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REVIEW

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Advances in luminescent fibers for interactive smart textiles

Shumao Xu | **Xiujun Fan** | **Songyue Chen** | **Farid Manshaii** | **Junyi Yin** | **Jun Chen**

Department of Bioengineering, University of California, Los Angeles, California, USA

Correspondence
Jun Chen.
Email: jun.chen@ucla.edu

Abstract

Recent advancements in luminescent fibers are transforming textiles by integrating lighting and display functionalities into fabrics for applications such as health monitoring, dynamic displays, and adaptive camouflage. Active electroluminescent fibers, powered by electric fields, enable tunable light emission, while passive photoluminescent fibers rely on photoluminescence or triboluminescence to emit light. Although challenges remain in achieving uniform luminescence and ensuring durability, breakthroughs in materials science, structural engineering, and system integration are addressing these issues. Innovations such as chipless electroluminescent textiles and thermally drawn photoluminescent fibers highlight significant progress, pointing toward a future where clothing facilitates health monitoring and dynamic interaction, advancing natural human–machine interfaces.

KEYWORDS

luminescent fibers, personalized healthcare, photoluminescent textile, smart textiles

1 | INTRODUCTION

In modern society, display technologies are integral to human–machine interaction, facilitating effective communication across a wide range of devices.[1–8] With increasing demand for portable, flexible, and wearable displays, traditional rigid panels are being replaced by more adaptable formats that seamlessly integrate with daily life.[9–17] Luminescent fibers have garnered considerable attention as a promising avenue for integrating lighting and display functionalities of daily wearables, creating smart textiles that not only offer esthetic appeal but also serve practical applications such as health monitoring, dynamic displays, and adaptive camouflage.[18–27]

The flexibility, breathability, and lightweight nature of soft fibers make them essential for wearable technologies.[23,28,29] These fibers not only provide esthetic appeal but also serve practical functions, such as continuous health monitoring and adapting to environmental conditions.[17,19,28–31] This dual capability, merging esthetics with functionality, sets luminescent fibers apart from other display technologies such as light-emitting diodes (LEDs) and organic light-emitting diodes (OLEDs), which are generally rigid and designed for flat, planar surfaces. Unlike these traditional displays, luminescent fibers are lightweight, flexible, and capable of conforming to the human body, making them ideal for use in wearable systems. By embedding these fibers into fabrics, clothing can be transformed into interactive platforms

capable of real-time information display and adaptive responses to environmental stimuli.

Luminescent fibers can be broadly categorized into active and passive types[32–40] (Table 1). Active electroluminescent fibers, driven by electric fields, provide controllable and tunable light emission, allowing for dynamic lighting effects that can be adjusted on demand.[41] These fibers are powered by electroluminescent materials integrated into the textile structure, emitting light when voltage is applied. In contrast, passive luminescent fibers operate through photoluminescence or triboluminescence.[42–44] These fibers emit light in response to external light sources (photoluminescence)[42] or mechanical stress (triboluminescence),[43,44] functioning without the need for continuous power input. The simplicity of these passive systems makes them attractive for applications where energy efficiency is crucial, such as environmental sensors or safety textiles.

This review discusses the requirements for textile displays, highlighting their promising applications and recent advances in active materials, electrode interfaces, display modules, and functional integrations. By embedding sensors and luminescent elements that respond to user inputs or environmental changes, these interactive textiles provide feedback through visual cues or data transmission.[45–47] With their ability to bridge the gap between electronic functionality and textile comfort, luminescent fibers are not only enhancements of existing display technologies but represent a foundational innovation shaping the next generation of smart wearables.

2 | ACTIVE LUMINESCENT TEXTILES

Early development of luminescent textiles has been challenged by the need to attach bulky LEDs or electroluminescent panels to flexible substrates, compromising textile flexibility and comfort.[48–50] The miniaturization of light-emitting components and their direct integration into fibers have been driven by advances in electroluminescent reagents with high-efficiency dopants. One example is Cu-doped ZnS, which emits light when exposed to ultraviolet (UV) excitation or mechanical stress.[51–53]

Electroluminescent polymers are also crucial in the development of flexible luminescent textiles (Table 2).[54–60] These polymers emit light when an electric field excites their electrons, causing them to release energy in the form

TABLE 1 Materials in photoluminescence, electroluminescence, and triboluminescence.

	Photoluminescence	Electroluminescence	Triboluminescence
Mechanism	Absorbs photons (UV light) and reemits visible light	Light emission in response to an electric field	Light emission when undergoing mechanical stress
Typical materials	ZnO, ZnS: Cu (green),[32] ZnS: Mn (orange-yellow)[33] etc.	ZnS,[34] GaN,[35] ZnS: Mn,[36] ZnS: Cu[34] etc.	Crystalline ZnS,[37] ZnS: Cu,[38] ZnS: Mn,[39] EuD4TEA[40] etc.
Energy levels	Localized states introduced by dopants	Energy levels created by dopants	Suitable energy levels for charge recombination
Quantum efficiency	High desired (~90%)	High desired (>70%)	Efficient charge separation and recombination
Excitation source	UV light	Electric field (AC voltage)	Mechanical stress (rubbing, crushing)
Electrical properties	NA	Voltage: 3–20 V	NA
Mechanical properties	NA	Flexibility for integration into textiles	Ability to fracture or deform under stress
Process requirements	High purity, uniform doping	Multilayer structures, conductive electrodes	Piezoelectric properties, crystalline structure
Fabrication techniques	Coating, electrospinning	Dip-coating, twisting	Crystal growth techniques
Charge carrier mobility	Moderate to high	High	Moderate
Stokes shift	Large stokes shift desired to reduce self-absorption	NA	NA

TABLE 2 Parameters of common luminescent polymers.

Parameter	PPV[54]	PFO[55]	P3HT[56,57]	F8BT[58,59]	PFB[60]
Emission color[a]	Yellow-green	Blue	Orange-red	Green	Blue-green
Quantum efficiency	5%–10%	Up to 50%	1%–5%	Up to 70%	Up to 45%
Band gap (eV)	2.3–2.5	2.8–3.2	1.9–2.1	2.2–2.4	2.3–2.7
Luminescence efficiency	Moderate	High	Moderate	High	High
Thermal stability	Moderate	High	Moderate to high	High	High
Hole mobility ($cm^2\ V^{-1}\ s^{-1}$)	~10^{-5} to 10^{-4}	~10^{-3} to 10^{-2}	~10^{-4} to 10^{-3}	~10^{-4} to 10^{-3}	~10^{-4} to 10^{-3}
Lifespan	Limited, affected by oxygen and moisture exposure	Good stability under ambient conditions	Moderate, affected by oxygen and moisture exposure	Good stability under ambient conditions	Good stability under ambient conditions

Abbrevations: F8BT: Poly(9,9-dioctylfluorene-co-benzothiadiazole); PFB: Poly(9,9-dioctylfluorene-co-bithiophene); PFO: Polyfluorene; P3HT: Poly (3-hexylthiophene); PPV: Poly(p-phenylene vinylene).

[a]Adjustable emission color through copolymerization.

of visible photons, which allows for efficient light emission from fibers.[61–65] Theoretically, the emission wavelength of an electroluminescent polymer is determined by its band gap—the energy difference between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO).[66–68] Polymers with smaller band gaps emit longer wavelengths in the red or orange spectrum,[66] while those with larger band gaps emit shorter wavelengths, producing blue or green light.[69–71] Examples include poly(p-phenylene vinylene) (PPV), which emits yellow-green light due to its band gap of 2.3–2.5 eV, and polyfluorene (PFO), which emits blue light with a band gap of 2.8–3.2 eV.[55] Quantum efficiency, which represents the ratio of photons emitted to electrons injected, is critical for determining the brightness of the polymer.[72,73] For instance, PPV has a lower quantum efficiency of 5%–10%,[54] while PFO has a quantum efficiency of up to 50%, making it suitable for high-luminance applications including display screens, signage, and other scenarios where bright and uniform light is crucial for functionality and visibility.[55,74–76] The choice of polymer also depends on its luminescence efficiency and hole mobility, which affect the overall performance of the electroluminescent textile. Polymers like poly(9,9-dioctylfluorene-co-benzothiadiazole) (F8BT)[77–79] and PFO[80–82] have high luminescence efficiency, making them excellent candidates for achieving bright and stable luminescence. Hole mobility measures the ease with which charge carriers move through the polymer. The common PFO polymer has a hole mobility of ~10^{-3}–10^{-2} $cm^2\ V^{-1}\ s^{-1}$,[75,83,84] which contributes to its efficient charge transport and light-emitting capabilities. Thermal stability is another crucial parameter as it determines the polymer's resilience under different environmental conditions. A typical fabrication of electroluminescent fibers begins by dip-coating a stainless-steel wire with a ZnO electron transfer layer, followed by the application of a PFB polymer mixed with crosslinking ethoxylated trimethylolpropane triacrylate (ETT-15) and lithium trifluoromethane sulphonate (LiTf). This is then wrapped with a conductive CNT sheet to create the light-emitting fiber[14] (Figure 1a). Additionally, electroluminescent display textiles can also be fabricated by dispersing ZnS phosphor within an insulating polymer matrix, typically polyurethane, which is activated by an alternating electric field[16] (Figures 1b,c). These textiles integrate luminescent warp fibers coated with ZnS phosphor and transparent conductive weft fibers, produced by melt-spinning ionic-liquid-doped polyurethane gel, showing stable and robust luminescence under mechanical stress and various environmental conditions[16] (Figure 1d). Table 3 outlines the typical structure and materials used for electroluminescent fibers compared to LEDs.

Mechanical deformations directly influence the electrical conductivity of the fibers by modifying their internal structure, which can lead to changes in how efficiently electrical energy is converted into light.[85–87] The stability of the luminescence under various environmental and mechanical stresses can be modeled by considering the strain energy density in the fibers. The strain energy function (W) is expressed as follows:[85,88]

$$W = \frac{2\mu_1}{\alpha_1^2}\left(\overline{\lambda}_1^{\alpha_1} + \overline{\lambda}_2^{\alpha_1} + \overline{\lambda}_3^{\alpha_1} - 3\right) + \frac{1}{D_1}(J-1)^2 \quad (1)$$

where $\overline{\lambda}_i$ is the principal stretch modified by the mechanical interactions within the fibers, capturing how external forces alter the internal structure; μ_1 is the shear

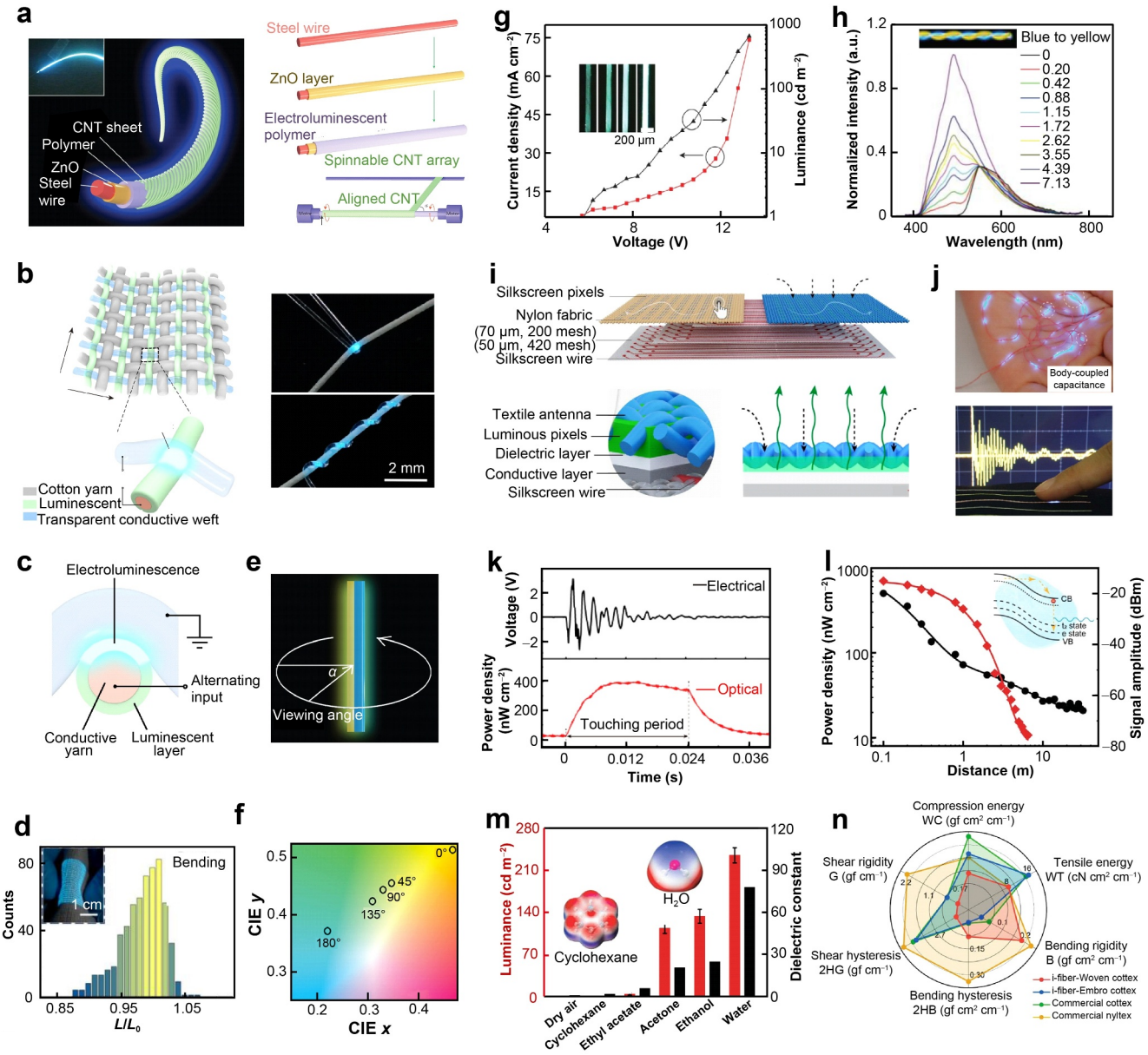

FIGURE 1 Active electroluminescent fibers: (a) light-emitting fiber fabrication; (b) display textiles including electroluminescent warps and conductive wefts, and their light emission during contact and knotting; (c) electroluminescent unit emitting light under alternating voltage; (d) statistical distribution of luminance variations after bending cycles; (e, f) chromaticity coordinates variation with the viewing angle; (g) current density, luminance, and driving voltage properties of twisted electroluminescent devices, and (inset) is the device at 6, 7, 8, and 9 V (left to right); (h) luminescent spectra and brightness ratios of blue to yellow of two assembled light-emitting fibers; (i) chipless display electroluminescent textile and its structure; (j) optical response upon powering and touch; (k) optical and electrical signals over time; (l) attenuation of wireless optical and electrical signals with distance, and ZnS: Cu electro-emission process; (m) impact of air and liquids on light emission; (n) Kawabata fabric style evaluation of compression energy, tensile energy, bending rigidity, bending hysteresis, shear rigidity, and shear hysteresis for light-emitting fiber woven and embroidered cottex versus commercial cottex and nylontex. (a, e, f, h) Reproduced with permission from Ref. 14. Copyright 2015, Nature. (b–d) Reproduced with permission from Ref. 16. Copyright 2021, Nature. (g) Reproduced with permission from Ref. 95. Copyright 2024, Nature. (i–n) Reproduced with permission from Ref. 96. Copyright 2024, Science.

modulus, representing the material's resistance to deformation (a higher value typically implies increased resistance to deformation); α_1 adjusts the nonlinearity of the stress–strain response—higher values indicate increased stiffness at large deformations; J is the determinant of the deformation gradient, which measures the change in volume during deformation; and D_1 relates to the compressibility (a lower value represents highly

TABLE 3 Structure comparison of light-emitting textiles with LED.

	Light-emitting textiles	LED
Core/substrate	Metal wires (e.g., stainless steel, silver-coated fibers, conductive yarns)	ITO, Si
Electron transport layer	Optional (e.g., ZnO)	Metal oxides (e.g., TiO_2, ZnO, SnO_2)
Electroluminescent layer	Electroluminescent polymers (e.g., PPV, PFO, P3HT, F8BT); or ZnS phosphor in polymer matrix	(In)organic light-emitting materials (e.g., perovskites, OLED materials)
Hole transport layer	CNT sheets, PEDOT:PSS, or conductive polyurethane	Spiro-OMeTAD or PEDOT:PSS
Encapsulation	Flexible polymers (e.g., silicone resin)	Optional (e.g., glass)
Processing techniques	Spin coating, dip-coating, thermal drawing, electrospinning, twisting, etc.	Spin coating, vacuum deposition, inkjet printing, etc.

incompressible materials). Maintaining a suitable compressibility level is important because excessive deformation could lead to changes in the internal conductive pathways, resulting in leakage currents or loss of luminescence efficiency.

This strain energy function accounts for both the nonlinear elastic response and the compressibility of the material, making it suitable for describing the mechanical behavior of luminescent fibers subjected to stretching, bending, or other deformations. It models how these mechanical deformations impact the internal structure, which in turn can influence the electrical conductivity and luminescence properties of the fibers. Additionally, the strain model by Equation (1) can capture the cumulative effects of repetitive stress scenarios, such as folding or washing, helping predict material fatigue and structural changes over time.[89] By analyzing the response of fibers under repeated loading, it becomes possible to identify failure points and design fibers that maintain mechanical stability, minimize leakage currents, and preserve the brightness and uniformity of luminescence, even after prolonged use.[90–94]

The impact of mechanical deformation on electrical properties also extends to chromaticity control. By adjusting the strain on different fibers, it is possible to tune the chromaticity coordinates. For example, changing the brightness ratio of blue to yellow lights by altering the applied voltage or the deformation of the fibers allows for tunable color outputs[14] (Figures 1e, f). Weaving together fibers that emit different colors, such as yellow and blue, can achieve a wide range of chromaticity values by adjusting the brightness ratio of the individual fibers. Luminance in the fiber increases with the applied voltage, showcasing its efficient and responsive luminescent control[95] (Figure 1g). Specifically, while maintaining constant brightness in the yellow fibers, increasing the voltage applied to the blue fibers adjusts the overall color emitted, providing a flexible mechanism for color control[14] (Figure 1h). This flexibility allows for a broad range of chromaticity values by mixing light sources with different power ratios. However, integrating luminescent materials directly into fibers, whether coaxial or twisted, presents challenges in ensuring uniform luminescence and maintaining mechanical durability.

To address these issues, recent advances have introduced chipless electroluminescent multilayered textiles.[96] These textiles feature a solution-processed multilayered structure with a textile antenna, ZnS: Cu-based luminous pixels, a $BaTiO_3$ dielectric layer, a conductive layer, and silkscreen wire. Recent advances have introduced chipless electroluminescent textiles, comprising a solution-processed multilayered structure with a textile antenna, ZnS: Cu-based luminous pixels, a $BaTiO_3$ dielectric layer, a conductive layer, and silkscreen wire[96] (Figure 1i). The textile antenna captures external electromagnetic energy, which is stored in the dielectric layer and used to power the luminous pixels. The conductive layer facilitates the seamless transmission of electrical signals across the fiber, ensuring uniform light emission. The electroluminescent units are made from ZnS: Cu fibers embedded in an insulating vinyl and acetoxy silicone resin matrix and activated by alternating electric fields. The body-coupled chipless interactive textile system could capture ambient energy through interface contact capacitance to generate visible light upon skin contact[96] (Figure 1j). Faraday's law and Ampere–Maxwell's law can be utilized to explain the generation of electroluminescent signals. According to Faraday's law, the rapid change in the electric displacement field during plasma discharge induces an electric current, while Ampere–Maxwell's law describes how this varying electric field generates a magnetic field, resulting in electrical oscillations. When the electric field intensity at the contact interface exceeds the air

breakdown threshold, it causes a localized plasma discharge, resulting in rapid electric displacement field variations, which induces both electrical oscillations and visible light emission[96] (Figure 1k). The transmission distance and strength of electroluminescent signals are crucial for user-oriented interaction[96] (Figure 1l). The distribution of dyes in the luminous layer ensures that the light-emitting fiber emits a mix of wavelengths within the ZnS: Cu emission range (440–540 nm). This electroluminescent process involves electrons transitioning from the conduction band (CB) to various excited states (e-state and t-state) before recombining with holes in the valence band (VB), resulting in the emission of visible light. The electroluminescence performance in various ambient media shows superior luminance in water due to differences in molecular configuration and polarity[96] (Figure 1m). The chip-less textile, combining a silver-plated nylon antenna and silicone resin-based electroluminescent layer, showcases significant durability and stability under mechanical stress such as bending and folding[96] (Figure 1n).

Flexible electroluminescent textiles eliminate the need for traditional rigid components, such as bulky LEDs, glass-based OLED panels, and inflexible circuit boards, opening new possibilities for applications in healthcare monitoring,[19,29,30] interactive clothing,[17,28,31] virtual reality (VR),[97–99] augmented reality (AR),[99–101] and smart home systems,[102] where flexibility, comfort, and dynamic interaction are paramount. In healthcare monitoring, luminescent fibers can be embedded into garments to monitor vital signs in real time, offering a comfortable and nonintrusive way to keep track of health metrics such as heart rate,[29] oxygen saturation,[30] or body temperature.[29] These textiles can provide visual feedback directly on the garment itself, allowing both patients and healthcare providers to easily monitor changes. Interactive clothing is another promising application where luminescent fibers can create garments that respond to user input or environmental changes.[17,28,31] By incorporating light-emitting fibers that react to touch, motion, or ambient light conditions, these garments can provide an interactive experience for the wearer. This could be applied in entertainment, performance arts, and safety gear where visibility is crucial. For instance, jackets with luminescent panels could increase visibility for cyclists or pedestrians at night, thereby improving safety.[103] In VR and AR environments, luminescent fibers can enhance user immersion by providing responsive visual cues integrated into VR suits or gloves.[99] These fibers can emit different colors and intensities based on in-game actions or scenarios, contributing to an engaging experience. The ability to dynamically adjust light emission in response to the virtual environment can deepen the sensory experience, bridging the gap between the digital and physical worlds. Meanwhile, luminescent textiles can be used in curtains, upholstery, or wall hangings that can adaptively change color or brightness based on the user's preferences or environmental conditions for smart home applications.[104] These textiles can act as ambient displays, showing information like room temperature, notifications, or even dynamic artworks, enhancing the functionality and esthetic appeal of living spaces. The flexibility and versatility of luminescent fibers make them ideal for integration into everyday household items, enabling smart environments that are intuitive and visually interactive.[105]

However, achieving high brightness with low energy consumption remains a critical hurdle, as current materials and designs often suffer from inefficiencies and challenges related to heat management.[16,90,106] High-efficiency electroluminescent materials that can convert electrical energy into light with minimal losses are needed to overcome these issues. Additionally, managing heat generated during operation is crucial to prevent material degradation and maintain overall performance.[107,108] Ensuring long-term durability under various environmental conditions, such as exposure to moisture and mechanical stress, is another significant challenge.[109,110]

To address these challenges, innovative structural and system integration designs such as multilayered composites, stretchable conductive networks, thermally insulating encapsulation layers, and seamless integration of power sources and control circuits, are essential for enhancing both mechanical robustness and thermal management.[111–114] The development of flexible, resilient encapsulation layers—such as silicone-based coatings, polyurethane films, and breathable nanomembranes—can provide effective protection against moisture, and mechanical wear, while preserving the fibers' flexibility, durability, and comfort.[109,115–118] Moreover, optimizing the textile architecture through the use of thermally conductive fibers, porous weaves for enhanced airflow, and layered structures that distribute heat evenly will be essential for achieving reliable, long-lasting performance.[119,120] The incorporation of nanomaterials, such as Fe_3O_4 for enhanced thermal conductivity and $BaTiO_3$ for improved luminescent efficiency and dielectric properties, can play a crucial role in overcoming challenges related to heat management and light emission.[121–123]

By tackling these challenges, luminescent fibers have the potential to provide not only esthetic value but also functional capabilities that enhance the quality of life. Their integration into healthcare, interactive clothing, virtual reality, and smart home systems represents a step toward creating more connected, responsive, and

adaptive environments, seamlessly blending technology into the fabric of everyday life.

3 | PASSIVE PHOTOLUMINESCENT TEXTILES

Photoluminescence typically involves the absorption of photons from external UV light sources, exciting electrons from the ground state (S_0) to higher singlet states (S_1, S_2, S_3), leaving behind holes in the ground state[42,124–128] (Figure 2a). These electron-hole pairs are essential to the photoluminescence process. After excitation, electrons lose some energy via non-radiative relaxation, dissipating heat. The remaining electrons may return to the ground state by either fluorescence, a fast radiative transition from S_1 to S_0 occurring within nanoseconds, or by undergoing intersystem crossing (ISC) to the triplet state (T_1). From T_1, electrons emit photons through phosphorescence, a slower radiative process taking microseconds to seconds.[129–132] In contrast, electroluminescence relies on electric excitation rather than photon absorption. Electrons and holes are injected from n-type and p-type regions, respectively, and migrate toward the luminescence center under an electric field. At the luminescence center, they recombine radiatively, emitting light. However, some electrons may enter trap states, resulting in non-radiative recombination and heat loss (Figure 2b).

The efficiency of photoluminescence depends on the material's bandgap, the presence of dopants, and the overall quantum efficiency. The bandgap determines the energy difference between the valence and conduction bands, which in turn dictates the wavelength (and thus the color) of the emitted light. Materials like ZnS or ZnO, which have a wide bandgap (~3.6 eV), are often used for photoluminescent fibers.[32,33] These materials are typically doped with Cu or Mn to introduce specific localized energy levels within the bandgap. These dopants act as intermediaries, providing energy levels that facilitate the emission of light at desired wavelengths. ZnS: Cu phosphors absorb UV photons, which excite electrons across the bandgap.[32] The electron-hole pairs then recombine at Cu sites, resulting in the emission of green light. Similarly, ZnS: Mn emits orange-yellow light upon recombination.[33] The dopants play a crucial role in determining the specific color of the emitted light by altering the recombination pathways and energy states involved.

A recent breakthrough has introduced thermally drawn photoluminescent fibers capable of emitting multiple colors that can be controlled and varied, which ensures consistent light emission along the fiber's length, overcoming the key hurdle of uneven light distribution in previous designs.[133] Heated to a viscous state and drawn by gravity, these fibers utilize a polymethyl methacrylate (PMMA) light-guiding layer that undergoes total internal reflection of UV light, exciting a fluorescent layer of CaS phosphor particles in polyvinylidene fluoride (PVDF) to emit visible light (Figure 3a). The uniform transmission of light along the fiber is ensured by the saturable absorption effect of the fluorescent materials, where the absorption decreases at higher light intensities, preventing uneven light distribution.

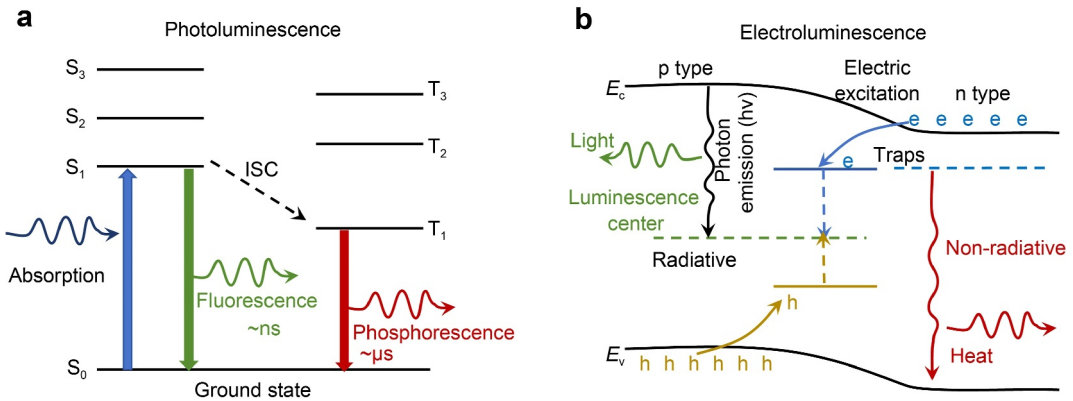

FIGURE 2 Mechanisms of photoluminescence and electroluminescence: (a) photoluminescence: This process begins with the absorption of photons, which excites electrons from the ground state (S_0) to higher singlet states (S_1, S_2, or S_3). After partial energy loss via non-radiative relaxation, electrons return to the ground state through either fast fluorescence (green arrow, nanosecond timescale) or slower phosphorescence (red arrow, microsecond timescale) via triplet states (T_1, T_2, and T_3). ISC from the singlet to the triplet state highlights the transition to a longer-lived state for phosphorescence; (b) electroluminescence: this process involves electric excitation, where electrons (e^-) and holes (h^+) are injected from the n-type and p-type regions, respectively. The charge carriers move toward the luminescence center under an electric field, where they recombine radiatively to emit light (green arrow). Some electrons may get trapped in intermediate states, resulting in non-radiative recombination and heat dissipation (red arrow).

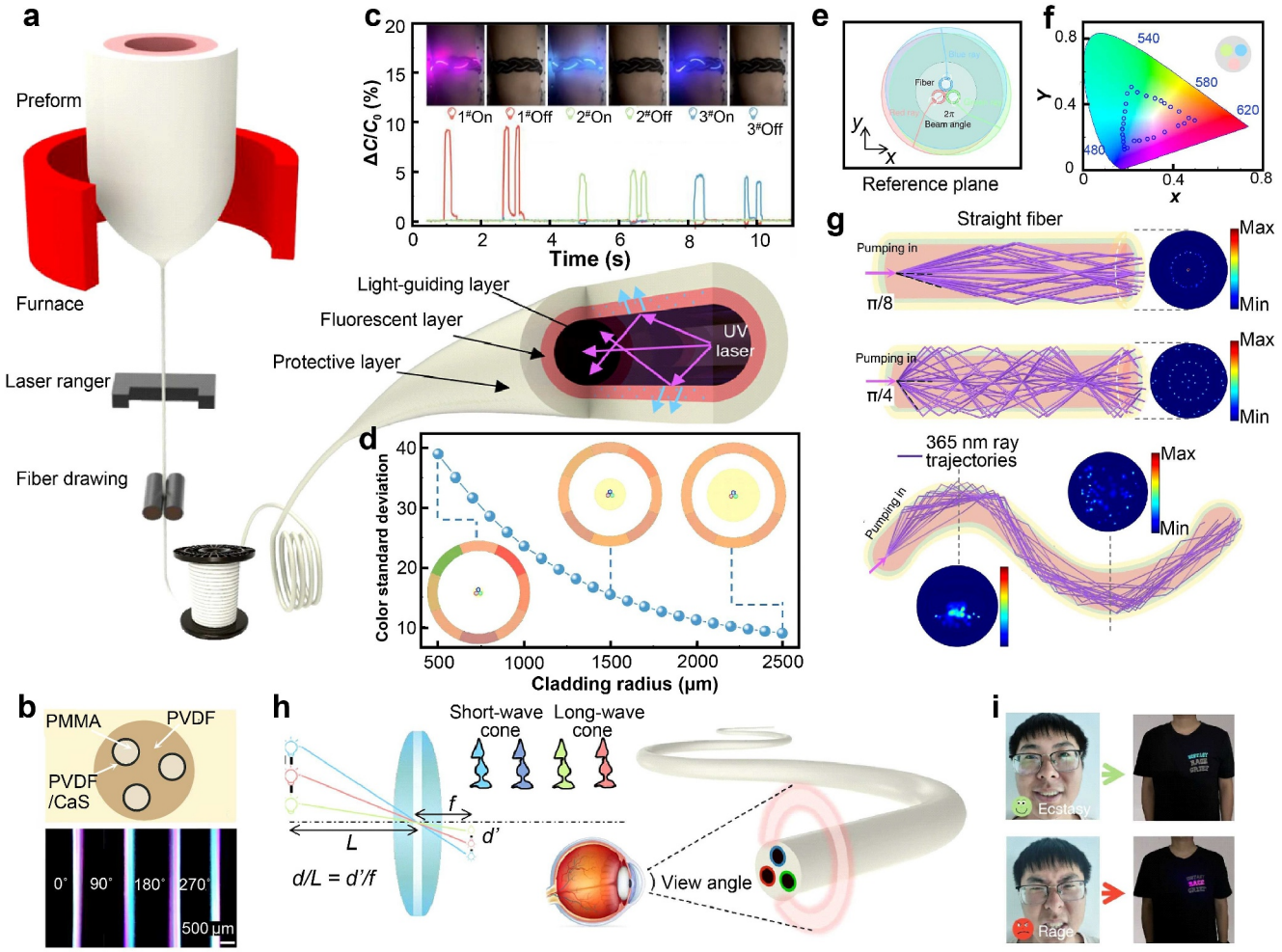

FIGURE 3 Passive photoluminescent fibers: (a) fabrication of photoluminescent fiber; (b) tri-core photoluminescent fiber cross-sections and radial views; (c) capacitance response and light-emitting colors by touch position; (d) color standard deviation versus cladding radius; (e) light field distribution of three-color fluorescence in fiber cross-section; (f) full chromaticity control by core light power mixing; (g) refraction and total internal reflection in straight and bent fibers; (h) adjusting shape and size parameters optimizes circumferential color mixing and minimizes visual distance for multicore photoluminescent fiber; (i) wearable display reflecting user emotions. Reproduced with permission from Ref. 133. Copyright 2024, Nature.

Numerical aperture (NA) plays a crucial role in defining the fiber's light-gathering capability and, consequently, the efficiency of light guiding and emission.[134,135] The NA of an optical fiber is defined by Equation (2):[136]

$$\mathrm{NA} = \sqrt{n_{\mathrm{core}}^2 - n_{\mathrm{cladding}}^2} \tag{2}$$

where n_{core} and n_{cladding} are the refractive indices of the core and cladding materials, respectively. An optimal NA value ensures that the fiber can efficiently guide light while maintaining high photoluminescence efficiency.

Various fluorescent layers integrated into the photoluminescent fiber achieve multiple emission peaks, controlled by adjusting the power ratios of the coupled light sources. This is demonstrated in the triple-core fiber structure (Figure 3b), where each core consists of a different fluorescent layer. These fibers emit multiple colors simultaneously and uniformly, which are visible from various angles, as shown in the radial views (Figure 3b). This design could be directly coupled with external light sources for precise control (Figure 3c), ensuring uniform directional and circumferential radiation. The ray power simulated by Multiphysics COMSOL reveals that chromatic aberration decreases as the cladding radius increases, with 1500 μm being the optimal radius for achieving the balance between mechanical properties and color mixing (Figure 3d). This optimal radius minimizes color deviation, ensuring uniform color distribution and enhanced structural integrity. The finite element modeling of the fiber cross-section indicates the light field distribution for three-color fluorescence and

their respective beam angles (Figure 3e). Keeping the power input of the green light-guiding core constant while varying the blue core adjusts the luminance ratio and excitation spectrum, changing the x and y chromaticity coordinates (Figure 3f). Coupling red, green, and blue cores in pairs with different power ratios achieves a wide range of chromaticity values within the triangle, controlled by adjusting the light power of different cores. The overall light intensity in curved fibers is more evenly distributed but less focused compared to straight fibers (Figure 3g). This property can be leveraged to reduce hot spots for improved comfort, enhance visibility and safety in photoluminescent textiles for health monitoring, and improve color mixing in the red, green, and blue (RGB) lighting systems. Figure 3h shows the design principles for multicore fibers to achieve optimal color mixing and resolution for the human eye. The fiber consists of multiple light-guiding cores surrounded by cladding materials to ensure total internal reflection.

Numerical aperture plays a significant role in determining the critical angle for total internal reflection and thus the effectiveness of light guidance through the fiber. Light rays from these cores are projected through a lens system, with the focal length crucial for effective light combination. Adjusting the power levels of light sources fine-tunes color intensity, ensuring uniform illumination. By optimizing core distances, the critical distance of ~1 mm ensures that the eye perceives the combined light as uniform, enhancing color mixing and resolution. Adjusting the lens system's focal length and aperture to balance light intensity and depth of field could achieve consistent color perception across different angles. A designed circuit precisely controls the light source coupled with the fibers to display patterns with varying brightness, and integrating facial expression detection algorithms with displayable textiles allows the system to classify emotions and adjust the corresponding light patterns on the fabric (Figure 3i). The ability to weave these photoluminescent fibers into garments and other textile products without compromising their functionality or comfort allows for the creation of wearable e-skin, responsive and adaptive to its wearer's needs.[137] By designing the multicore fiber structure, optimizing core and cladding parameters,[22,138] and adjusting light source power, the photoluminescent fibers achieve optimal color mixing and high-resolution color perception, opening new avenues for human–machine interfaces that are more natural and integrated into our daily lives.

However, prolonged UV exposure and heat buildup can significantly affect the efficiency of photoluminescent materials, often leading to luminescence degradation and reduced performance over time.[139,140] UV radiation can cause photodegradation,[141] breaking down the chemical bonds within luminescent materials and thereby reducing their ability to emit light effectively. This degradation results in uneven light emissions and diminished functionality, especially under prolonged use. Heat buildup exacerbates this issue by accelerating the degradation process.[107] High temperatures can destabilize the luminescent centers, causing molecular changes that further diminish quantum efficiency and light output. The combination of UV exposure and heat buildup leads to material fatigue, which weakens the mechanical properties of the fibers and results in reduced luminescence efficiency and overall performance.

To mitigate these challenges, it is crucial to develop photoluminescent materials that exhibit enhanced resistance to environmental degradation. This involves synthesizing new polymers with higher stability,[142–144] incorporating protective coatings that shield the luminescent core from UV radiation and moisture,[145–148] and optimizing the molecular structure to improve quantum efficiency and mechanical durability, such as by introducing conjugated side chains to enhance electron mobility and cross-linkable functional groups to increase structural stability.[149–152] Additionally, high-resolution electrospinning and dip-coating including controlling withdrawal speed, solution viscosity, and environmental conditions,[104,153,154] along with real-time in-line optical monitoring,[155,156] can help maintain consistent quality by ensuring an even distribution of luminescent materials and detecting any inconsistencies during the production process. Addressing these challenges is essential to unlock the full potential of photoluminescent textiles in creating responsive, adaptive, and high-performance wearables.

4 | CONCLUSION AND PERSPECTIVES

Luminescent fibers are revolutionizing smart textiles, offering groundbreaking functionalities for healthcare monitoring, interactive clothing, virtual reality, and smart home systems.[157–160] Active electroluminescent fibers, driven by electric fields, enable controllable and tunable light emission, while passive photoluminescent fibers emit light in response to external light sources, creating dynamic displays.

Achieving high brightness with low energy consumption is critical for active luminescent fibers. This requires electroluminescent polymers and conductive materials that efficiently convert electrical energy into

light with minimal losses. Additionally, managing heat generation is crucial to prevent material degradation and maintain efficiency. Advances in materials science and fabrication techniques are essential for ensuring seamless connection with power sources and control systems while keeping the textiles flexible, comfortable, and durable.[161–166]

Passive luminescent fibers face challenges in achieving consistent luminescence and mechanical durability, especially when scaling up for industrial production. Variations in coating thickness during dip-coating and uneven dispersion of luminescent materials during electrospinning can lead to nonuniform luminescence. To address these issues, precise process controls of the withdrawal speed, viscosity of the coating solution, and environmental conditions such as temperature and humidity should be implemented during dip-coating to ensure a uniform application of luminescent and conductive layers. Another potential approach is the use of surfactants or dispersing agents in the coating solution to improve the uniform dispersion of luminescent particles. These agents help prevent aggregation, which can cause localized variations in luminescence intensity.

Ensuring strong adhesion between the luminescent coating and the fiber substrate is crucial to prevent delamination during mechanical deformation. Surface pretreatment of the fiber, such as plasma treatment or chemical priming, can enhance adhesion by increasing surface roughness and introducing functional groups that improve the bonding between the fiber and the coating. Additionally, multiple thin layers may be applied instead of a single thick layer to build up the coating gradually, which improves adhesion and reduces the risk of cracking or peeling during mechanical stress.

Ideal photoluminescent materials should also withstand exposure to UV light, moisture, and mechanical wear over long-term operation. Applying a protective polymer overcoat can provide additional protection against environmental factors, thereby extending the lifespan of the luminescent fibers. Optimizing the materials involved in photoluminescence and implementing these process controls are essential steps for enhancing the functionality of these fibers in wearable technology, medical textiles, and adaptive displays.

The integration of luminescent fibers into wearable medical devices has significant potential for clinical applications. Luminescent fibers could be used to create dynamic displays that monitor vital signs, such as heart rate, oxygen saturation, or temperature, directly on the clothing. This real-time, on-body visualization could greatly enhance patient care, enabling the monitoring of patients continuously without the need for bulky monitoring devices. Moreover, luminescent fibers could be developed into wound dressings that emit specific colors to indicate infection or healing progress, providing a noninvasive way to assess wound health.

Luminescent textiles could be also used to create garments that change color or display patterns in response to environmental stimuli or user input, adding an interactive dimension to clothing. The integration of luminescent fibers in virtual reality and augmented reality gear could enhance immersive experiences by providing responsive visual cues. For smart home systems, luminescent curtains or upholstery could serve as ambient displays, providing information or mood lighting that adapts to the user's preferences. The commercial success of luminescent textiles will depend on overcoming current challenges, such as achieving full-color displays, high resolution, and efficient integration with control systems. Advances in quantum dot technology could enable vibrant, high-resolution displays by harnessing their unique optical properties, such as narrow emission spectra and excellent color purity. Additionally, continuous production technologies, like roll-to-roll printing, will be pivotal in scaling up manufacturing to meet market demands while keeping costs low and ensuring consistent product quality.

The development of luminescent fibers also has implications for environmental protection and sustainability. By integrating energy-efficient luminescent materials, these textiles could reduce the power consumption of lighting and display systems. Sustainable production methods will be crucial to minimize the environmental impact of luminescent textiles. Using biodegradable or recyclable luminescent materials and reducing the use of hazardous substances during fabrication will contribute to green production practices. Additionally, continuous encapsulation processes could enhance the durability of luminescent fibers, reducing waste by extending the lifespan of the textiles.

Energy harvesting presents an exciting opportunity for the future of luminescent textiles. By incorporating materials that can harvest ambient energy—such as solar or mechanical energy—luminescent textiles could become self-sustaining systems.[167–170] For instance, photovoltaic fibers could be woven alongside luminescent fibers, generating power during the day to drive light emission at night.[171,172] Similarly, piezoelectric elements could be used to convert mechanical energy from body movements into electrical energy, powering wearable displays without the need for external batteries.[173,174] These energy-harvesting capabilities could be crucial for developing autonomous wearable systems that support extended operation without frequent recharging.[175]

To fully realize the potential of luminescent fibers in smart textiles, several challenges need to be addressed.

Achieving uniform luminescence, mechanical durability, and extended operational lifetimes are essential. The development of textile driving systems and microscale-to-nanoscale integration methods will be pivotal in enhancing the refresh rates, integration levels, and overall functionality of luminescent textiles. Techniques such as conductive yarns, printed electronics, and flexible circuits have already shown promise, but further innovations are needed to create fully integrated systems that combine sensing, processing, and display functionalities within a single textile structure.[176,177] The future of luminescent fibers lies in interdisciplinary collaboration, combining advances in materials science, textile engineering, electronics, and design. As these fields converge, the possibilities for smart textiles will expand—transforming clothing into highly functional, interactive platforms that support communication, environmental adaptation, and healthcare, ultimately making our everyday lives more connected and responsive.

Achieving these advances promises a future where clothing is not only protective but also highly functional, capable of communication, transformation based on environmental stimuli, and supporting health monitoring for more natural human–machine interfaces integrated into our daily lives.

AUTHOR CONTRIBUTIONS

Shumao Xu: Investigation; writing - original draft; visualization. **Xiujun Fan**: Investigation; writing - review & editing. **Songyue Chen**: Investigation; writing - review & editing. **Farid Manshaii**: Writing - review & editing. **Junyi Yin**: Writing - review & editing. **Jun Chen**: Investigation; visualization; funding acquisition; writing - review & editing; project administration; supervision.

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CONFLICT OF INTEREST STATEMENT

Jun Chen is an associate editor for cMat and was not involved in the editorial review or the decision to publish this article. The authors declare no conflicts of interests.

DATA AVAILABILITY STATEMENT

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

ORCID

Jun Chen https://orcid.org/0000-0002-3439-0495

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AUTHOR BIOGRAPHY

Jun Chen is currently an associate professor with tenure in the Department of Bioengineering at the University of California, Los Angeles. With a current H-Index of 120, his research focuses on soft matter innovation for healthcare and energy. Beyond his research activities, Dr. Chen serves as an associate editor for Biosensors and Bioelectronics, FlexMat, Soft Science, Med-X, VIEW Medicine, cMat, and Textiles. Additionally, he is a member of the advisory and editorial boards of over 15 journals, including Matter, Materials Today, Materials Today Energy, Cell Reports Physical Science, The Innovation, Biomedical Technology, among others.