGa}_2\text{O}_4:\text{Cr}^{3+}, \text{Ni}^{2+}$ spinel ceramic NIR-II source for smog-penetrating imaging. (t) Spatial-resolution testing under smog conditions. (u) Guided-filter-network image processing. (v) Target recognition under increasing smog concentrations. (w) Recognition-performance comparison under different smog concentrations. Reproduced with permission from literature [262]. Copyright 2025, Elsevier Ltd.

For deeper penetration and strongly scattering environments, NIR-II ceramic light sources show even greater value. Gu et al. constructed a laser-driven NIR-II source based on MgO: Ni²⁺, Cr³⁺ ceramics [57], achieving an output power of 214 mW, a spatial resolution of 5.29 lp/mm and an imaging contrast of 0.97. Imaging of internal microstructures in silicon wafers and metal sheets on plastic boxes demonstrates that NIR-II ceramic light sources are well suited to nondestructive testing and hidden-structure identification (Figure 23n–r). Li et al. further developed dynamic NIR-II sources using MgGa₂O₄: Cr³⁺, Ni²⁺ spinel transparent/translucent ceramics [262]. Combined with a guided-filter-network image-processing algorithm, this system can still identify targets in high-concentration smoke environments (Figure 23s–w). These results indicate that the development of NIR-II ceramic light sources is no longer limited to “material luminescence” but is beginning to couple with imaging algorithms and intelligent sensing systems.

Overall, applications of NIR phosphor ceramics are developing along two main routes. The first centers on Cr³⁺-activated broad-band NIR-I ceramics for night vision, vascular imaging, food inspection, and spectral recognition. The second is based on Cr³⁺→Ni²⁺ energy transfer or Ni²⁺ emission, extending toward NIR-II deep penetration, imaging in strongly scattering environments and algorithm-enhanced detection.

6.7 | Photothermal Stability and Device-Integration Challenges of Near-Infrared Phosphor Ceramics

The device value of NIR phosphor ceramics depends not only on emission wavelength and quantum efficiency, but also on their photothermal stability under high-power LED/LD excitation. For systems activated by transition-metal ions such as Cr³⁺ and Ni²⁺, broad-band NIR emission is usually accompanied by strong electron–phonon coupling, making thermal quenching, optical saturation, and reduced output efficiency likely under high temperature or high power density [263]. Materials design for NIR ceramics therefore requires a balance among broad-band emission, high luminescence efficiency, high thermal conductivity, and resistance to thermal quenching.

To compare the device potential of different systems more directly, Table 2 summarizes the emission range, FWHM, thermal stability, thermal conductivity, photoelectric conversion efficiency, and NIR output power of representative NIR phosphor ceramics. MgO: Cr³⁺, MgAl₂O₄: Cr³⁺, Ga/Sc oxide: Cr³⁺ and MgO: Ni²⁺, Cr³⁺ systems have already demonstrated high NIR output capability [264, 265]. Among them, high-thermal-conductivity MgO-based ceramics are favorable for increasing the upper limit of laser power handling. Spinel MgAl₂O₄: Cr³⁺ ceramics combine tunable broad-band emission with good thermal-management capability. Ga/Sc oxide ceramics achieve high EQE and stable laser-driven output through compositional regulation. MgO: Ni²⁺, Cr³⁺ ceramics further extend emission into the NIR-II region, showing potential for deep-penetration imaging and nondestructive testing [248, 265].

Nevertheless, NIR ceramic light sources still face several key challenges. First, unified evaluation standards are still lacking

for output power, conversion efficiency, surface temperature rise, and long-term stability under high-power excitation. Second, ceramic transparency, scattering strength, thickness, and blue-light absorption efficiency must be precisely matched, because either excessive or insufficient scattering can degrade light-extraction efficiency and imaging quality. Third, although NIR-II ceramic systems show outstanding application prospects, long-wavelength emission is more susceptible to multiphonon relaxation, and their external quantum efficiency and continuous-operation stability still require further improvement. Future development of NIR phosphor ceramics should therefore integrate luminescent-center design, defect regulation, ceramic microstructure optimization, and package-level heat-dissipation structures. Only by coupling intrinsic luminescence performance with device thermal management, light extraction, and long-term reliability can NIR and NIR-II phosphor ceramics move toward practical applications in high-brightness night vision, bioimaging, food inspection, and intelligent spectral recognition [266, 267].

7 | Glassy Composite Interfaces and Low-Temperature Heterogeneous Integration

7.1 | The Tension Between High-Temperature Ceramic Processing and Low-Temperature Integration

The garnet, multiphase, multicolor, and near-infrared phosphor ceramics discussed in the preceding chapters mostly rely on high-temperature sintering, hot pressing, SPS, or hot isostatic pressing (HIP) to achieve densification. The advantages of high-temperature ceramic processing are clear. On the one hand, sufficient sintering can effectively eliminate pores and improve thermal conductivity, mechanical strength, and ageing resistance. On the other hand, stable crystalline structures help preserve the local coordination environment of luminescent centers, thereby improving quantum efficiency, thermal stability, and output reliability under high-power LED/LD excitation. For thermally stable systems such as YAG: Ce, LuAG: Ce, GAGG: Ce/Cr³⁺, MgAl₂O₄: Cr³⁺ and MgO: Cr³⁺, high-temperature ceramic integration remains an important route to high-brightness light-conversion materials.

However, as phosphor ceramics move toward more complex device integration, high-temperature processing routes also reveal clear limitations. First, many luminescent materials cannot withstand prolonged high-temperature treatment. Systems containing volatile components, low-melting constituents, or variable-valence luminescent ions may undergo phase decomposition, compositional segregation, abnormal grain growth, or valence-state changes at high temperature, leading to reduced luminescence efficiency [274, 275]. Second, high-temperature sintering usually requires ceramics to be prepared independently and then packaged with chips, metal heat sinks, sapphire substrates, or glass windows, increasing the number of interfaces and the complexity of the process [276, 277]. Thermal-expansion mismatch, insufficient wetting, and inadequate bonding strength at these interfaces can further cause cracking, delamination, and increased thermal resistance.

TABLE 2 | Comparison of the performance parameters of ceramic phosphors.

Material	Emission (nm)	FWHM (nm)	Thermal stability	Thermal conductivity	PCE	NIR output power
YAGG: Cr-Ni [268]	600–900; 1100–1700	131; 377	63% @ 373 K	8.018 W m ⁻¹ K ⁻¹	—	—
Y _{3-x} Ca _x Al _{5-x} Si _x O ₁₂ : Cr ³⁺ [117]	760	160	90.6% @ 150 °C	—	21.2%	62.6 mW @ 100 mA
GAGG: Cr ³⁺ [61]	650–950	—	96.8% @ 150 °C	—	31%	1.6 W (LD)
GSAG: Cr ³⁺ [265]	762	116.9	79.8% @ 423 K	—	14.91% @ 30 mA	112.19 mW @ 300 mA
GAGG-Al ₂ O ₃ : Cr ³⁺ [269]	—	—	94.3% @ 150 °C	—	28% @ 350 mA	236 mW
Mg ₂ Al ₄ Si ₅ O ₁₈ -MgAl ₂ O ₄ [270]	700–1400	—	—	—	—	—
MgAl ₂ O ₄ : Cr ³⁺ [62]	686–928	315	—	19.4 W m ⁻¹ K ⁻¹	21.3%	2.13 W @ 10 W mm ⁻²
β-Ga ₂ O ₃ : Cr ³⁺ [271]	600–1200	187	89% @ 423 K	1.2 W m ⁻¹ K ⁻¹	13%	568 mW @ 500 mA
Ga _{1.98-x} Sc _x O ₃ : 0.02Cr ³⁺ [63]	820	147	72% @ 423 K	8.76 W m ⁻¹ K ⁻¹	29%	893 mW @ 3 W mm ⁻²
MgO: x%Cr ³⁺ [253]	—	—	87.5% @ 423 K	52 W m ⁻¹ K ⁻¹	29%	6.36 W @ 22 W mm ⁻²
Na ₂ SrGe ₆ O ₁₄ : Cr ³⁺ [142]	815	214	65% @ 150 °C	—	9.1%	922.4 mW @ 600 mA
CaF ₂ : Cr ³⁺ [272]	700–1400	297	40% @ 100 °C	—	—	—
MgO: Cr ³⁺ , Ni ²⁺ [57]	808 and 1330	—	92.11% @ 478 K	31.28 W m ⁻¹ K ⁻¹	—	214 mW @ 21.43 W mm ⁻²
Na ₂ SrXGe ₅ O ₁₄ : Cr ³⁺ (X = Si, Ge, Ti) [273]	650–1100	209–215	92.11% @ 100 °C	—	5.4%	360.6 mW @ 200 mA

From the device perspective, future high-power lighting, laser displays, near-infrared detection, and miniaturized light sources increasingly require light-conversion materials that can be processed at low temperature, patterned, fabricated over large areas, and heterogeneously integrated [278, 279]. LED/LD chips, metal heat-spreading substrates, transparent windows, optical adhesive layers, and micro/nano-optical structures generally cannot tolerate the high temperatures required for ceramic sintering. A central contradiction therefore emerges between the materials-side pursuit of high-temperature densification and the device-side demand for low-temperature integration: high temperature favors dense, thermally conductive, and stable ceramics, whereas low temperature is more compatible with real device structures, packaging processes, and multimerial interfaces [280].

This contradiction is particularly pronounced in high-power applications. Low-temperature resin encapsulation offers simple processing and good interfacial adaptability, but resins have low thermal conductivity and poor heat resistance, and can easily age, yellow, or fail under high blue-light flux or laser irradiation. Fully dense ceramics, by contrast, provide excellent photothermal stability, but may suffer from high processing temperatures, difficult shape processing, and complex heterogeneous-interface integration [280, 281]. An ideal light-conversion material must therefore establish a new balance between “ceramic stability” and “low-temperature processability.”

Glassy composite interfaces have attracted attention in this context. Glassy phases possess relatively low softening temperatures, good flowability, and strong interfacial wetting capability, allowing phosphor particles, ceramic plates, metal substrates, or transparent supports to be bonded under comparatively mild conditions. Crystalline phosphor phases, meanwhile, provide efficient luminescence and spectral conversion. Through PiG, PiGF, glass-ceramics, and ceramic-glass heterogeneous composites, it becomes possible to balance low-temperature processing, interfacial bonding, optical regulation, and thermal-management requirements to some extent. Accordingly, the development logic of phosphor ceramics expands from simple “high-temperature densification” to the cooperative integration of “crystalline luminescent phase-glassy interface-device substrate.”

The following sections therefore discuss PiG, PiGF, glass-ceramics, and various heterogeneous composite structures, with emphasis on how glassy interfaces affect light propagation, heat diffusion, and interfacial reliability. We also analyze how emerging organic-inorganic glassy materials, including MOF glasses, may inspire low-temperature composite light-conversion systems.

7.2 | PiG, PiGF, and Glass-Ceramic Light-Conversion Materials

PiG, PiGF, and glass-ceramic light-conversion materials share a common feature: phosphor particles are encapsulated by a glassy phase, which provides low-temperature bonding, interfacial buffering, and film-forming support. Compared with all-ceramic routes, these materials are more amenable to thin-film fabrication, patterning, and multiphosphor integration. Their performance, however, is still limited by the low thermal con-

ductivity of the glass matrix, phosphor/glass interfacial corrosion, film thickness, and scattering losses. This section therefore focuses on glassy light-conversion materials and film-forming processes, while heterogeneous heat-dissipation structures are discussed in Section 7.3.

Figure 24a,b show typical low-temperature PiGF fabrication routes, including screen printing, blade coating, drying, and subsequent sintering [282, 283]. In addition, glass-ceramic routes can regulate internal scattering and thermal stability through controlled crystallization, and Figure 24c shows the influence of crystallization control on luminous-flux output under laser excitation [284]. Beyond crystallization, fillers such as AlN and boron nitride (BN) can also be introduced into the glassy phase to improve heat conduction, scattering, and light extraction (Figure 24d–g) [285, 286]. These approaches share a common goal: to enhance the intrinsic stability and output capability of the glassy light-conversion layer without relying on complex heterogeneous heat-dissipation structures.

In terms of compositional regulation, Yang et al. introduced hexagonal boron nitride (h-BN) into YAG: Ce PiGF to construct a local heat-conduction and scattering-regulation network [287]. Figure 24h–j show the changes in film surface morphology at different h-BN contents. Figure 24k,l further demonstrate that, at a fixed film thickness, the 6 wt% h-BN sample exhibits superior luminous flux and saturation threshold, indicating that PiGF performance is governed not only by external heat dissipation, but also by the microstructure jointly formed by the glassy phase, phosphor particles, and fillers.

Red compensation further highlights the advantage of PiGF in multicolor integration. Yang et al. prepared red (Sr,Ca)AlSiN₃: Eu²⁺ (SCASN: Eu) PiGF. Cross-sectional SEM and high-resolution transmission electron microscopy (HRTEM) show that SCASN: Eu particles are encapsulated by the glassy phase and that the interfacial reaction region is narrow (Figure 24m,n). On this basis, red SCASN: Eu PiGF can be combined with green YAGG: Ce PiGF to construct red-green segmented phosphor wheels (Figure 24o–s), improving the spectral composition, color rendering, and display performance of laser-driven white light [288]. Overall, PiG/PiGF and glass-ceramic routes provide flexible platforms for low-temperature encapsulation, multicolor compositing, and patterned conversion, whereas heat diffusion and structural support under higher-power operation require the heterogeneous composite architectures discussed in Section 7.3.

7.3 | Ceramic-Glass, Ceramic-Metal, and Ceramic-Sapphire Composite Structures

Unlike the routes discussed in Section 7.2, which focus on intrinsic regulation of PiG, PiGF, and glass-ceramic materials, ceramic-glass, ceramic-metal, and ceramic-sapphire composite structures emphasize device-level heterogeneous integration. Their design principle is to assign luminescence conversion, interfacial bonding, mechanical support, and heat diffusion to different functional layers. Phosphor ceramics or PiGF layers are responsible for blue-light absorption and wavelength conversion; the glassy phase enables low-temperature film formation and interfacial bonding; and sapphire, Al₂O₃, diamond, or metal heat

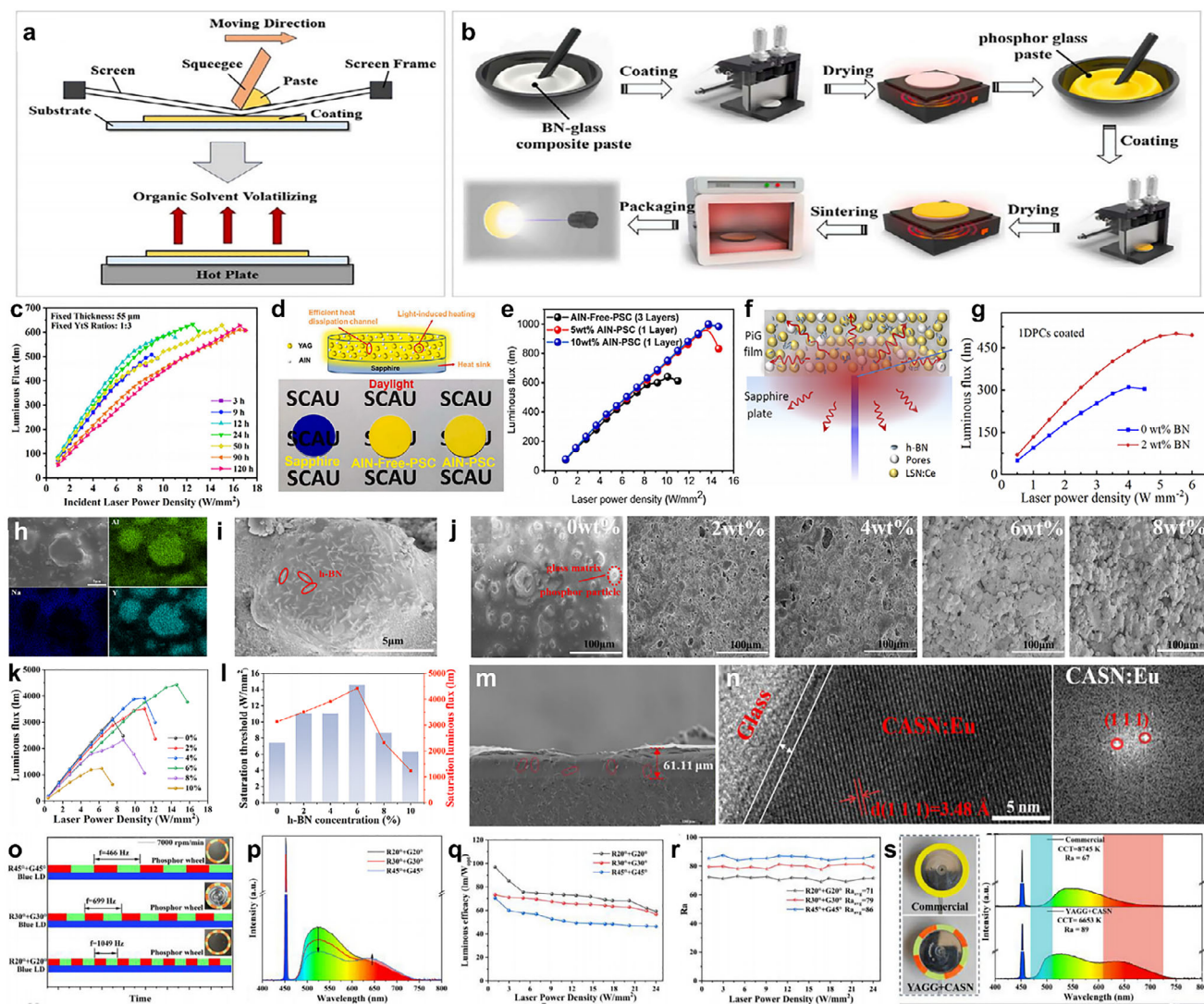


FIGURE 24 | PiG/PiGF and glass-ceramic color-converting materials: preparation routes, microstructure regulation, and multicolor laser-lighting applications. (a) Screen-printing and drying process for PiGF coatings [282]. Copyright 2023, Royal Society of Chemistry. (b) Coating, drying, sintering, and packaging procedure for a BN-glass/phosphor-glass paste based converter. Reproduced with permission from literature [283]. Copyright 2022, Elsevier. (c) Luminous flux of glass-ceramic PiGF samples as a function of incident laser power density after different sintering durations. Reproduced with permission from literature [284]. Copyright 2022, Wiley-VCH. (d) Schematic and photographs of AlN-free and AlN-containing PSC converters, showing the role of AlN in heat dissipation. (e) Luminous flux comparison of AlN-free PSC and AlN-containing PSC samples under increasing laser power density. Reproduced with permission from literature [285]. Copyright 2022, Elsevier. (f) Schematic light-scattering and heat-transfer pathways in an h-BN-containing LSN: Ce PiG/PiGF film on sapphire. (g) Luminous flux of IDPC-coated films with 0 and 2 wt% BN under laser excitation. Reproduced with permission from literature [286]. Copyright 2022, Optica Publishing Group. (h) SEM image and the corresponding EDS mappings of B-Y PiGF@Al₂O₃. (i) SEM image of the enlarged region of B-Y PiGF@Al₂O₃. (j) Surface SEM images of h-BN-YAG: Ce PiGF films with different h-BN contents. (k) Luminous flux of h-BN-YAG: Ce PiGF films as a function of laser power density. (l) Saturation threshold and saturation luminous flux of h-BN-YAG: Ce PiGF films as a function of h-BN concentration. (m) Cross-sectional SEM image of CASN: Eu PiGF. (n) HRTEM image of the SCASN: Eu/glass interface and the corresponding FFT pattern of SCASN: Eu. Reproduced with permission from literature [287]. Copyright 2025, Wiley-VCH GmbH. (o) Red-green angular configurations of the YAGG: Ce-SCASN: Eu PiGF phosphor wheel. (p) Electroluminescence spectra of PiGF phosphor wheels with different red-green angular configurations. (q) Luminous efficacy of different red-green PiGF phosphor-wheel configurations as a function of laser power density. (r) R_a of different red-green PiGF phosphor-wheel configurations as a function of laser power density. (s) Photographs and electroluminescence spectra of a commercial YAG: Ce phosphor wheel and a YAGG: Ce-SCASN: Eu PiGF phosphor wheel. Reproduced with permission from literature [288]. Copyright 2025, Wiley-VCH GmbH.

sinks provide efficient heat dissipation and structural support. Thus, the focus of this section is no longer a single glass-based light-conversion material, but the design of composite interfaces between the light-conversion layer and high-thermal-conductivity substrates.

Xi et al. proposed a transparent ceramic@sapphire composite architecture to address local heat accumulation in single phosphor ceramics under high-power laser irradiation [126]. Taking Lu_{2-x}CaMg₂Si₃O₁₂: xCe³⁺@sapphire as an example, cross-sectional SEM and EDS mapping show that the

$\text{Lu}_{2-x}\text{CaMg}_2\text{Si}_3\text{O}_{12}:x\text{Ce}^{3+}$ (LCMS: Ce) ceramic layer forms a relatively continuous composite interface with the sapphire substrate, with clearly separated elemental distributions (Figure 25a,b). Thermal simulations further reveal that, compared with standalone LCMS: Ce ceramics, where heat is confined near the laser-irradiated region, LCMS: Ce@sapphire enables more efficient lateral heat spreading through the sapphire substrate, thereby reducing local temperature rise and delaying luminescence degradation (Figure 25c–f). This indicates that sapphire is not merely a transparent support layer, but a functional substrate that contributes simultaneously to heat diffusion, optical-path stability, and mechanical support.

Zhao et al. further introduced high-thermal-conductivity Al_2O_3 substrates into PiGF systems and regulated photothermal behavior through three-dimensional patterned architectures [289]. They constructed planar, valley-like, and hill-like Al_2O_3 /PiGF composite structures. SEM and elemental mapping confirmed that $\text{La}_3\text{Si}_6\text{N}_{11}$ (LSN) phosphor particles were embedded in the glass matrix and bonded to the Al_2O_3 substrate (Figure 25g–i). Compared with planar PiGF-P, PiGF-V, and PiGF-H increase the blue-light propagation length, sidewall reflection frequency, and heat-dissipation area through three-dimensional surfaces, with PiGF-H showing superior luminous flux and luminous efficacy (Figure 25j,k). Optical-path and energy-distribution analyses indicate that three-dimensional patterned substrates can simultaneously enhance blue-light utilization and heat spreading, allowing more input energy to be converted into useful output light (Figure 25l,m).

Zhang et al. proposed a sapphire@PiGF@sapphire (S@PiGF@S) sandwich structure, in which YAG:Ce PiGF is placed between two sapphire layers to form dual-sided heat-diffusion channels [84]. Cross-sectional SEM, EDS mapping, and sample photographs demonstrate stable integration between the PiGF layer and the two sapphire plates (Figure 25n). Thermal simulations show that heat in S@PiGF@S can be conducted simultaneously through both the upper and lower sapphire layers, whereas conventional PiGF@sapphire or sapphire@PiGF structures are more prone to local heat concentration (Figure 25o–q). With optimized sapphire thickness, S@PiGF@S exhibits improved luminous flux, luminous efficacy, and saturation threshold, while maintaining a lower operating temperature under high laser power density (Figure 25r–w). The key advantage of this sandwich architecture is its conversion of single-sided heat dissipation into dual-sided cooperative heat dissipation.

Yu et al. further used transparent diamond as a heat-spreading substrate for PiGF and constructed a $\text{La}_3\text{Si}_6\text{N}_{11}: \text{Ce}^{3+}$ PiGF@diamond (LSN: Ce PiGF@diamond) composite converter [290]. Cross-sectional and surface SEM images show that LSN: Ce phosphor particles are encapsulated by the glassy phase and immobilized on the diamond surface (Figure 26a–d). Owing to the extremely high thermal conductivity of diamond, heat in PiGF@diamond can be rapidly transferred from the luminescent film into the diamond substrate, giving this structure a markedly higher thermal conductivity than PiGF@sapphire (Figure 26e,f). Under blue-laser excitation, PiGF@diamond exhibits a lower surface temperature rise and more stable luminous-flux increase, and its output capability can be further improved by adjusting the laser spot area (Figure 26g–j). These results show that high-

thermal-conductivity transparent substrates can substantially increase the power-handling limit of PiGF in projection displays and high-brightness laser lighting.

Cheng et al. advanced interfacial heat dissipation from a single high-thermal-conductivity substrate to a multichannel thermal-conduction architecture [291]. Their multichannel thermal-conduction PiGF (MTC-PiGF), composed of YAG:Ce PiGF, grooved Al_2O_3 , bonding glass and a sapphire cover plate, forms coupled vertical and lateral heat-dissipation pathways (Figure 26k). Compared with conventional PiGF@ Al_2O_3 structures, which show pronounced local heat concentration, MTC-PiGF lowers the temperature of the luminescent layer through multipath heat conduction (Figure 26l). Cross-sectional SEM and elemental mapping further confirm the composite structure among PiGF, bonding glass, and grooved Al_2O_3 (Figure 26m). With optimized bonding-glass thickness, this architecture achieves higher luminous flux and lower operating temperature under high laser power density, indicating that a thin bonding layer helps reduce interfacial thermal resistance and improve heat-diffusion efficiency (Figure 26n–r).

In addition to sapphire, Al_2O_3 and diamond substrates, ceramic-metal composites are also important for device-level thermal management. Related studies and reviews show that PiGF or ceramic films can be integrated with Al_2O_3 , AlN, Ag layers, solder layers, copper heat sinks, and aluminum heat sinks to construct packaging systems with lower thermal resistance (Figure 26s–w) [56, 292–295]. These designs do not directly modify the luminescent phase itself; instead, they reduce device thermal resistance through metal heat sinks, soldering layers, and high-thermal-conductivity ceramic substrates. Overall, the studies by Xi, Zhao, Zhang, Yu, and Cheng collectively demonstrate that the development of high-power light-conversion materials is shifting from improving the intrinsic stability of the luminescent layer alone toward the cooperative design of luminescent layers, glassy interfaces, and high-thermal-conductivity device substrates.

7.4 | Effects of Glassy Interfaces on Light Propagation, Heat Diffusion, and Interfacial Reliability

In PiG, PiGF, and glass-ceramic light-conversion materials, glassy interfaces are not merely bonding media; they are functional units that simultaneously participate in light propagation, heat diffusion, and interfacial stabilization. Unlike Section 7.3, which focuses on ceramic-sapphire, ceramic-metal, diamond-based, and multichannel heat-dissipation structures, this section emphasizes the common mechanisms behind these architectures: how the glassy phase regulates blue-light scattering and yellow-light extraction, how it affects heat transfer from phosphor particles to substrates, and how it determines the chemical stability and long-term reliability of phosphor/glass interfaces (Figure 27).

Lin et al. summarized that refractive-index contrast, phosphor particle size, pores, and crystallized phases in the glassy matrix can all modify blue-light scattering [7]. Mie scattering theory indicates that stronger scattering is not always beneficial (Figure 27a). When the average scattering length is too long, blue-light

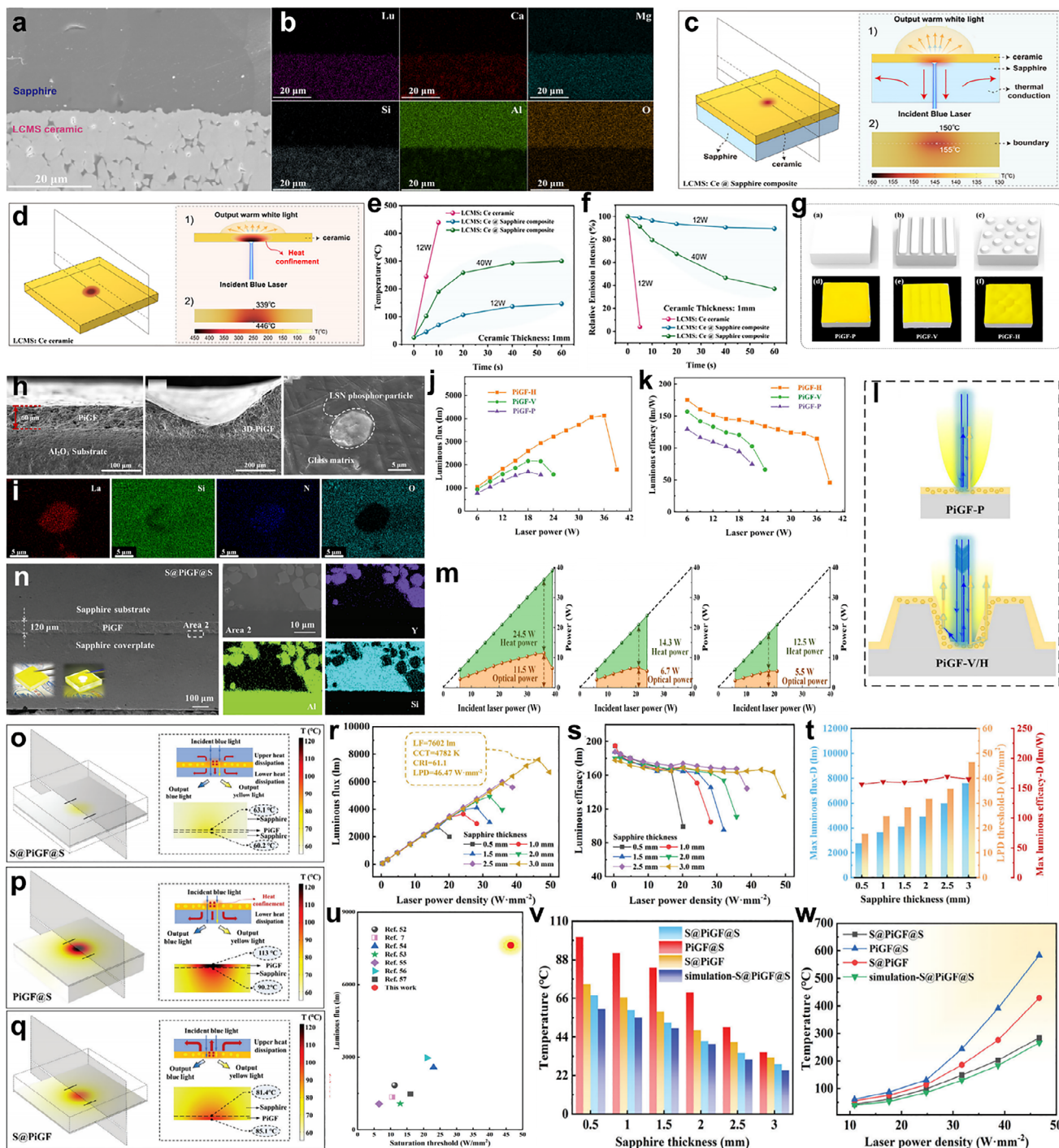


FIGURE 25 | Sapphire- and patterned- Al_2O_3 -assisted heterogeneous phosphor-conversion structures for high-power laser lighting. (a) Cross-sectional SEM image of the LCMS: Ce ceramic@sapphire composite interface. (b) EDS elemental maps of Lu, Ca, Mg, Si, Al, and O across the LCMS: Ce ceramic@sapphire interface. (c) Thermal-conduction model and simulated temperature field of the LCMS: Ce ceramic@sapphire composite under blue-laser excitation. (d) Thermal model and simulated temperature field of the monolithic LCMS: Ce ceramic, showing stronger heat confinement. (e) Temperature variation as a function of ceramic thickness for LCMS: Ce ceramic and LCMS: Ce ceramic@sapphire converters. (f) Time-dependent relative emission intensity of LCMS: Ce ceramic and LCMS: Ce ceramic@sapphire converters under laser irradiation. Reproduced with permission from literature [126]. Copyright 2025, Wiley-VCH GmbH. (g) Flat, valley-like, and hill-like Al_2O_3 substrates and the corresponding PiGF-P, PiGF-V, and PiGF-H converters. (h) Cross-sectional SEM images of the 3D-PiGF/ Al_2O_3 composite and the LSN phosphor/glass microstructure. (i) Elemental maps of La, Si, N, and O in the LSN phosphor/glass region. (j) Luminous flux of PiGF-H, PiGF-V, and PiGF-P as a function of laser power. (k) Luminous efficacy of PiGF-H, PiGF-V, and PiGF-P as a function of laser power. (l) Schematic comparison of light propagation in flat and patterned PiGF/ Al_2O_3 converters. (m) Optical-output and heat-power partitioning of PiGF-H, PiGF-V, and PiGF-P under increasing incident laser power. Reproduced with permission from literature [289]. Copyright 2026, Wiley-VCH GmbH. (n) Cross-sectional SEM image, EDS maps, and photographs of the sapphire@PiGF@sapphire sandwich converter. (o) Simulated thermal field and light/heat transport in the S@PiGF@S structure. (p) Simulated thermal field and heat confinement

utilization is insufficient; when scattering is too strong, light can become trapped in the film and suffer extraction losses. Only moderate scattering can balance blue-light absorption and light-extraction efficiency (Figure 27b). Yang et al. further demonstrated, using hexagonal boron nitride-YAG:Ce phosphor-in-glass films (h-BN-YAG:Ce PiGF) [287], that fillers and pores can simultaneously construct scattering centers and local heat-conduction channels, thereby improving color uniformity and thermal management (Figure 27c,d). The three-dimensional patterned PiGF reported by Lin et al. also shows that inclined sidewalls can increase the blue-light reflection path and enhance the probability of phosphor excitation (Figure 27e) [284].

Glassy interfaces also determine whether heat can rapidly leave the luminescent layer. In YAG: Ce phosphor-in-silica glass ceramic/phosphor-in-silica ceramic (PiSGC/PiSC) systems, Lin et al. introduced a glass-crystallization mechanism in which precipitated SiO₂ microcrystals establish heat-diffusion networks within the film, reducing local thermal quenching [284]. Analysis of thermal-saturation and optical-saturation contributions shows that, as laser power density increases, local temperature rise gradually becomes a major factor limiting conversion efficiency (Figure 27f). The multichannel thermal-conduction PiGF (MTC-PiGF) reported by Cheng et al. further demonstrates that a thinner bonding-glass layer helps reduce interfacial thermal resistance [291], enabling heat to be rapidly conducted through the sapphire cover plate and grooved Al₂O₃. By contrast, an overly thick glass layer weakens heat diffusion and increases the operating temperature (Figure 27g,h).

Interfacial chemical stability is another key factor in maintaining luminescence performance. The glass-ceramic interface results summarized by Lin et al. show that different glass systems and heat-treatment conditions can generate reaction layers of varying thickness at the phosphor/glass interface [7]. Excessive interdiffusion may alter the local environment of luminescent centers and reduce efficiency (Figure 27i). In La₃Si₆N₁₁: Ce phosphor-in-glass (LSN: Ce-PiG), You et al. used CL mapping, TEM, HRTEM, and fast Fourier transform (FFT) analysis to show that LSN: Ce crystalline particles maintain clear boundaries with the amorphous glass [296], indicating that low-reactivity interfaces can better preserve the original phosphor structure and luminescence properties (Figure 27j1–5). Stable glassy interfaces also improve thermal-quenching resistance and ageing reliability. Compared with YAG: Ce-PiG, the La₃Si₆N₁₁: Ce glass film (LSN: Ce-PiG) reported by You et al. retains higher relative emission intensity during heating and ageing [296], demonstrating that phosphor structural stability and low interfacial reactivity are beneficial for long-term operation (Figure 27k,l). The h-BN composite PiGF reported by Yang et al. shows slower luminous-flux degradation and lower local spot temperature under continuous laser irradiation, further confirming that an appropriate filler

content can simultaneously improve scattering, heat conduction, and stability (Figure 27m,n).

Overall, the design of glassy composite interfaces should balance refractive-index matching, moderate scattering, thin-layer heat conduction, low interfacial reactivity, and thermal-expansion matching. The value of the glassy phase lies not only in lowering processing temperature, but also in establishing tunable photothermal transport and reliable bonding between crystalline luminescent phases and device substrates.

7.5 | Inspiration From MOF Glasses and Organic-Inorganic Glassy Interfaces for Low-Temperature Integration of Phosphor Ceramics

In phosphor ceramic research, glassy phases are commonly used as media for low-temperature bonding, particle encapsulation, shape formation, and interfacial connection. PiG, PiGF, and glass-ceramic routes complement conventional high-temperature ceramic sintering because glassy phases can soften, wet, and encapsulate phosphor particles at relatively low temperatures, thereby preventing thermally sensitive red phosphors, heterogeneous substrates, and patterned device structures from being exposed to high-temperature sintering. However, conventional inorganic glasses also suffer from low thermal conductivity, interfacial reactions, thermal-expansion mismatch and long-term photothermal ageing. Future low-temperature integration of phosphor ceramics therefore requires not only glassy phases that can encapsulate, but glassy interfacial layers that can be designed.

MOF glasses and organic-inorganic glassy composites offer new inspiration for this challenge. As shown in Figure 28a–d, Zn(Im)_{1.75}(bIm)_{0.25} (ZIF-62), can be transformed from crystalline powder into glassy films through film formation and heat treatment [297]. This vitrification process not only disrupts long-range order but also alters local packing and luminescence behavior. Figure 28e,f further show that, whether in metal-ligand coordination units within MOF glasses or local structural units in inorganic phosphate glasses, glassy materials are not simply disordered bonding phases, they are functional networks with tunable local structures [86]. For phosphor ceramics, this suggests that glassy interfaces can evolve from passive encapsulation layers into active regulation layers. This concept is closely related to phosphor-particle dispersion and interfacial stability in glassy phases. Figure 28g–i show interfacial interactions and dispersion behavior of YAG: Ce particles in glass melts, indicating that the wetting behavior, interfacial energy, and rheological properties of the glassy phase directly affect phosphor uniformity and aggregation [298]. Furthermore, Figure 28j summarizes composite systems such as luminescent MOF glasses, quantum dot@MOF (QD@MOF) glasses and rare-earth-related MOF (RE@MOF)

in the PiGF@S structure. (q) Simulated thermal field and heat transport in the S@PiGF structure. (r) Luminous flux of S@PiGF@S converters with different sapphire thicknesses as a function of laser power density. (s) Luminous efficacy of S@PiGF@S converters with different sapphire thicknesses as a function of laser power density. (t) Maximum luminous flux, luminous efficacy, and maximum incident laser power density as a function of sapphire thickness. (u) Operating temperature comparison of S@PiGF@S, PiGF@S, and S@PiGF converters with different sapphire thicknesses. (v) Comparison of maximum luminous flux and saturation threshold between S@PiGF@S and reported laser phosphor converters. (w) Operating temperature of S@PiGF@S, PiGF@S, and S@PiGF as a function of laser power density. Reproduced with permission from literature [84]. Copyright 2024, Wiley-VCH GmbH.

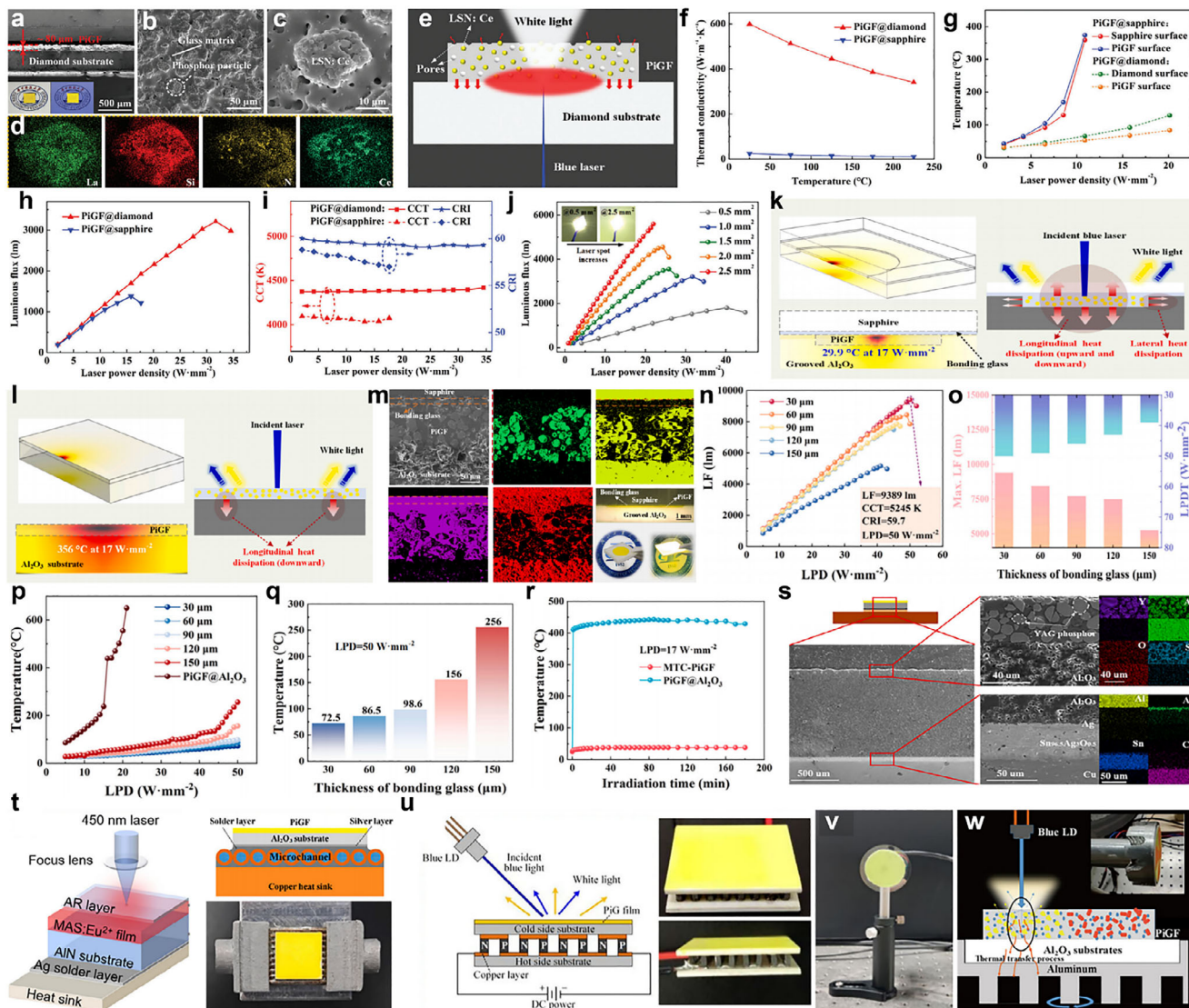


FIGURE 26 | Diamond-, multi-channel-, and metal-assisted thermal-management structures for PiGF and ceramic-film laser converters. (a) Cross-sectional SEM image of the LSN: Ce PiGF@diamond converter. (b) SEM image showing the glass matrix and embedded phosphor particles in PiGF@diamond. (c) SEM image of an individual LSN: Ce phosphor particle. (d) EDS elemental maps of the PiGF@diamond composite. (e) Schematic illustration of blue-laser excitation, white-light output, and heat spreading through the diamond substrate. (f) Temperature-dependent thermal conductivity of PiGF@diamond compared with PiGF@sapphire. (g) Surface temperature of PiGF@diamond and PiGF@sapphire as a function of laser power density. (h) Luminous flux of PiGF@diamond and PiGF@sapphire as a function of laser power density. (i) Correlated color temperature and color rendering index of PiGF@diamond and PiGF@sapphire under increasing laser power density. (j) Luminous flux of PiGF@diamond under different laser spot areas. Reproduced with permission from literature [290]. Copyright 2024, Wiley-VCH GmbH. (k) Simulated heat-flow path and temperature field of the multi-channel thermal-conductive PiGF structure. (l) Simulated heat-flow path and temperature field of the conventional PiGF@Al₂O₃ structure. (m) Cross-sectional SEM image, EDS maps, and photographs of the MTC-PiGF composite. (n) Luminous flux of MTC-PiGF converters with different bonding-glass thicknesses as a function of laser power density. (o) Maximum luminous flux and laser power density threshold as a function of bonding-glass thickness. (p) Operating temperature of MTC-PiGF converters with different bonding-glass thicknesses and conventional PiGF@Al₂O₃ under increasing laser power density. (q) Operating temperature at 50 W mm⁻² as a function of bonding-glass thickness. (r) Long-term temperature stability of MTC-PiGF and PiGF@Al₂O₃ under continuous laser irradiation. Reproduced with permission from literature [291]. Copyright 2025, Elsevier B.V. (s) Cross-sectional architecture, SEM images, and EDS maps of a PiGF/Al₂O₃/metal heat-sink assembly. Reproduced with permission from literature [292]. Copyright 2024, Elsevier. (t) Schematic of a reflective laser-lighting converter using a MAS: Eu²⁺ film, anti-reflection layer, AlN-based heat-spreading substrate, and solder layer. Reproduced with permission from literature [56]. Copyright 2023, Wiley-VCH. (u) Schematic and photograph of a PiGF/Al₂O₃ converter integrated with a copper heat sink through a silver/solder interlayer. Reproduced with permission from literature [293]. Copyright 2020, IEEE. (v) Photograph of a phosphor-converter module mounted on a heat-sink holder for laser excitation. Reproduced with permission from literature [294]. Copyright 2022, Wiley-VCH. (w) Schematic of a PiGF/Al₂O₃ converter coupled to an aluminum heat sink under blue-LD excitation. Reproduced with permission from literature [295]. Copyright 2023, The Author(s). Published by Tsinghua University Press.

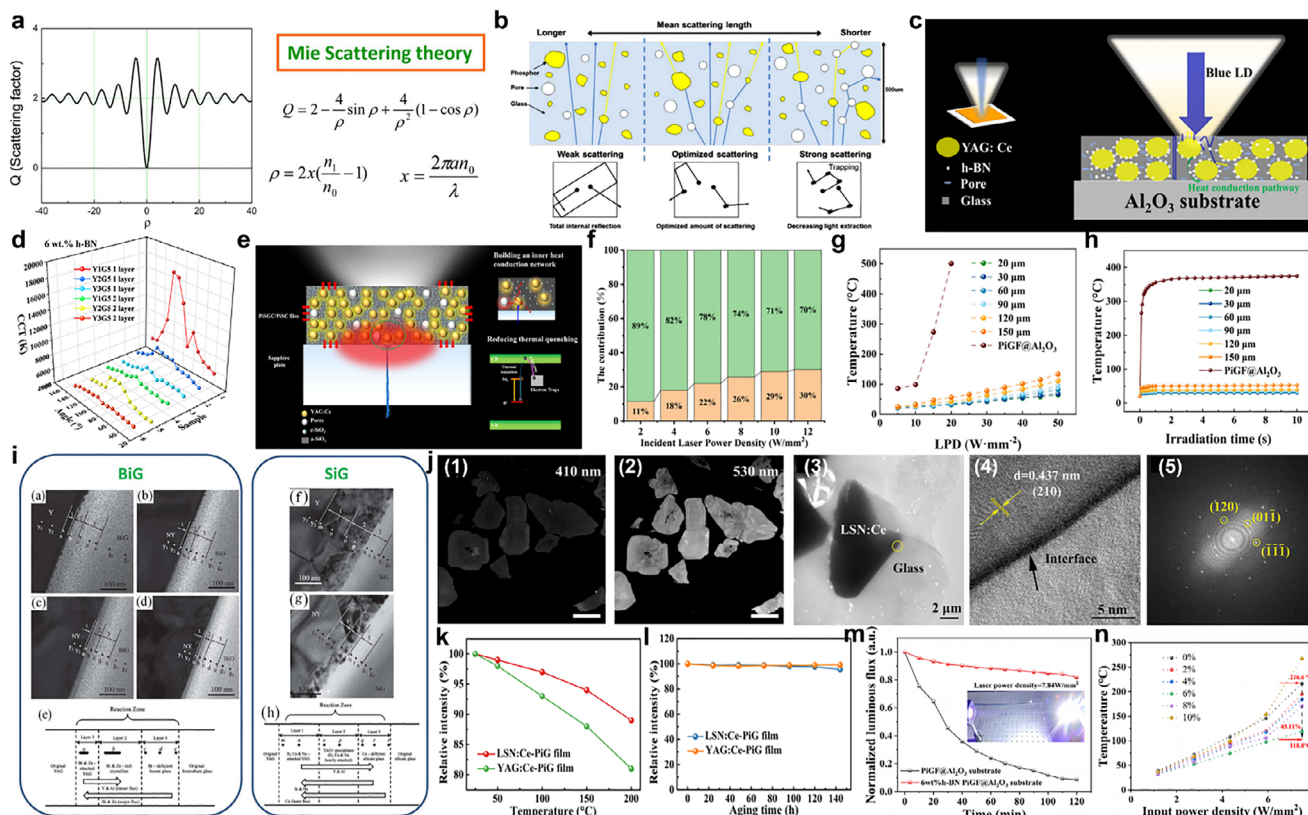


FIGURE 27 | Effects of glassy interfaces on light propagation, heat transport, interfacial reactions, and reliability in phosphor-conversion composites. (a) Scattering factor calculated according to Mie scattering theory (n_0 and n_1 are the RI of medium and scatterer, respectively; a is the radius of scatterer, and λ is the wavelength of the incident light). (b) Schematic illustration of weak, optimized, and strong scattering in phosphor-glass composites with different mean scattering lengths. Reproduced with permission from literature [7]. Copyright 2018, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (c) Schematic mechanism of h-BN-modified YAG: Ce-PiGF on an Al_2O_3 substrate, showing blue-laser excitation and heat-conduction pathways. (d) Angular CCT distribution of 6 wt% h-BN-containing B-Y PiGF@t- Al_2O_3 with different YAG: Ce/glass ratios and printing layers. Reproduced with permission from literature [287]. Copyright 2025, Wiley-VCH GmbH. (e) Luminescence-enhancement mechanism of YAG: Ce PiSGC/PiSC film-on-sapphire through internal heat-conduction networks. (f) Calculated contributions of optical saturation and thermal saturation under increasing incident laser power density. Reproduced with permission from literature [284]. Copyright 2022, Wiley-VCH GmbH. (g) Working temperature of MTC-PiGF converters with different bonding-glass thicknesses as a function of laser power density, compared with PiGF@ Al_2O_3 . (h) Temperature evolution of MTC-PiGF converters with different bonding-glass thicknesses under laser irradiation, compared with PiGF@ Al_2O_3 . Reproduced with permission from literature [291]. Copyright 2025, Elsevier B.V. (i) TEM images and reaction-zone models of phosphor/glass interfaces in BiG and SiG glass ceramics. Reproduced with permission from literature [7]. Copyright 2018, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (j1) CL mapping image of LSN: Ce-PiG monitored at 410 nm. (j2) CL mapping image of LSN: Ce-PiG monitored at 530 nm. (j3) Bright-field TEM image of an LSN: Ce particle embedded in the glass matrix. (j4) HRTEM image of the LSN: Ce/glass interface. (j5) FFT pattern corresponding to the selected interfacial region. (k) Temperature-dependent relative emission intensity of LSN: Ce-PiG and YAG: Ce-PiG films. (l) Aging-time-dependent relative emission intensity of LSN: Ce-PiG and YAG: Ce-PiG films. (m) Long-term normalized luminous flux of PiGF@ Al_2O_3 and 6 wt% h-BN PiGF@ Al_2O_3 under continuous laser irradiation. (n) Local temperature of PiGF@ Al_2O_3 converters with different h-BN contents as a function of input power density. Reproduced with permission from literature [296]. Copyright 2018, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

glasses, demonstrating that crystalline functional units and glassy matrices can form diverse composite architectures [299]. This shares a similar interfacial logic with the “phosphor particle-glassy phase-ceramic/substrate” structures found in phosphor ceramics.

Inspired by this concept, three low-temperature interfacial strategies may be explored in future work. First, thin organic-inorganic glassy coating layers could be constructed on the surfaces of $(\text{Sr,Ca})\text{AlSiN}_3$: Eu^{2+} (CASN: Eu), K_2SiF_6 : Mn^{4+} (KSF: Mn^{4+}), Eu^{2+} -activated oxides or $\text{Cr}^{3+}/\text{Ni}^{2+}$ -activated near-infrared phosphors to reduce corrosion during glass melting or sintering [300, 301]. Second, low-temperature bonding interlayers could be

introduced into PiGF, ceramic-glass, or ceramic-metal/sapphire composites to buffer thermal-expansion mismatch and improve adhesion. Third, rare-earth ions, quantum dots or sensitizing centers could be immobilized within glassy networks and coupled with conventional inorganic phosphor ceramics to form composite luminescent layers.

It should be emphasized that MOF glasses cannot currently replace high-power phosphor ceramics such as YAG: Ce, LuAG: Ce, $\text{Al}_2\text{O}_3/\text{YAG}$: Ce, or MgAl_2O_4 : Cr^{3+} . Their thermal conductivity, hygrothermal stability, photothermal ageing resistance, scalable forming capability, and reliability under high-power laser irradiation are still insufficient for mature light converters.

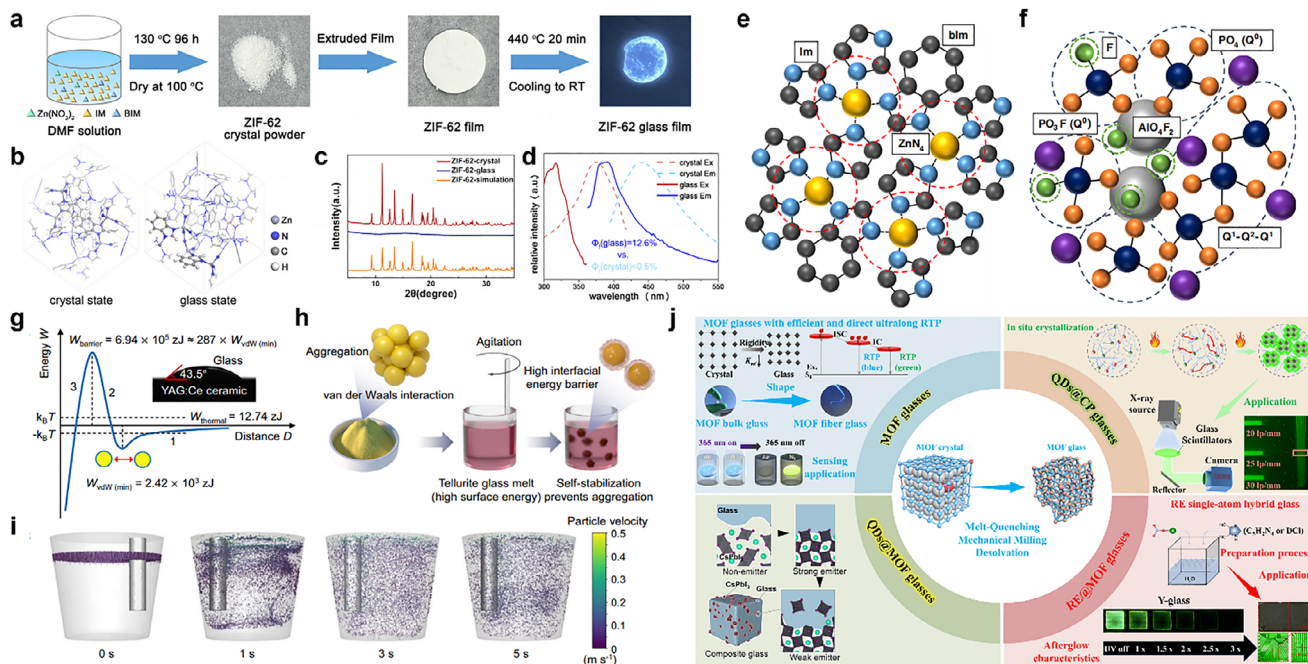


FIGURE 28 | MOF glasses and glass-state composite interfaces for low-temperature phosphor ceramic integration. (a) Preparation of a ZIF-62 glass film from solution-synthesized ZIF-62 crystal powder through film extrusion and thermal vitrification. (b) Structural models of ZIF-62 in the crystalline and glassy states. (c) XRD patterns of crystalline ZIF-62, ZIF-62 glass, and simulated ZIF-62. (d) Excitation and emission spectra of crystalline and glassy ZIF-62, showing the luminescence change after vitrification. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [297]. Copyright 2025, The Author(s). The Royal Society of Chemistry. (e) Local coordination structure of ZIF-62 with Zn_4N nodes and imidazolate/benzimidazolate linkers. (f) Representative local structural units in inorganic phosphate-based glass networks. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [86]. Copyright 2020, The Author(s). Published by Springer Nature. (g) Potential energy diagram of YAG:Ce particles self-stabilization. (h) Schematic diagram of uniform dispersion and self-stabilization of YAG:Ce particles in tellurite glass melt. (i) Time-dependent fluent simulation of YAG particles dispersed in tellurite glass melt (at different stages of 0, 1, 3, and 5 s) under the agitation speed of five revolutions per second (rev s^{-1}), and the color depth of the particle represents the velocity at that moment. Images used courtesy of ANSYS, Inc. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [298]. Copyright 2024, The Author(s). Published by Springer Nature. (j) Overview of luminescent MOF-glass systems and related applications, including MOF glasses, QD@MOF glasses, and rare-earth-containing MOF glasses. Reproduced with permission from literature [299]. Copyright 2026, Elsevier B.V.

The purpose of this section is therefore not to present MOF glasses as a new primary materials system, but to use them as conceptual inspiration for low-temperature heterogeneous interface design. Through designable glassy networks, new links may be established among phosphor-particle protection, glass-phase compatibility, interfacial stress buffering, and multifunctional luminescent integration.

7.6 | Device Integration and Application Expansion of Low-Temperature Composite Light Converters

The preceding sections of Chapter 7 show that the significance of glassy composite interfaces lies not only in lowering processing temperature, but also in driving phosphor ceramics from monolithic bulk materials toward light-conversion devices that are film-formable, patternable, thermally manageable, and system-integrable. Conventional transparent ceramic routes mainly address high density, high thermal stability, and strong resistance to laser irradiation. By contrast, PiG, PiGF, cold-sintered PiC, and glass-crystallization-derived translucent ceramic routes further

address a more application-oriented question: how can the light-conversion layer work cooperatively with sapphire, Al_2O_3 , metal heat sinks, rotating color wheels, laser projection systems, and visible light communication systems? The focus of Section 7.6 therefore shifts from “whether the material can be fabricated” to “how the material enters devices.”

The rapid thermal processing route for PiGF proposed by Wang et al. provides an important strategy for fast shaping and high-throughput screening of low-temperature composite light converters [80]. As shown in Figure 29a, phosphor powders, glass powders, and organic vehicles are mixed, coated onto a sapphire substrate, dried, and then converted into PiGF by rapid thermal treatment. The key to this process is the use of high-power infrared irradiation to achieve second-scale heating and short-time sintering; the rapid thermal annealing (RTA) apparatus, finite-element temperature simulation and experimental temperature profiles are shown in Figure 29b–e. Compared with conventional long-duration sintering, rapid thermal treatment markedly shortens the contact time between phosphor particles and softened glass, thereby reducing thermal corrosion and interfacial reactions. More importantly, Wang et al. combined this

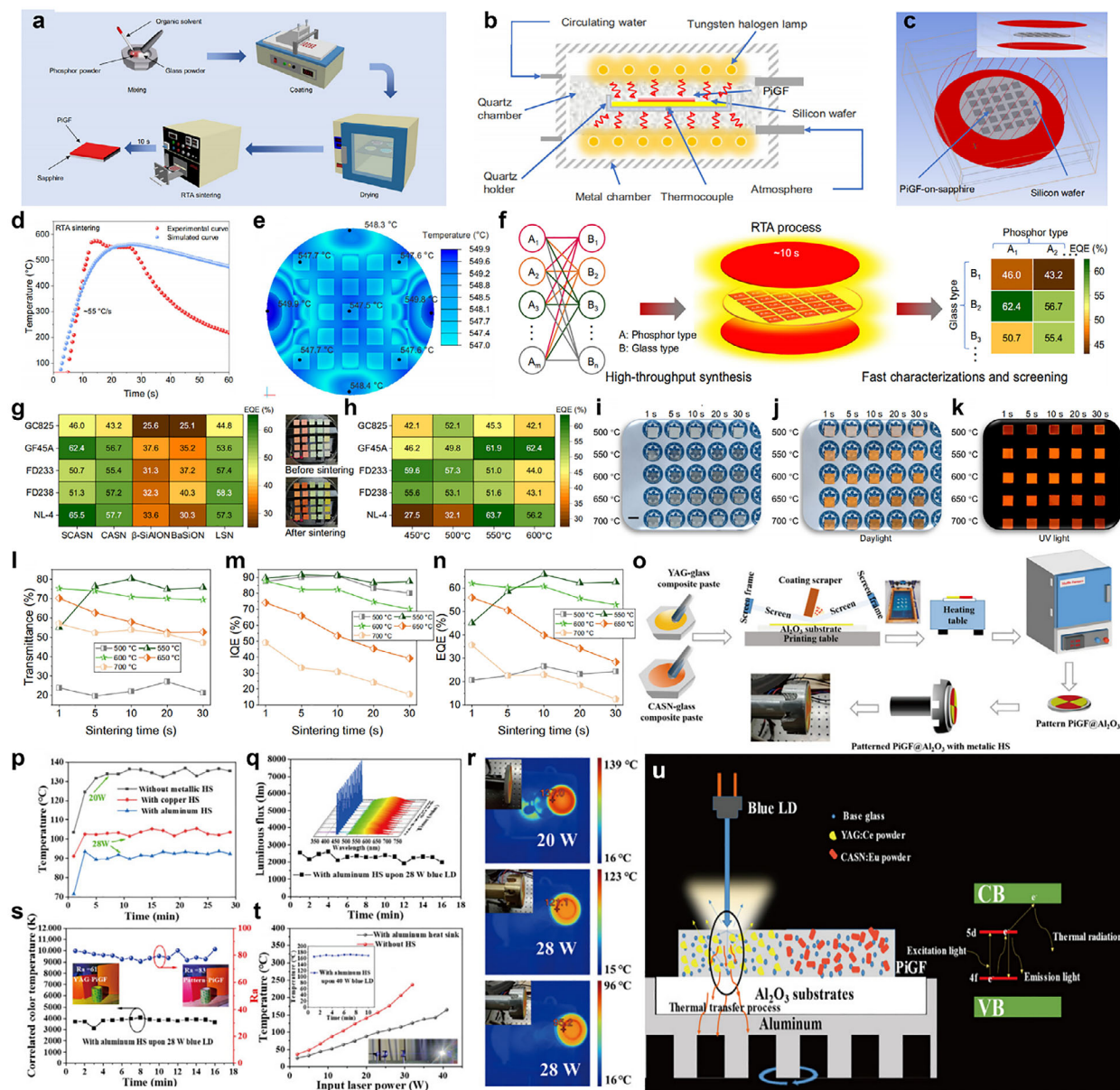


FIGURE 29 | Rapid PiGF processing, high-throughput screening, and patterned PiGF thermal management for laser-driven applications. (a) Schematic illustration of the RTA fabrication process for PiGF, including phosphor/glass powder mixing, coating, drying, and RTA sintering. (b) Internal structure of the RTA apparatus, showing the quartz chamber, tungsten halogen lamps, silicon wafer, thermocouple, atmosphere control, and water-cooling system. (c) Three-dimensional finite-element model of PiGF-on-sapphire samples placed on a silicon wafer for thermal simulation. (d) Experimental and simulated temperature-time profiles during the RTA process. (e) Simulated temperature distribution of the sample array on the silicon wafer during RTA. (f) Workflow for high-throughput synthesis and rapid screening of PiGFs with different phosphor and glass combinations. (g) EQE map of PiGFs prepared from different phosphor/glass combinations, with photographs of the sample array before and after sintering. (h) EQE map of representative PiGFs processed under different RTA temperatures. (i) Photographs of screened samples processed at different temperatures and sintering times. (j) Daylight photographs of PiGF arrays prepared under different RTA conditions. (k) UV-light photographs of PiGF arrays, showing luminescence after different RTA treatments. (l) Transmittance of PiGF samples as a function of sintering time and temperature. (m) IQE of PiGF samples as a function of sintering time and temperature. (n) EQE of PiGF samples as a function of sintering time and temperature. Reproduced under the terms of the CC-BY-NC-ND Creative Commons Attribution 4.0 International license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>) [80]. Copyright 2025, The Author(s). Published by Springer Nature. (o) Fabrication schematic of patterned CASN:Eu PiGF-YAG:Ce PiGF@Al₂O₃ integrated with a metallic heat sink. (p) Local laser-spot temperature evolution of patterned PiGF@Al₂O₃ samples with and without metallic heat sinks under blue-LD excitation. (q) Luminous flux stability of patterned PiGF@Al₂O₃ with an aluminum heat sink under 28 W blue-LD excitation. (r) Infrared thermal images of patterned PiGF@Al₂O₃ devices under different blue-LD powers and heat-sink configurations. (s) CCT and CRI stability of patterned PiGF@Al₂O₃ with an aluminum heat sink under 28 W blue-LD excitation. (t) Comparison of device temperature as a function of input laser power with and without heat-sink-assisted thermal management. (u) Schematic mechanism of thermal management and luminescence enhancement in patterned PiGF@Al₂O₃ with a metallic heat sink. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [295]. Copyright 2025, The Author(s). Published by Tsinghua University Press.

process with high-throughput screening. By constructing combinatorial matrices of different phosphor and glass compositions, they rapidly compared EQE, transmittance, IQE, and overall luminescence performance (Figure 29f–n). This demonstrates that low-temperature PiGF routes have evolved from single-sample fabrication into device-material platforms suitable for rapid screening and scalable optimization.

At the device-structure level, the patterned $\text{CaAlSiN}_3\text{:Eu}^{2+}$ (CASN: Eu) PiGF-YAG: Ce PiGF/ Al_2O_3 composite reported by Yang et al. further shows that glassy interfaces can directly serve laser displays and thermal management [295]. As shown in Figure 29o, YAG: Ce and CASN: Eu glass composite pastes can be blade-coated or printed onto Al_2O_3 substrates to form patterned luminescent layers, which are then integrated with metal heat sinks. In this design, different luminescent regions perform different spectral functions: the YAG: Ce region provides efficient yellow conversion, the CASN: Eu region compensates the red component, and the Al_2O_3 substrate and metal heat sink provide heat spreading. Figure 29p–t shows that the metal heat sink substantially reduces local temperature rise under laser irradiation and improves the stability of luminous flux, CCT, and CRI during long-term operation. Figure 29u further illustrates the thermal-management mechanism: heat generated by laser excitation is rapidly conducted through the PiGF/ Al_2O_3 /metal heat-sink pathway, suppressing thermal quenching and improving emission stability under high-power laser driving.

The cold-sintered CaF_2 nanoceramic-based PiC reported by Gao et al. provides another low-temperature ceramic-integration route [302]. Compared with conventional glass-based PiG, cold-sintered PiC is closer to an inorganic ceramic matrix. Compared with conventional high-temperature transparent ceramics, it can encapsulate thermally sensitive phosphors at much lower temperatures. As shown in Figure 30a, the isotropic CaF_2 matrix is favorable for improving light propagation and scattering pathways and can serve as a transparent inorganic encapsulation platform for multicolor phosphors such as YAG: Ce and $\text{CaAlSiN}_3\text{:Eu}^{2+}$ (CASN: Eu). Figure 30b,c shows the chromaticity-coordinate regulation of WLEDs with different yellow/red phosphor ratios, demonstrating that cold-sintered PiC can achieve warm-white and high-color-rendering output through compositional design. Figure 30d further compares CaF_2 -PiC with PiG, phosphor-in-silicone (PiS) and other encapsulation systems, showing a favorable balance between luminous efficacy and CRI. Figure 30e indicates that PiC exhibits higher luminescence stability than PiS under elevated temperature. The core value of cold-sintered PiC is therefore that it provides a low-temperature inorganic ceramic-encapsulation window for thermally sensitive red phosphors and advances multicolor high-color-rendering white converters from “glass encapsulation” toward “ceramic encapsulation.”

Sun et al. prepared wafer-scale Ce^{3+} -doped garnet-type $\text{Lu}(\text{Ca,Mg})\text{Al}_3\text{Si}_2\text{O}_{12}\text{:Ce}^{3+}$ (LCMAS: Ce) translucent ceramics through a mild stepwise crystallization strategy in aluminosilicate glass [303]. This material is not a conventional powder-sintered transparent ceramic but is obtained by a glass-to-ceramic full-crystallization process that regulates crystallization barriers, ion-migration channels, and dense crystallization behavior. Figure 30f–h shows that this method can produce 5 cm-scale

translucent ceramic wafers and ring-shaped samples, with dense grain structures and polycrystalline orientation distributions. Figure 30i,j show that stepwise crystallization drives the transition from precursor glass to high-crystallinity ceramic. Figure 30k,l further demonstrate that this translucent ceramic outperforms conventional glass-based composites in hardness, thermal conductivity, and thermal stability. More importantly, Figure 30m,n shows that, under blue-laser excitation, the LCMAS: Ce translucent ceramic can deliver high luminous flux and high luminous efficacy, demonstrating its potential as a high-power light-conversion medium. Sun et al. further extended the application of phosphor ceramics from lighting to visible light communication [303]. As shown in Figure 31a, laser-driven LCMAS: Ce ceramic white-light sources were envisioned for low-altitude intelligent networks, transportation, shipping, and urban information interconnection. Figure 31b shows the visible light communication (VLC) testing system, in which a blue LD is converted by the ceramic into a white-light signal, which is then received and decoded using a detector, oscilloscope, and computer. Figure 31c,d show that this light source exhibits nanosecond-scale response characteristics, and that after filtering out the slow-decay fluorescence component, the -3 dB bandwidth increases from 7.4 MHz to 71.8 MHz. The eye diagrams in Figure 31e,f further demonstrate recognizable signal openings at data rates from 10 Mbps to 100 Mbps. Finally, Figure 31g–i shows letter-signal decoding, an outdoor white-light communication demonstration over approximately 1200 m, and a comparison of communication distance with existing technologies. These results indicate that phosphor ceramics are no longer merely passive light-conversion plates in lighting devices, but can become photonic engines integrating illumination, communication, and information transmission.

Taken together, Figures 29–31 show that the future development of low-temperature composite light converters should proceed along three directions. The first is platform-oriented processing, in which rapid thermal treatment, high-throughput screening, and short-time sintering are used to reduce interfacial reactions and improve fabrication efficiency. The second is device-oriented structuring, in which PiGF patterning, Al_2O_3 /metal heat-sink coupling and cold-sintered ceramic encapsulation enable multicolor spectral regulation and high-power thermal management. The third is application-oriented intelligence, in which glass-crystallized translucent ceramics and laser-driven systems expand phosphor ceramics into new scenarios such as laser displays, long-distance white-light communication, and low-altitude intelligent networks. The future development of phosphor ceramics should therefore not focus only on the emission intensity of a single material, but on integrated design across phosphor stability, glass/ceramic interfaces, heat-diffusion architectures, optical-field regulation, and system-level functionality.

7.7 | Bottlenecks and Future Directions of Glassy Composite Interfaces and Low-Temperature Heterogeneous Integration

Building on the device-oriented perspective discussed above, glassy composite interfaces and low-temperature heterogeneous

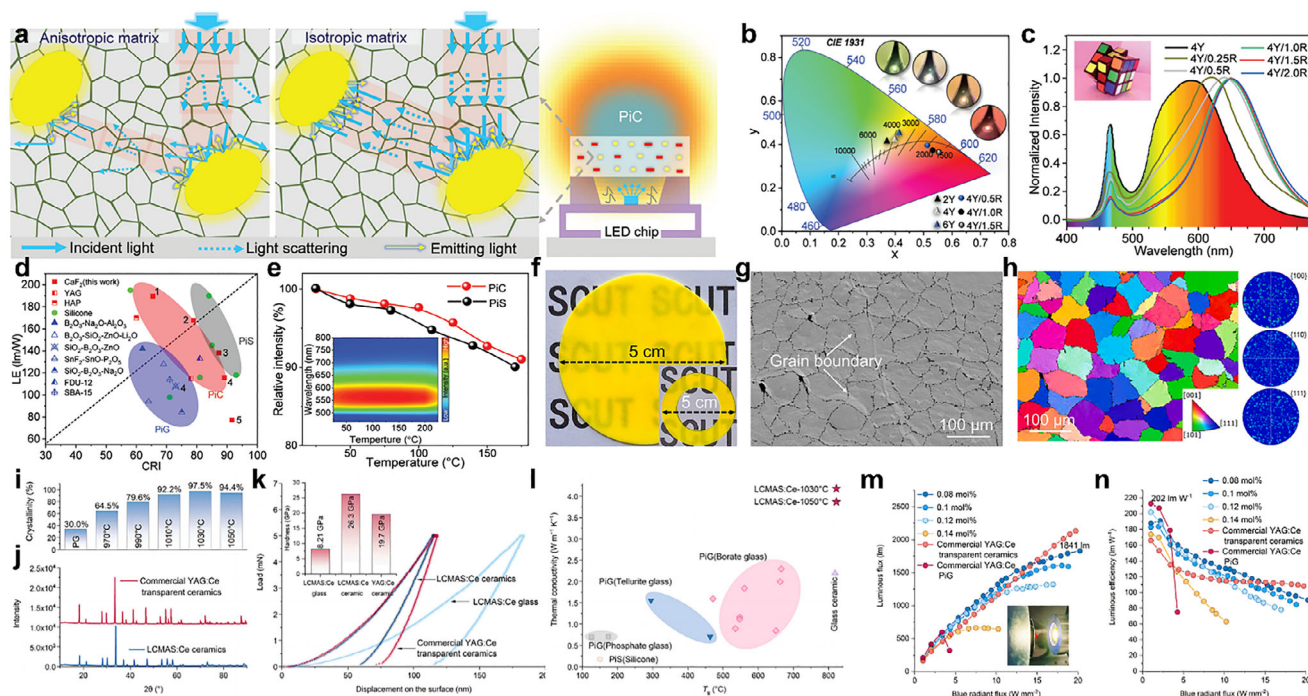


FIGURE 30 | Low-temperature ceramicized phosphor converters and glass-crystallized quasi-transparent ceramics for high-power photonic conversion. (a) Schematic comparison of light propagation in fluorescent ceramic composites with anisotropic and isotropic matrices, together with the assembled WLED device based on PiC. (b) CIE 1931 chromaticity coordinates of WLEDs constructed from blue chips and CaF_2 -based PiC converters with different yellow/red phosphor ratios. (c) Lighting picture under the operating 4Y/1.5R WLED and EL spectra of PiC with various contents of phosphors, with 0.5 mm thickness. (d) Comparison of luminous efficacy and color rendering index among CaF_2 -based PiC converters and reported PiG, PiS, silicone, and other phosphor-conversion systems. (e) Temperature-dependent relative fluorescence intensities of PiC and phosphor-in-silicone (PiS), showing improved thermal stability of the PiC converter. Reproduced with permission from literature [302]. Copyright 2023, Wiley-VCH GmbH. (f) Optical photograph of a wafer-scale LCMAS: Ce quasi-transparent ceramic disc and ring with a diameter of 5 cm. (g) SEM image with grain-boundary mapping of the LCMAS: Ce quasi-transparent ceramic. (h) EBSD grain-orientation map and corresponding pole figures of the LCMAS: Ce quasi-transparent ceramic. (i) Crystallinity evolution of LCMAS: Ce samples after stepped crystallization at different temperatures. (j) XRD patterns of LCMAS: Ce ceramics compared with commercial YAG: Ce transparent ceramics. (k) Nanoindentation load-displacement curves and hardness comparison of LCMAS: Ce glass, LCMAS: Ce ceramic, and commercial YAG: Ce transparent ceramics. (l) Thermal conductivity versus glass transition temperature comparison among LCMAS: Ce ceramics, PiG, PiS, and reported glass-ceramic systems. (m) Luminous flux of LCMAS: Ce ceramics and reference YAG: Ce transparent ceramics/PiG as a function of blue radiant flux. (n) Luminous efficiency of LCMAS: Ce ceramics and reference YAG: Ce transparent ceramics/PiG as a function of blue radiant flux. Reproduced with permission from literature [303]. Copyright 2026, Elsevier Inc.

integration still face several unresolved challenges. The first is the trade-off between low-temperature processability and high-power reliability. Lower processing temperatures can protect thermally sensitive phosphors and reduce interfacial reactions, but they may also result in residual porosity, incomplete densification, weak interfacial bonding, or limited heat conduction through the glassy phase. Therefore, low-temperature processing should not be evaluated solely by processing temperature; the resulting density, interfacial thermal resistance, mechanical integrity, and long-term photothermal stability must also be considered.

The second challenge is the coupled optimization of optical transport and thermal management. Glass composition, phosphor loading, filler content, layer thickness, pore structure, and refractive-index contrast jointly determine blue-light absorption, scattering, emission extraction, and heat diffusion. Insufficient scattering may reduce excitation-light utilization, whereas excessive scattering or an overly thick conversion layer can trap emitted photons, reduce light-extraction efficiency, and increase

local heat accumulation. Similarly, thermally conductive fillers or substrates may improve heat spreading, but excessive filler loading can dilute the emitting phase, modify the optical path and reduce the effective conversion volume. The optimal design therefore requires a balance among optical absorption, scattering, extraction, thermal conduction, and luminescent-phase fraction.

A third bottleneck concerns interfacial chemical and mechanical reliability. Reactions between phosphors and glass, moisture penetration, thermal-expansion mismatch, insufficient wetting, and repeated laser-induced thermal cycling may progressively degrade interfacial adhesion, chromaticity stability, and output performance. These effects are particularly important for patterned, multilayer and substrate-integrated converters, in which multiple interfaces participate simultaneously in light propagation and heat dissipation. In addition, comparisons among reported low-temperature composite converters remain difficult because processing route, layer thickness, excitation power density, substrate, heat-sink configuration, and thermal boundary conditions are not yet consistently reported.

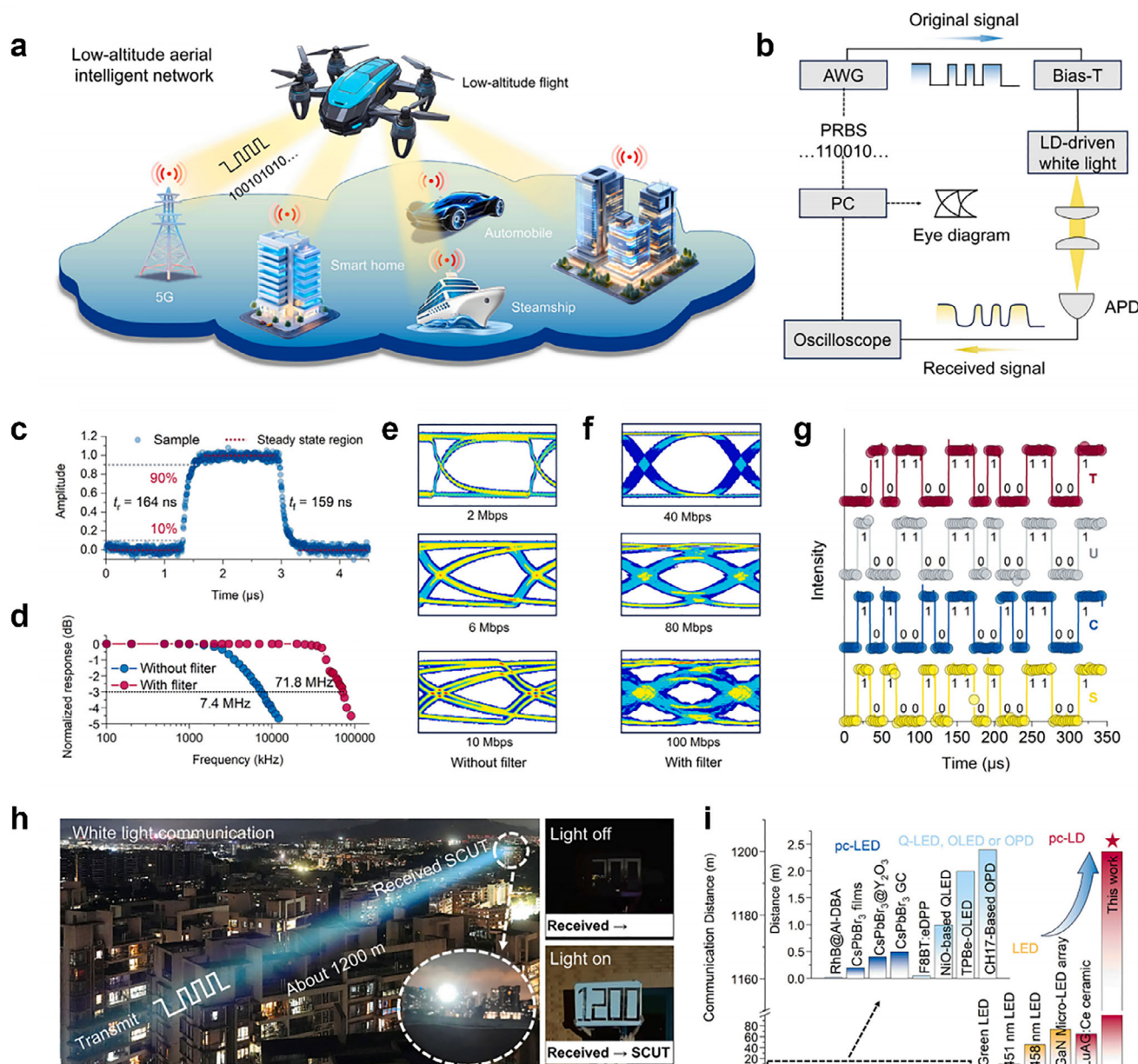


FIGURE 31 | Laser-driven LCMAS: Ce ceramic white-light source for visible-light communication. (a) Schematic illustration of a low-altitude aerial intelligent network enabled by laser-driven LCMAS: Ce ceramic white-light sources. (b) Experimental setup for visible-light communication, including the arbitrary waveform generator, bias-tee, LD-driven white-light source, avalanche photodiode, oscilloscope, computer, and eye-diagram analysis. (c) Time-domain response of the laser-driven white-light source, showing rise and fall times of the modulated signal. (d) Frequency response curves of the laser-driven white-light source with and without a blue band-pass filter, showing enhanced -3 dB bandwidth after filtering. (e) Eye diagrams measured without the blue filter at data rates of 2, 6, and 10 Mbps. (f) Eye diagrams measured with the blue filter at data rates of 40, 80, and 100 Mbps. (g) Decoded waveform signals corresponding to the transmitted letters “S,” “C,” “U,” and “T.” (h) Outdoor long-distance white-light communication demonstration over approximately 1200 m, with photographs of the transmitted and received signals. (i) Comparison of communication distance between this work and reported visible-light communication technologies. Reproduced with permission from literature [303]. Copyright 2026, Elsevier Inc.

Future studies should therefore combine chemically stable low-melting glass compositions with thermally conductive and optically compatible fillers or substrates, graded, or multilayer interfaces, and rapid low-temperature processing strategies. Coupled optical-thermal modelling, in situ temperature monitoring and long-term ageing tests should be used to optimize scattering, light extraction, heat spreading, and interfacial bonding simultaneously. Evaluation should also move beyond isolated EQE, transmittance, or thermal-

conductivity values and include common device-level metrics, such as output power, conversion efficiency, surface-temperature rise, chromaticity drift, saturation threshold, and continuous-operation lifetime under application-relevant excitation. Such an integrated strategy will be essential for translating low-temperature composite converters from laboratory demonstrations into scalable laser lighting, displays, visible-light communication, and other high-power photonic systems.

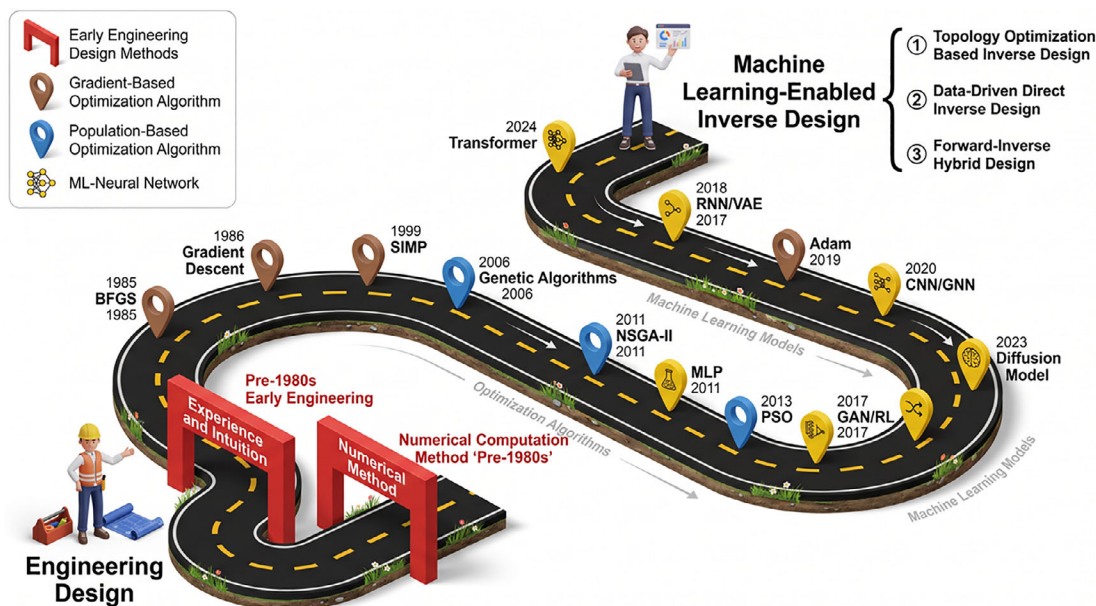


FIGURE 32 | The development history of inverse design in the field of engineering. From the initial trial-and-error approach to the current three ML-based inverse design methods. Adapted with permission from literature [306]. Copyright 2026, Wiley-VCH GmbH.

8 | Machine-Learning-Guided Design of Phosphor Ceramics

8.1 | From Empirical Trial-and-Error to Data-Driven Design

The conventional design of phosphor ceramics relies largely on empirical trial and error. Candidate hosts are first selected according to known crystal structures, ionic-radius matching, valence stability, and luminescent-center preference, and are then gradually optimized through dopant regulation, powder synthesis, ceramic sintering, and device testing [304, 305]. This strategy has promoted the development of systems such as YAG: Ce, LuAG: Ce, $\text{Al}_2\text{O}_3/\text{YAG}$: Ce, and MgAl_2O_4 : Cr^{3+} . However, its efficiency becomes clearly limited when facing multicomponent compositions, multiple luminescent centers, numerous processing parameters, and multiple device metrics. The introduction of ML aims to establish predictable relationships between composition/structure/processing and performance within this complex variable space.

As shown in Figure 32, Lin et al. summarized the evolution of engineering design from early empirical design to numerical calculation, gradient optimization, population-based optimization and, ultimately, ML-assisted inverse design [306]. For phosphor ceramics, this transition means that research no longer needs to proceed only by “synthesizing a material and then testing its properties.” Instead, one can start from target performance metrics, such as emission wavelength, thermal-quenching temperature, quantum efficiency, transmittance, thermal conductivity, or laser saturation threshold, and inversely screen possible host structures, activator ions, dopant concentrations, and ceramic-processing windows.

For phosphor materials specifically, Lee and Bröckh summarized a general workflow for machine-learning-enabled discovery of

light-emitting diode-compatible phosphors (Figure 33a) [307]. This workflow begins with the collection of literature data, structural databases, and experimental datasets, followed by the transformation of material composition, crystal structure, and local coordination into computable descriptors, and then data cleaning, model training, and model validation. Behara et al. further proposed a phosphor-design workflow from the perspective of an “inverse problem” (Figure 33b) [308]. Target properties such as λ_{ex} , λ_{em} , CCT, CRI, and LE are first defined, the search space and algorithms are then selected; and the candidate composition range is progressively narrowed through training sets, test sets, validation sets, and experimental feedback. For phosphor ceramics, this workflow must further incorporate ceramic-processing data, including sintering temperature, phase stability, grain size, porosity, transmittance, thermal conductivity, and interfacial reaction tendency.

Descriptor selection is central to the effectiveness of data-driven design. Zhuo et al. used Debye temperature as a proxy descriptor for structural rigidity, employed a support vector regression (SVR) model to predict the Debye temperatures of candidate hosts, and combined these predictions with density functional theory (DFT)-calculated bandgaps to screen efficient and thermally stable inorganic phosphor hosts [91]. Figure 33c,d show that the model predicts Debye temperature with good accuracy. Figure 33e combines predicted Debye temperature (Θ_D) with calculated bandgap to construct a materials-screening map. When further classified by host type, borates, nitrides, silicates, phosphates, aluminates, and fluorides show distinct distributions in the screening space (Figure 33f-i) [309]. This “physical proxy descriptor + machine-learning prediction” strategy is particularly valuable for phosphor ceramics, because ceramic light converters require not only high luminescence efficiency, but also good thermal stability, structural rigidity, and potential ceramic processability.

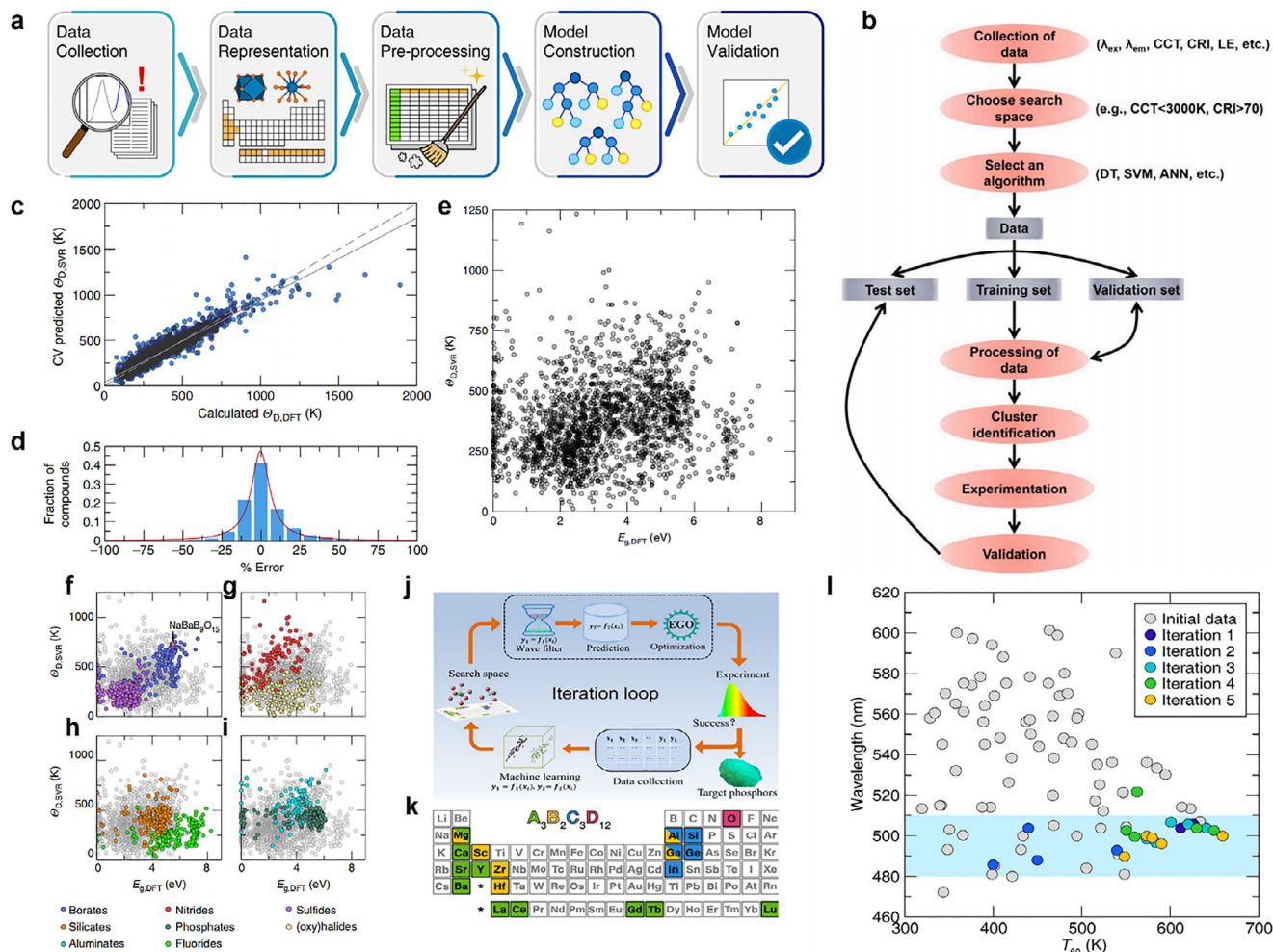


FIGURE 33 | Machine-learning workflow, descriptors, and active-learning examples for phosphor design. (a) Schematic image of ML workflow for material discovery. Reproduced with permission from literature [307]. Copyright 2025, Wiley-VCH GmbH. (b) Flow chart for phosphor design using ML-based approach. Reproduced with permission from literature [308]. Copyright 2021, Elsevier B.V. (c) Ten-fold cross-validation (CV) predicted Debye temperature (Θ_D , SVR) versus calculated Debye temperature (Θ_D , DFT). The ideal line is shown as dashed line and the fit line is shown as solid line. (d) Fraction of compounds according to their percent error between CV predicted Θ_D , SVR, and Θ_D , DFT. The red curve shows the trend. (e) ML predicted Debye temperature (Θ_D , SVR) against the density functional theory calculated bandgap (E_g , DFT) for 2071 compounds predicted. The darker regions occur where there are overlapping data. Classes of common phosphor hosts are highlighted, including. (f) Borates and sulfides, (g) Nitrides and (oxy)halides, (h) silicates and fluorides, and (i) aluminates and phosphates. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [91]. Copyright 2018, The Author(s). Published by Springer Nature. (j) Schematic diagram of phosphor design assisted by ML with active learning, augmenting experimental data into the initial data to improve the inference and design for each loop. (k) The search space of the garnet structure. Chemical elements occupying the site of the garnet structure are highlighted. (l) Iteration results from the final ML models in the spatial distribution of experimental emission wavelength and T_{60} . Reproduced with permission from literature [309]. Copyright 2022, American Chemical Society.

Under small-data conditions, active learning can further improve screening efficiency. Figure 33j,k shows a typical active-learning loop: the search space is first defined and an initial model is trained; candidate materials are then predicted and experimentally validated; new data are collected and fed back into the model for the next iteration. For phosphor ceramics, this loop can be expanded into “composition design-powder synthesis-ceramic sintering-microstructure characterization-photothermal performance testing-model updating.” This section therefore establishes a design logic for phosphor ceramics: starting from powder luminescence data, incorporating crystal-structure, ceramic-processing, and device-performance data, and ultimately enabling

coordinated prediction of materials, processing, and application metrics.

8.2 | Data-Driven Prediction and Model Validation of Phosphor Properties

When ML is applied to phosphor ceramic design, reliable data sources and well-defined prediction targets are essential. Yuan et al. combined high-throughput experiments with a decision-tree model to establish correlations among the Ce/Eu doping ratio, oxidation temperature, and emission color [310]. As shown in Figure 34a–c, this strategy converts complex experimental

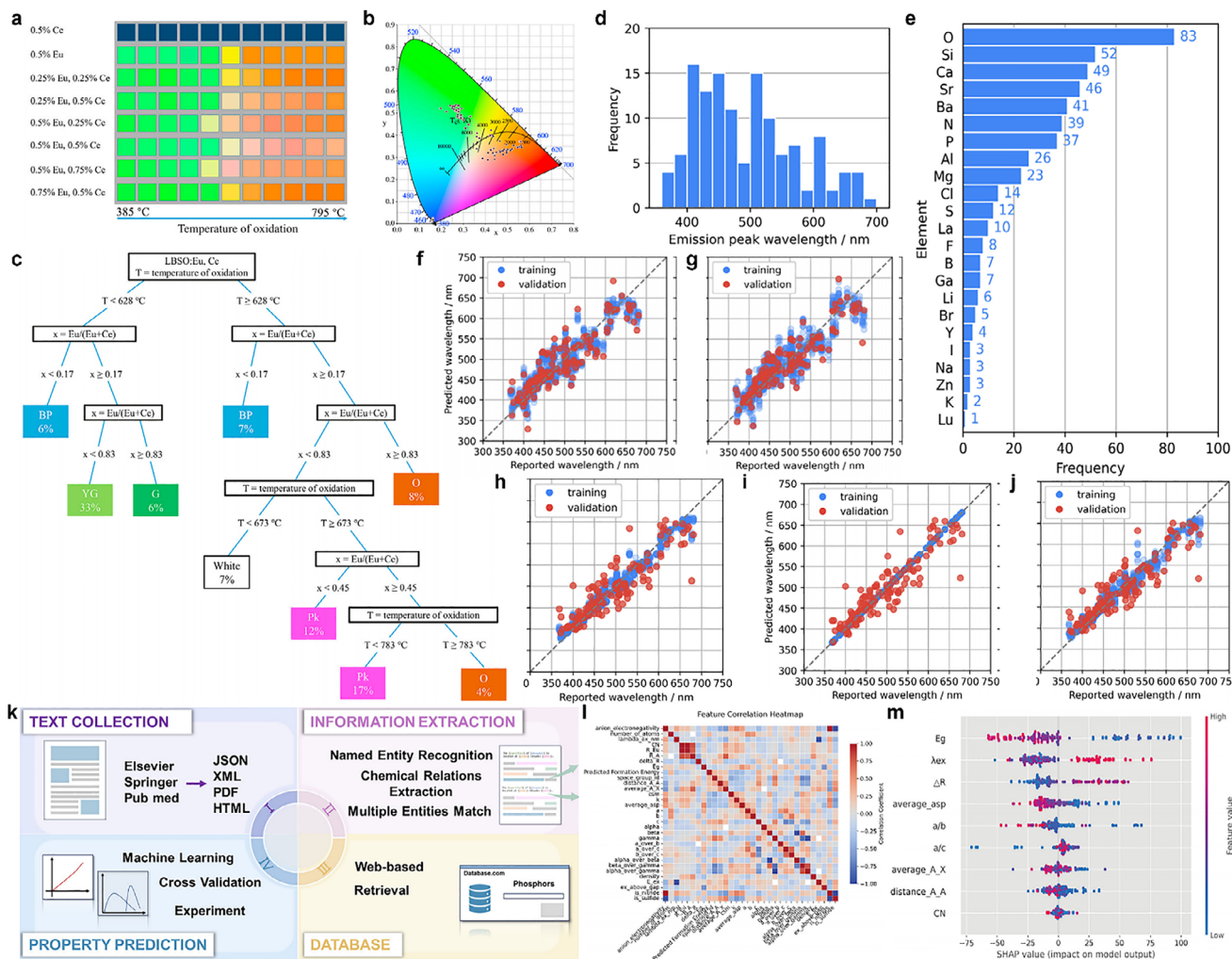


FIGURE 34 | Data sources, descriptors, and interpretable ML for phosphor design. (a) Eighty-eight LBSO: Ce, Eu samples prepared by varying dopant composition and oxidation temperature under a temperature gradient. (b) CIE chromaticity coordinates 88 samples. (c) Decision-tree classification of emission colors using oxidation temperature and Eu/(Eu+Ce) ratio. BP, bluish-purple; YG, yellow-green; G, green; Pk, pink; O, orange. Reproduced with permission from literature [310]. Copyright 2021, Elsevier Inc. (d) Histogram of emission peak wavelengths in the Eu²⁺-activated phosphor dataset. (e) Frequency of constituent elements in the Eu²⁺-activated phosphor dataset. Predicted emission peak wavelengths with respect to reported values for the training (blue) and validation (red) data in the cross validation using (f) ridge, (g) automatic relevance determination (ARD), (h) random forest (RF), (i) gradient boosted regression trees (GB), and (j) bagging of GB methods. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/>) [311]. Copyright 2023, The Author(s). The Royal Society of Chemistry. (k) Workflow of text-mining-assisted property prediction, including text collection, information extraction, database construction, and machine-learning prediction. (l) Feature correlation heatmap for the extracted phosphor dataset. (m) SHAP analysis showing the influence of selected features on emission-wavelength prediction. Reproduced under the terms of the CC-BY-NC-ND Creative Commons Attribution 4.0 International license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>) [312]. Copyright 2026, The Author(s). Published by Springer Nature.

conditions into classifiable color outputs, providing a basis for condition screening in single-phase white-emitting phosphors.

Koyama et al. further constructed a dataset for Eu²⁺-activated phosphors that included emission peak positions and elemental compositions [311]. Figure 34d,e shows the distribution of emission wavelengths and elemental occurrence frequencies, indicating that literature-derived data can provide a practical foundation for model training. Figure 34f-j compares the predictive performance of several regression models for emission wavelength, demonstrating that compositional and structural descriptors can effectively capture how host lattices regulate Eu²⁺ emission color. Huang et al. expanded the data source through

text mining [312]. Figure 34k-m shows that literature text can be converted into structured ML-ready data through information extraction, database construction, feature-correlation analysis, and Shapley additive explanations (SHAP). Figure 35 further compares the learning curves and coefficient-of-determination (R²) scores of Extreme Gradient Boosting (XGBoost), multilayer perceptron (MLP), random forest, SVR, and ridge regression models, showing that model generalization improves progressively as the training dataset increases.

Overall, the role of ML in phosphor ceramic design is not to replace experiments or mechanistic analysis, but to connect literature data, high-throughput experiments, descriptor

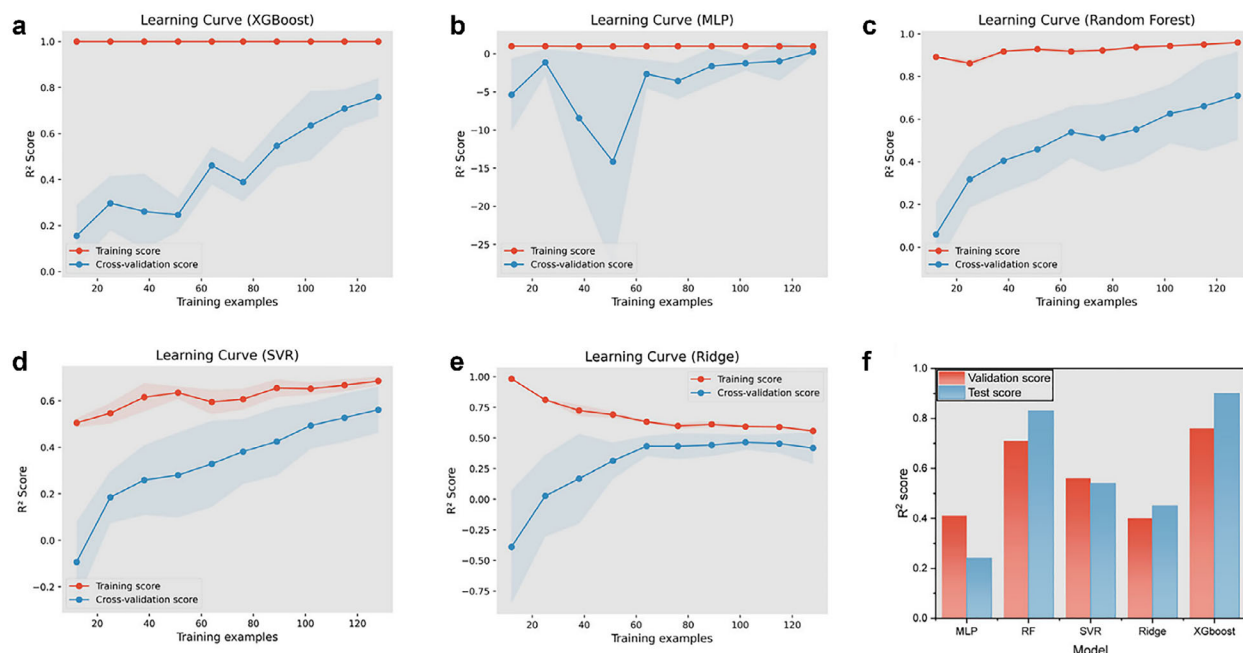


FIGURE 35 | Model comparison for emission-wavelength prediction. (a) Learning curve of the XGBoost model. (b) Learning curve of the multilayer perceptron model. (c) Learning curve of the random forest model. (d) Learning curve of the support vector regression model. (e) Learning curve of the ridge regression model. (f) Validation and test R^2 scores of the five models, showing the comparative prediction performance of MLP, random forest, SVR, ridge regression, and XGBoost. Reproduced under the terms of the CC-BY-NC-ND Creative Commons Attribution 4.0 International license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>) [312]. Copyright 2026, The Author(s). Published by Springer Nature.

screening, and experimental validation into a closed loop, thereby accelerating the discovery and optimization of new materials.

8.3 | Machine-Learning-Assisted Screening and Validation of Candidate Phosphor Ceramic Systems

In the preceding section, ML was mainly discussed in terms of dataset construction, descriptor selection, and predictive modelling. This section shifts the focus to how model predictions can guide the screening of candidate phosphor ceramic systems. For this review, the endpoint of ML should not be limited to discovering a powder phosphor; rather, it should help identify, at an early stage, which host-activator combinations are likely to combine high luminescence efficiency, strong thermal stability, and practical ceramic-forming potential.

Koyama et al. developed an emission-peak prediction model for Eu^{2+} -activated phosphors and validated its extrapolation capability using newly reported literature data [311]. As shown in Figure 36a, the predicted emission wavelengths agree well with reported values, indicating that ML can rapidly identify materials with target emission colors. For phosphor ceramic design, such models can serve as front-end screening tools: systems with mismatched emission wavelengths can be excluded first, allowing experimental efforts to focus on candidates more likely to satisfy white-light compensation, full-spectrum reconstruction, or near-infrared conversion requirements.

Zhang et al. advanced this strategy by moving the screening target from emission color to thermal stability [313]. As shown in Figure 36b–k, they established an interpretable ML framework for

Eu^{3+} -activated red phosphors and screened thermally stable oxide candidates using parameters such as the thermal-quenching temperature T50, Debye temperature, and band gap. Figure 36c–e shows that the models can predict T50 with good accuracy and allow comparison of prediction errors among different algorithms. Figure 36f–k further present candidate distributions across different compound families and the final screening region. This strategy is highly relevant to phosphor ceramics, because ceramic light converters require not only high luminescence efficiency but also stability during high-temperature sintering, high-power blue-light/laser excitation, and long-term thermal cycling.

For NIR ceramic phosphors, Xu et al. proposed a co-training ML strategy for Cr^{3+} -doped garnet systems [314]. As shown in Figure 37, this approach starts from the application requirements of NIR pc-LEDs, extracts descriptors such as A/B/C-site compositions in garnets, ionic radii, electronegativity, and thermal conductivity, and employs SVR and kernel ridge regression (KRR) as two weak learners for semi-supervised co-training. This design is particularly suitable for Cr^{3+} -doped garnets, because the garnet structure itself is an important host family for NIR phosphor ceramics, offering high-temperature stability and a strong basis for ceramic processing.

Figure 38 further illustrates the model-training process reported by Xu et al. [314]. As co-training proceeds, the cross-validation errors of the SVR and KRR models gradually decrease, and the final predicted emission peak positions show good agreement with the experimental values. More importantly, the model not only provides numerical predictions but also uses interpretability analysis to reveal how different compositional features influence

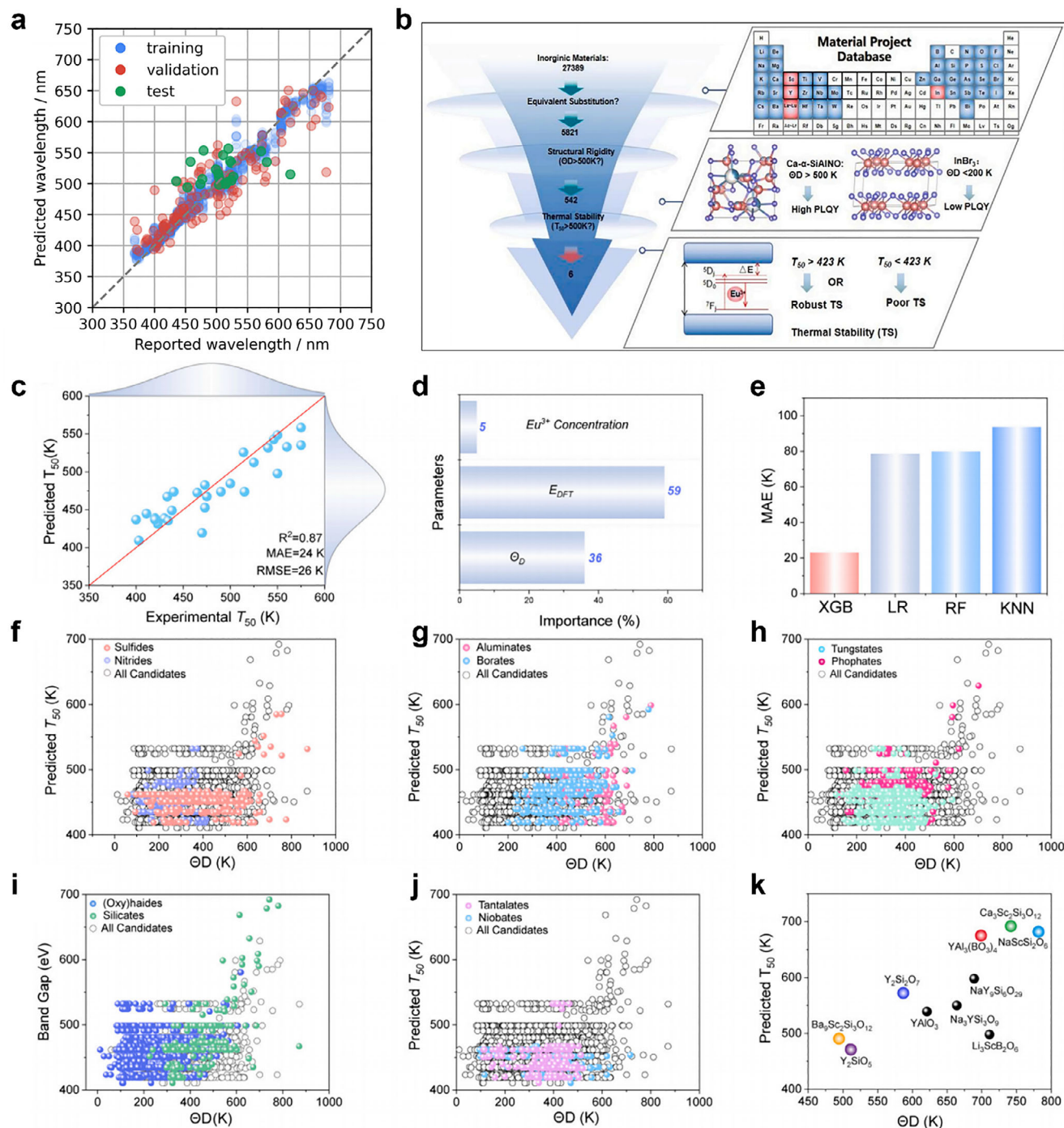


FIGURE 36 | Machine-learning-assisted screening of phosphor candidates. (a) Predicted versus reported emission wavelengths for Eu^{2+} -activated phosphors reported. Reproduced with permission. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license (<http://creativecommons.org/licenses/by/4.0/>) [311]. Copyright 2023, The Author(s). The Royal Society of Chemistry. (b) Screening workflow for thermally stable Eu^{3+} -activated red phosphors proposed. (c) Cross-validation plot for predicting thermal quenching temperature T_{50} . (d) Feature importance for T_{50} prediction. (e) MAE comparison of different machine-learning models. (f–j) Screening maps of potential phosphor candidates from different compound families. (k) Enlarged screening region showing selected oxide candidates for experimental validation. Reproduced with permission from literature [313]. Copyright 2025, Elsevier B.V.

the emission peak position, thereby translating ML outputs back into actionable materials-design rules.

Finally, Figure 39 presents the experimental validation of the predicted candidates. Xu et al. synthesized a series of Cr^{3+} -activated garnet NIR phosphors and evaluated their PL/PLE

spectra [314], prediction errors, and temperature-dependent emission intensities. The results show that the model-screened candidates can deliver broad-band NIR emission with appreciable thermal stability. This validation step is central to this section, ML narrows the candidate space, experimental testing confirms the luminescence performance, and subsequent studies must

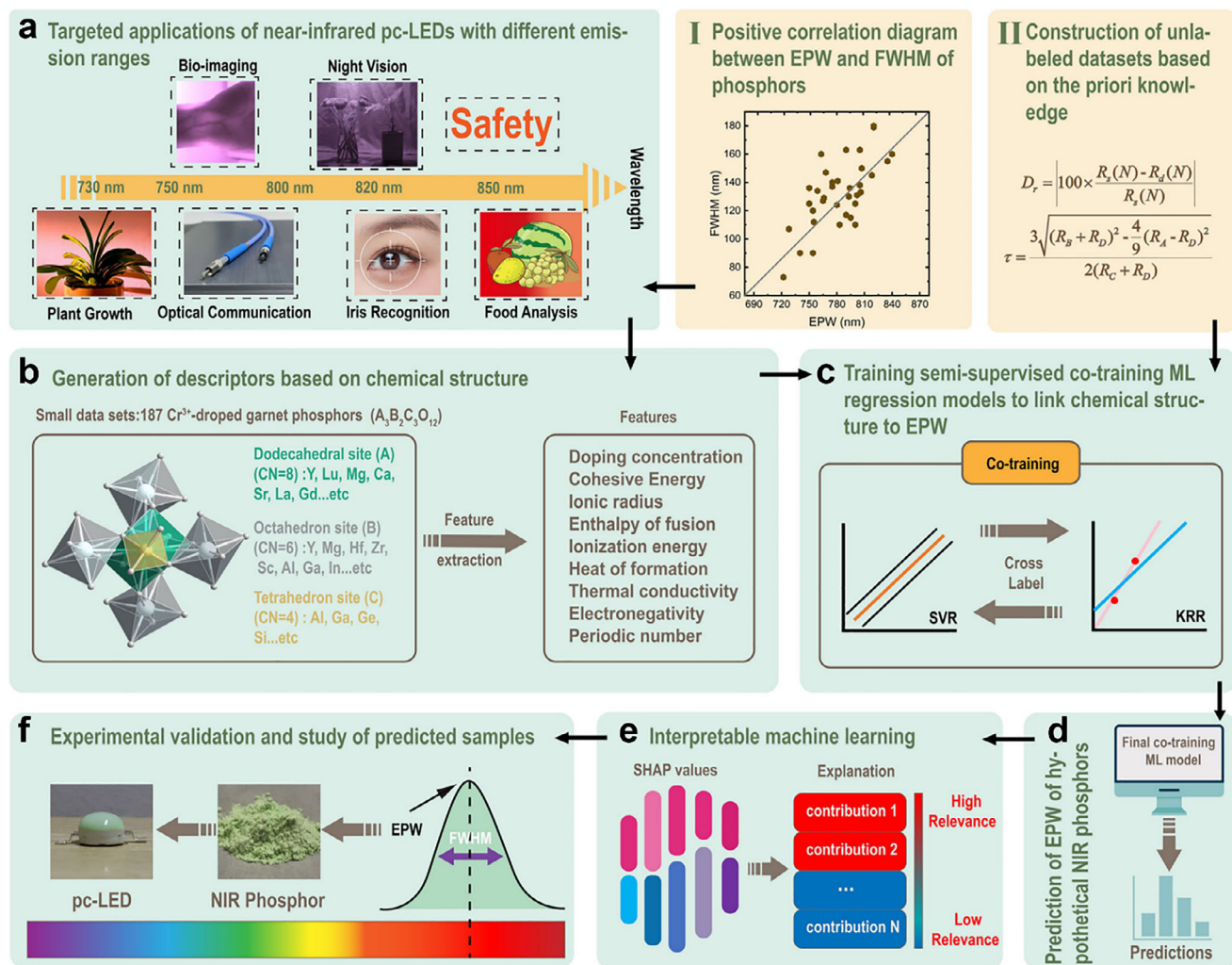


FIGURE 37 | Workflow for designing target NIR phosphors with the assistance of co-training ML model. (a) Different applications of NIR light according to the EPW. (b) The acquirement of chemical descriptors for each phosphor and the feature extraction. (c) The constructing of co-training ML model. The unlabeled dataset is built based on priori knowledge (I) and (II). (d) The utilization of proposed model for predicting EPW of hypothetical NIR phosphors in a greatly expanded chemical space. (e) Extraction of valuable insights from the model using the SHAP values. (f) The validation of model based on the experiment. Reproduced under the terms of the CC-BY-NC-ND Creative Commons Attribution 4.0 International license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>) [314]. Copyright 2024, The Author(s). Published by Springer Nature.

further examine sintering-phase stability, ceramic transmittance, thermal conductivity, and LED/LD device output before these materials can truly enter phosphor ceramic applications. Thus, ML provides phosphor ceramics with a strategy for prioritizing candidate systems. It first helps researchers identify promising luminescent hosts from vast compositional spaces, then guides experimental verification of emission wavelength, efficiency, and thermal stability, ultimately offering clearer material entry points for transparent/semitransparent ceramic fabrication, high-power light conversion, and device packaging.

8.4 | Machine-Learning-Driven Closed-Loop Optimization of Processing, Structure, and Performance in Phosphor Ceramics

In Section 8.3, ML was mainly used to screen candidate phosphor systems. For phosphor ceramics, however, once a candidate

material has been identified, further questions must be addressed: whether it can be processed into a ceramic, how it should be ceramicized, and whether it can be integrated into a device. The luminescence performance of a powder cannot be directly equated with the performance of a ceramic device, because sintering temperature, atmosphere, sintering aids, grain size, porosity, transmittance, scattering strength, and thermal conductivity can all reshape light extraction, heat accumulation, and high-power stability.

As shown in Figure 40a, phosphor ceramics may include single-phase transparent ceramics, multiphase ceramics, layered ceramics, and other structural forms. Their performance is jointly governed by composition, processing, and microstructure. Therefore, ML models should not rely only on compositional features such as host lattices and activator ions, but should also incorporate descriptors related to sintering conditions, phase composition, density, grain/pore structure, and ceramic thickness.

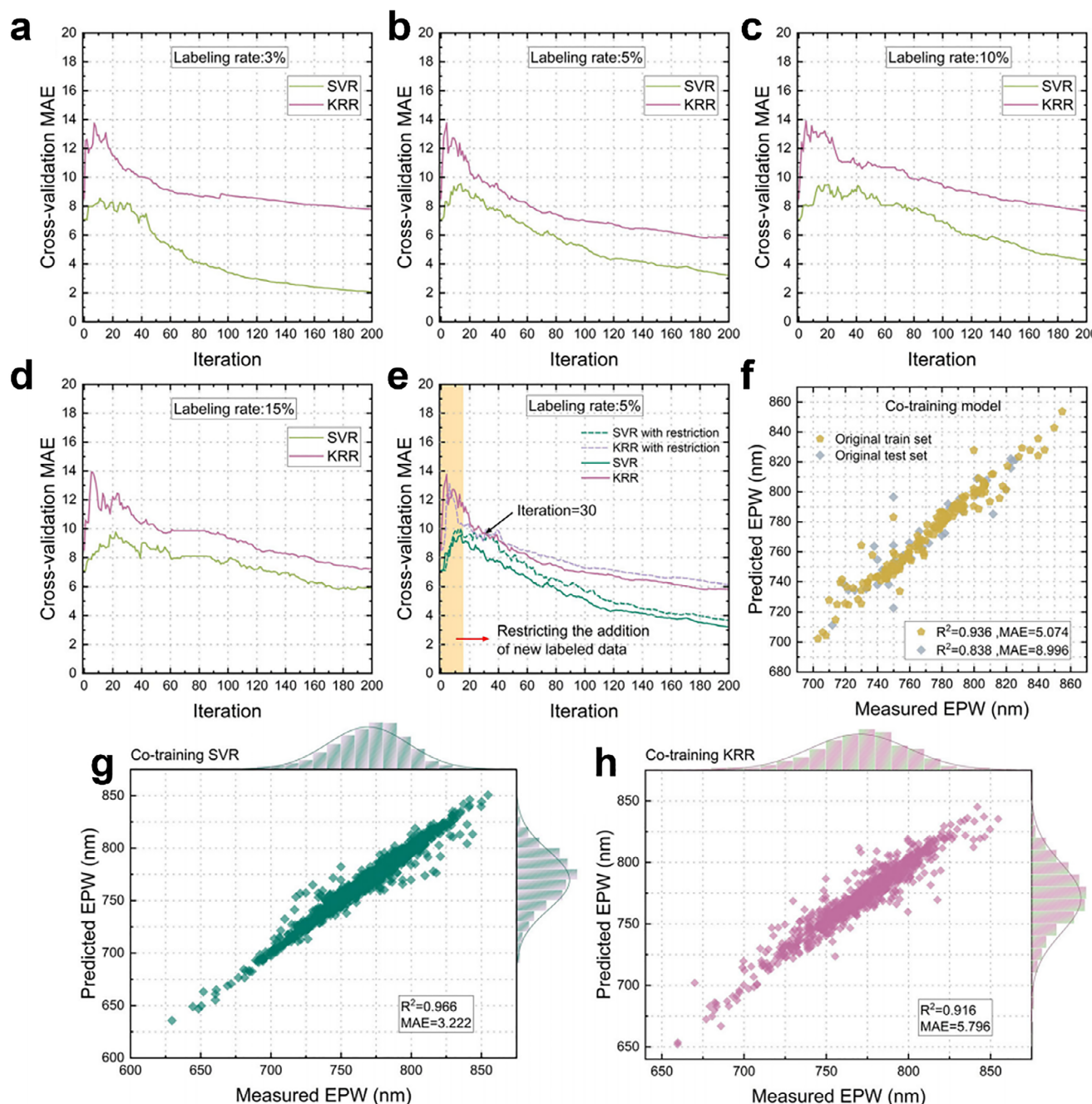


FIGURE 38 | Performance of co-training model. The performance of SVR and KRR under (a) 3.0%, (b) 5.0%, (c) 10.0%, and (d) 15.0% labeling rates. (e) Comparison of model performance under different conditions at a 5.0% labeling rate. (f) The fitting performance of the ensemble model on the original label set. The fitting performance of (g) SVR and (h) KRR models on the final labeled set after co-training. Reproduced under the terms of the CC-BY-NC-ND Creative Commons Attribution 4.0 International license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>) [314]. Copyright 2024, The Author(s). Published by Springer Nature.

Figure 40b further illustrates the central role of ML at this stage. Through feature-correlation and feature-importance analyses, ML can identify which ceramic variables most strongly influence target properties such as PLQY, thermal-quenching temperature T₅₀, transmittance, thermal conductivity, and saturation threshold. Such analysis can convert complex empirical processing knowledge into quantifiable design rules, helping determine whether priority should be given to pore-mediated scattering control, densification improvement, activator concentration optimization, or sintering-window refinement.

The optimization of phosphor ceramics is not a matter of maximizing a single metric, but of balancing multiple objectives. Figure 40c summarizes the coupling from emission wavelength, transmittance, scattering, and heat transport to device output. High-power LED/LD applications require ceramics to simultaneously provide suitable spectra, efficient blue-light absorption, controlled scattering, effective heat dissipation, and stable luminous flux/lifetime. Excessive transparency may lead to insufficient absorption, whereas excessive scattering can increase optical losses and local heat accumulation. An optimal

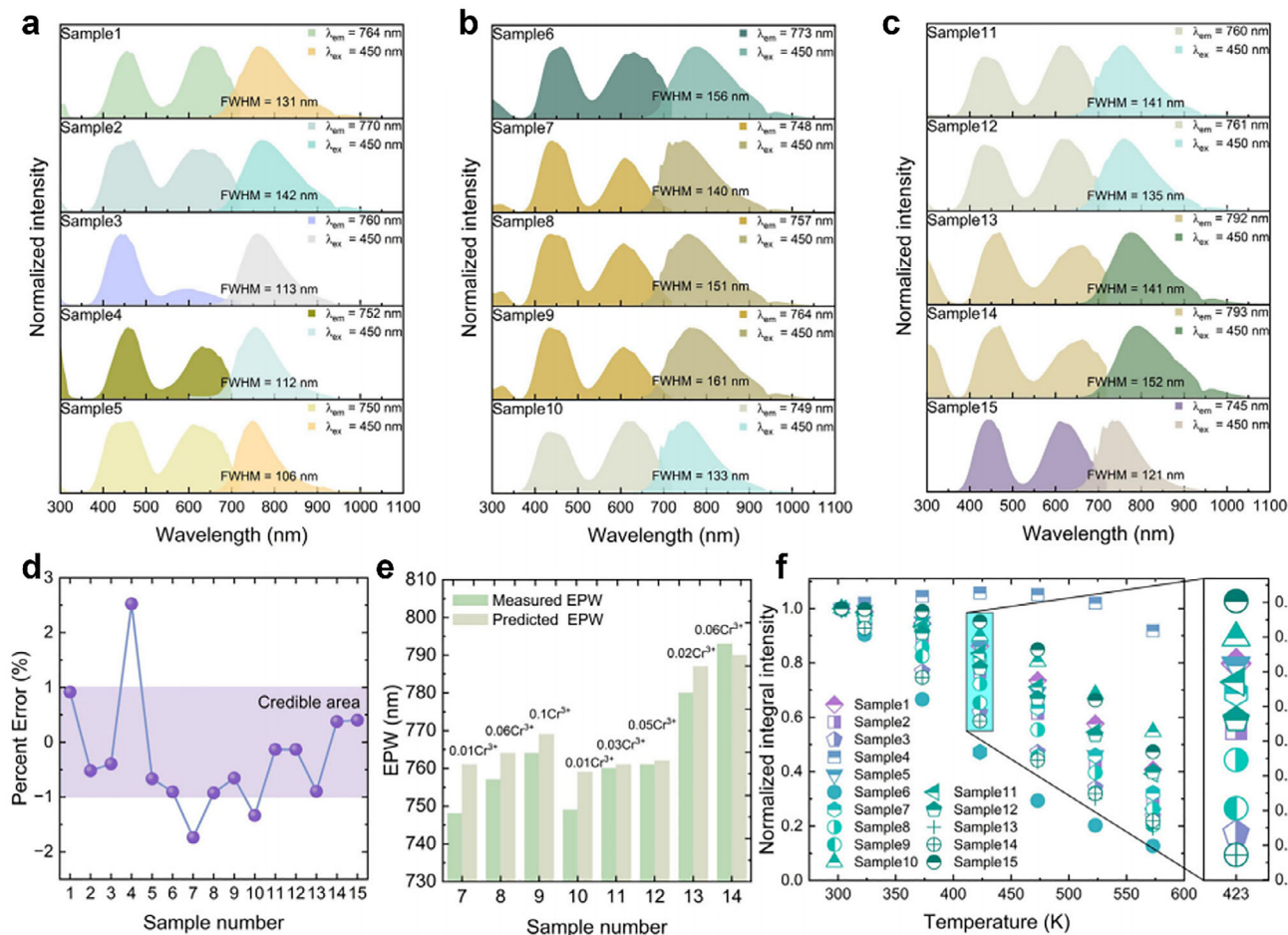


FIGURE 39 | The validation of models by experiments. (a–c) The photoluminescence and excitation spectra of the as-prepared samples. (d) The percent error between the measured and predicted values of EPW for the samples. (e) The changing trends of the predicted and the measured EPWs for Samples 7–9: $\text{Lu}_{2.5}\text{Mg}_{0.5}\text{In}_2\text{Ga}_{2.5}\text{Ge}_{0.5}\text{O}_{12}$, Samples 10–12: $\text{Lu}_2\text{CaAl}_2\text{Ga}_2\text{GeO}_{12}$, and Samples 13, 14: $\text{Y}_{2.5}\text{Sr}_{0.5}\text{In}_2\text{Ga}_{2.5}\text{Si}_{0.5}\text{O}_{12}$ with different DCs. (f) The temperature dependence of luminescence intensities normalized according to those at room temperature. Reproduced under the terms of the CC-BY-NC-ND Creative Commons Attribution 4.0 International license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>) [314]. Copyright 2024, The Author(s). Published by Springer Nature.

window must therefore be identified among optical, thermal, and structural parameters.

Ultimately, ML should support closed-loop ceramic design. As shown in Figure 40d, the workflow can progress from powder phosphors to ceramic samples and then to optimized light converters, while active learning recommends new compositions, sintering parameters, and device architectures. Monolithic ceramics, multiphase ceramics, layered ceramics, and patterned or rotating ceramic wheels can all serve as targets for model recommendation and experimental validation. Device data obtained from LED/LD testing, including luminous flux, temperature rise, color quality, NIR output, and lifetime, can then be fed back into the model to continuously update feature correlations and prediction results.

A recent representative example was reported by Wang et al., who coupled second-level rapid sintering with ML to guide the composition design of Ce^{3+} -doped $\text{A}_3\text{B}_5\text{O}_{12}$ garnet phosphor ceramics [315]. As illustrated in Figure 41a, this closed-loop framework integrates site engineering, first-principles-derived geometric and

chemical descriptors, ML prediction, rapid ceramic synthesis, and iterative experimental feedback. Starting from an experimentally prepared library of 48 compositions, the dataset was progressively expanded to 64 compositions, reducing the mean absolute error (MAE) for emission-peak prediction from 9.79 nm to 7.22 nm (Figure 41b). The agreement between the predicted and experimentally measured emission wavelengths, including four newly predicted and experimentally validated compositions, further demonstrates the practical predictive capability of the model (Figure 41c). Consequently, experimentally verified emission peaks spanning 495–605 nm with intervals of approximately 5 nm were achieved (Figure 41d). This study provides a representative example of AI-assisted phosphor development and illustrates how target-oriented composition selection, rapid standardized synthesis, and experimental feedback can jointly advance data-driven inverse materials design and closed-loop optimization at the ceramic level.

Therefore, the central message of Section 8.4 is that the value of ML in phosphor ceramics lies not merely in discovering new phosphors, but in establishing a closed-loop optimization

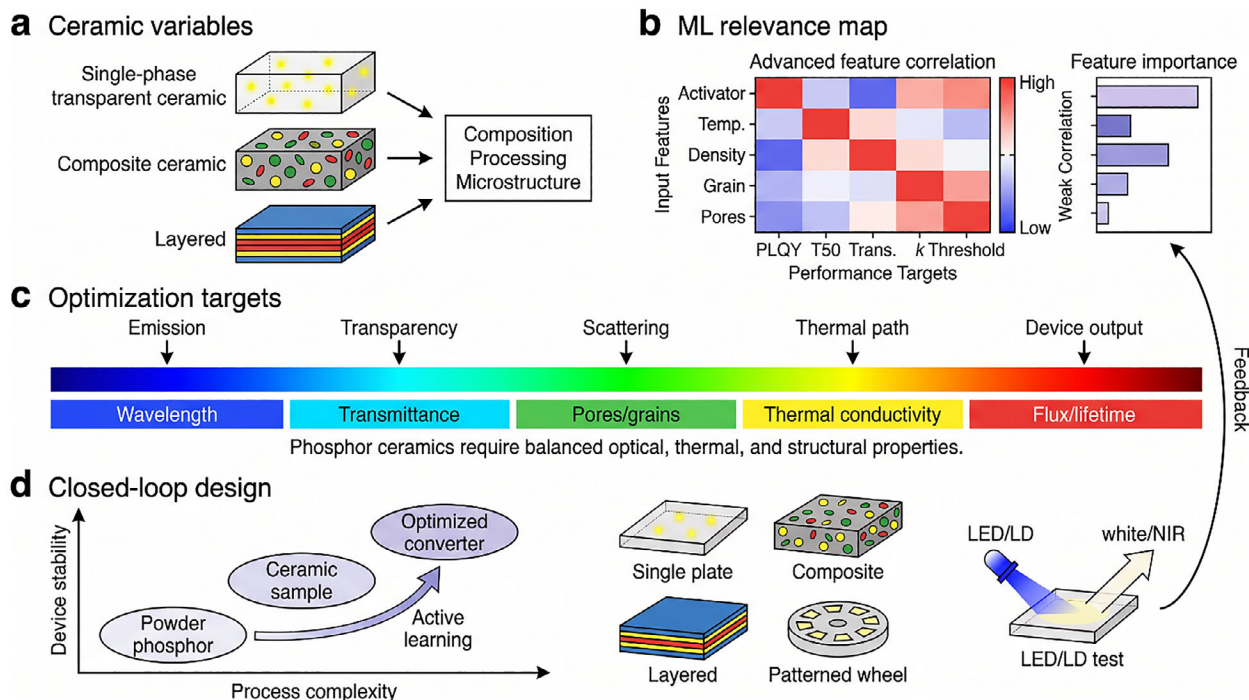


FIGURE 40 | Machine-learning-assisted optimization of phosphor ceramics. (a) Ceramic variables and descriptor construction. (b) Feature correlation and importance analysis for target properties. (c) Key optimization targets for optical, thermal, and device performance. (d) Closed-loop design from powder phosphors to optimized ceramic converters.

framework linking composition, processing, microstructure, and device performance. Only by incorporating ceramic processing and high-power device validation into data-driven models can phosphor ceramics advance from candidate materials to practical light-conversion devices. To realize this closed-loop vision, several challenges must still be addressed. The construction of reliable and sufficiently diverse datasets requires the harmonization of composition, synthesis conditions, microstructural descriptors, optical properties, thermal parameters, and device-level performance metrics obtained from different studies. Descriptor selection should therefore extend beyond chemical composition to include processing history, phase distribution, grain-boundary characteristics, porosity, interface quality, and excitation conditions. In addition, model interpretability and uncertainty quantification are essential for distinguishing physically meaningful correlations from data-specific statistical relationships. Most importantly, ML-predicted candidates should be validated through iterative experiments that examine not only phase formation and intrinsic luminescence, but also ceramic densification, heat dissipation, optical extraction, saturation behavior, and long-term stability under high-power excitation. These developments will help establish reliable physics-informed and experimentally closed-loop strategies for the practical development of high-flux phosphor ceramics.

9 | Conclusions and Perspectives

The development of phosphor ceramics marks a transition of light-conversion materials from dispersed luminescent powders to structured inorganic components for high-power devices. Unlike conventional phosphors, which are commonly evaluated

using emission wavelength, quantum efficiency, and thermal-quenching behavior, phosphor ceramics must simultaneously function as luminescent media, photon-transport structures, heat-diffusion pathways, and mechanically integrated device components. Their performance is therefore governed not only by activator ions and host lattices, but also by ceramic densification, defects, grain boundaries, secondary phases, scattering, interfacial reactions, and device-level heat dissipation. Phosphor ceramics should consequently be understood as systems that coordinate photon and heat transport under high-flux excitation, rather than simply as bulk forms of phosphor powders.

The material systems discussed in this review occupy different performance spaces and should not be ranked using a single parameter. YAG: Ce, LuAG: Ce, and GAGG: Ce ceramics remain mature platforms for high-power visible-light conversion because of their structural stability, favorable thermal properties, and established processing routes, although their spectral flexibility is limited when red compensation or application-specific emission is required. Eu^{2+} and Mn^{4+} activated red converters and Cr^{3+} or Ni^{2+} -activated NIR ceramics broaden the accessible spectral range, but may face stronger nonradiative losses, reabsorption, luminescence saturation, or thermal-management constraints, depending on the activator and host. Multiphase, layered, and glass-integrated architectures provide opportunities to regulate light scattering and heat transport independently, but may also introduce luminescent-phase dilution, optical loss, interfacial thermal resistance, phase incompatibility, and long-term reliability problems. These competing effects explain why high quantum efficiency, thermal conductivity, transparency, or scattering strength alone cannot guarantee superior device performance.

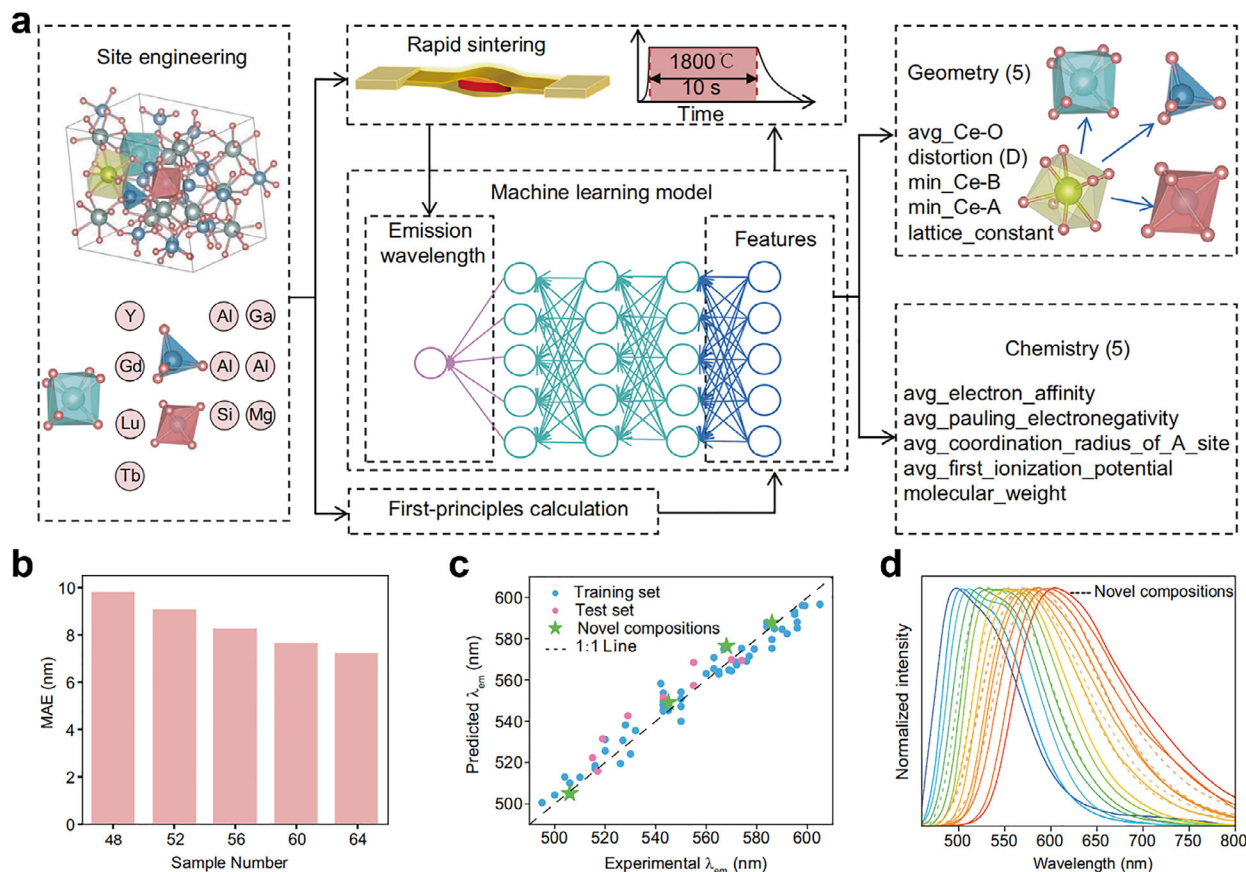


FIGURE 41 | Machine-learning-assisted closed-loop composition design and experimental validation of Ce^{3+} -doped garnet phosphor ceramics. (a) Closed-loop workflow integrating site engineering, second-level rapid sintering, first-principles-derived geometric and chemical descriptors, machine-learning prediction, and iterative experimental feedback. (b) Reduction in the mean absolute error as the experimental library is expanded from 48 to 64 ceramic compositions. (c) Comparison between predicted and experimentally measured emission peak wavelengths for the training set, test set, and four newly validated compositions. (d) Experimentally obtained emission spectra demonstrating emission-peak regulation from 495 nm to 605 nm with intervals of approximately 5 nm. Reproduced under the terms of the CC-BY-NC-ND Creative Commons Attribution 4.0 International license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>) [315]. Copyright 2026, The Author(s). Published by Springer Nature.

In our view, the principal limitation of the field is no longer simply the lack of efficient luminescent compositions. The more fundamental challenge is the absence of a predictive framework connecting local coordination and defect chemistry with ceramic processing, photon transport, heat flow, interfacial stability, and device degradation. Future evaluation should therefore move beyond isolated material parameters and define a photothermal operating envelope that relates absorbed excitation power, power density, illuminated area, converter thickness, temperature rise, saturation behavior, output stability, and continuous-operation lifetime. Such a framework would help distinguish intrinsic material performance from apparent improvements produced by device geometry or external cooling. Standardized reporting of these conditions would also enable more meaningful comparisons among dense ceramics, multiphase ceramics, PiG/PiC structures, and low-temperature composite converters.

The same cross-scale perspective should guide structural design. Conventional converters are generally assumed to possess uniform composition and microstructure, although light absorption, emission, extraction, and heat diffusion do not necessarily share the same optimum spatial distribution. Graded, layered, or

segmented architectures could assign these functions to different but optically and thermally coupled regions, thereby relaxing the competition among absorption, scattering, reabsorption, and heat transport. Grain boundaries and heterogeneous interfaces should likewise be treated as functional units rather than only as defects. Properly engineered interfaces may regulate photon residence time, interfacial heat transfer, stress relaxation, activator-valence stability, and chemical compatibility. Their value should therefore be assessed according to the balance they establish among optical extraction, thermal transport, mechanical reliability, and chemical stability.

Application-specific material–device co-design is also essential because a universally optimal phosphor ceramic is unlikely to exist. Visible lighting requires coordinated optimization of luminous flux, luminous efficacy, color rendering, correlated color temperature, chromaticity stability, and lifetime. Laser displays place greater emphasis on color gamut, spatial uniformity, scattering control, and resistance to localized irradiation. NIR imaging and spectroscopy depend more strongly on radiant output, spectral bandwidth, detector matching, penetration or contrast, and operational stability. Optical communication additionally requires appropriate luminescence lifetimes and

modulation bandwidths. Future studies should therefore define the target application, operating conditions, and dominant failure mechanism before selecting the luminescent composition and ceramic architecture.

Machine-learning-guided design may accelerate this transition, but its value will depend on whether it is connected to ceramic processing and device-level validation. Models based only on composition and crystal structure are insufficient for predicting the behavior of sintered and integrated converters. More useful datasets should include processing atmosphere, sintering history, density, porosity, grain size, secondary-phase distribution, optical transport, thermal properties, device geometry, and operating conditions. Model outputs should also extend beyond emission wavelength or quantum efficiency to experimentally actionable quantities such as processing windows, saturation thresholds, temperature rise, degradation rate, and operational lifetime. A closed loop linking model prediction, ceramic fabrication, high-power evaluation, accelerated ageing, and data feedback would allow ML to support reliability-centered optimization rather than candidate screening alone.

Phosphor ceramics are therefore evolving from materials optimized for initial luminescence performance into engineered systems designed for stable operation. Progress will depend on standardized device-level evaluation, spatial coordination of photon and heat pathways, function-oriented interface engineering, application-specific co-design, and data-driven optimization centered on reliability. The decisive question is not merely whether a ceramic can generate intense emission, but whether its optical, thermal, interfacial, and mechanical functions can remain coordinated during high-power operation. Addressing this challenge will determine whether phosphor ceramics can develop into reliable platforms for high-power lighting, laser displays, NIR sensing, and intelligent light-conversion technologies.

Author Contributions

Xiaoqing Pei: writing – review and editing, writing – original draft. **Tao Pang:** methodology. **Lingwei Zeng:** software. **Daqin Chen:** resources, supervision.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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