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Applications of Luminescence

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Abstract:

Luminescence applications are diverse, offering illumination, monitoring, and sensing across scientific, technical, industrial, and medical fields. They play significant roles in biological and industrial settings, often overlapping in function. Bioluminescent imaging enables visualization of biological processes at the molecular level without invasive techniques. Functional luminescent materials serve as components in light sources and tags that enhance manufacturing productivity and quality control. Additional applications include pest control, pollution detection, xerography, quantum cryptography, and medical imaging. Luminescence has been vital for both commercial and experimental growth since its inception. It is foundational for radio-luminescent clocks, lamps, photographic screens, and is crucial in LED and CCFL display manufacturing. Active research in areas like bolometers and thermo-luminescence, along with rising industrial demand, will broaden luminescence applications. (L. Fritzen et al., 2020)

Keywords: Luminescence, Pest control, Pollution detection, Xerography, Quantum cryptography, etc.

1. Introduction to Luminescence

Luminescence represents a widespread optical phenomenon encompassing the continual emission of light from a material system following an initial excitation event. In this framework, luminescence serves as a vehicle for applications spanning the biological, industrial, and technological domains. Numerous applications of luminescence have emerged during the last few decades. Luminescence has gained heightened interest within the biological arena during this timeframe. Despite these landmarks, the pioneering scientific figures remain comparatively unsung.

Luminescence images facilitate the diagnosis of diseases and the comprehension of biological processes through the interrogation of cells and their constituents. Color staining combined with dyes constitutes a robust and cost-effective approach for visualizing tissue structures and cellular details. The effectiveness of this methodology depends on the specific interactions between dyes and biological tissues and typically demands elevated concentrations of dye. Luminescence imaging techniques offer the advantage of background-free detection that does not require continuous excitation; consequently, issues related to tissue damage and limited penetration depth are mitigated (L. Fritzen et al., 2020). Persistent luminescent materials further advance biological imaging and photodynamic therapy by enabling protracted signal durations and a reduction in phototoxicity. The ongoing development of compounds capable of multi-functionality and responsive to light capable of penetrating tissues constitutes a pivotal direction for future research. The importance of organic luminescent dyes, inorganic phosphors, and quantum dots is noted throughout.

2. Types of Luminescence

Luminescence occurs when a substance emits light without heat. The substance receives energy from an external source and enters an excited state; light is emitted when it returns to the ground state. Luminescence is useful in biological, electrical and industrial applications. The main types of luminescence are photoluminescence, chemiluminescence, bioluminescence, electroluminescence and radioluminescence (L. Fritzen et al., 2020).

2.1. Photoluminescence

When substances are illuminated in the ultraviolet (UV) or visible regions of the electromagnetic spectrum, they can emit light either during the exposure to the light source or for some time after the source is no longer present. The phenomenon is known as photoluminescence and can be subdivided into fluorescence and phosphorescence.

Fluorescence occurs when light is emitted during the exposure to the exciting source (major emission) and also for very short time intervals after the exciting radiation has been interrupted (minor emission). The time interval is usually shorter than 10â□□7 seconds. Fluorescence is frequently observed in analytical applications involving high-performance liquid chromatography (HPLC), since many of the compounds present in the sample can emit fluorescence directly or after derivatization.

In phosphorescence, the emission lasts usually several seconds or even hours after the radiation is turned off (L. Fritzen et al., 2020). The emitting species can be molecules, atoms, atoms in excited states, or a particular class of defects existing in solids. The phenomenon has been extensively used in security applications including safety items. A great number of security inks is based on phosphorescence occurring for long time intervals (from minutes to hours) and, in particular, precision screws coated with luminescent paint are used in very specific fields of industry to indicate fastening or possible disassembly of a system.

2.2. Chemiluminescence

Defined as light emission from a chemical reaction, chemiluminescence was first described by Wiedemann in 1888. This process occurs naturally in species such as fireflies and certain marine organisms. Bioluminescence, in which a chemical reaction occurs within cells, represents a particular type of chemiluminescence. Chemiluminescent systems have attracted significant interest for biological assays and other applications (Cao, 2018).

In fireflies and bacteria, bioluminescent light results from an enzyme-catalysed oxidation of D-luciferin. Molecular oxygen, ATP and magnesium ions participate in this reaction. The excited product emits light centered around a wavelength of 560 nm. Bioluminescence has found widespread use as an analytical tool in biological research. Its principal advantage is the absence of external excitation, which greatly reduces background light (Hananya & Shabat, 2019). Developments in bioluminescence imaging have received considerable attention but this approach remains limited by the small number of suitable luciferin/luciferase pairs and its general requirement for genetic modification.

Luminol provides an alternative source of chemiluminescence. Mixing with an oxidizing agent under basic conditions generates an excited state that emits light. The reaction finds widespread application in chemical and biological analysis (Zhang et al., 2023).

2.3. Bioluminescence

Bioluminescence captures the chemical emission of visible light from living organisms, including bacteria, fungi, marine species, and terrestrial insects. This light originates from the oxidation of a substrate called luciferin, catalyzed by an enzyme known as luciferase. The interaction between luciferase and luciferin produces a transient complex that emits light upon oxidation. Bioluminescence has been exploited in diverse fields such as pharmaceuticals, bioimaging, environmental monitoring, and biosensing (N. Dunuweera et al., 2024).

Bioluminescence underpins the study of reporter gene expression, as well as the investigation of cell signaling pathways via NanoLuc luminescence. Bioluminescence-induced photo-uncaging of small molecules provides an avenue for precise spatiotemporal control of bioactive agents. Photodynamic therapy (PDT) systems driven by bioluminescence offer potential treatments against viral infections. In vivo glucose uptake can be evaluated through a bioluminescent glucose probe, while water pressure studies benefit from the use of naturally bioluminescent organisms. Furthermore, bioluminescent luciferase expression holds promise for the study of lung diseases.

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2.4. Electroluminescence

Electroluminescence (EL) designates the emission of incoherent light in visible and near-visible spectral ranges from solid materials under the influence of a strong electric field. Emission develops within rarefied gaseous regions, micro-plasma channels, granules of a dispersed phase embedded in an insulating layer, or impurities within such materials (Francisco Cabeza Martínez, 2008). Electron injection from the cathode and hole injection from the anode followed by radiative recombination provide emission in inorganic thin-film devices, Light-Emitting Diodes (LEDs), and Organic Light-Emitting Diodes (OLEDs). In thin-film El devices, the radiative recombination usually takes place in inorganic semiconductors made of phosphor particles dispersed within the insulating layer. In Powder Electroluminescence (P-EL) devices it occurs in the phosphor powder granules. In the case of LEDs, it takes place in the gap of a p-n junction fabricated between two doped adjacent semiconductor layers.

EL emissions differ from thermally stimulated luminescence emissions as their intensity increases with the electric field but decreases with temperature . The term EL was coined in 1950 by Destriau to characterize a phenomenon he observed when placing strontium aluminate activated with cerium (SrAl2O4:Ce3+) into the electric field produced between aluminum electrodes immersed in a transparent oil and subjected to a sufficient voltage (Bredol & Schulze Dieckhoff, 2010). EL distinguishes from incandescence, in which the emission intensity increases with temperature. Incandescence is caused by electron collisions with solids generating heat .

2.5. Radioluminescence

Radioluminescence, also called radio-photoluminescence, is the emission of light from a material excited by X-rays, γ rays, α particles, β particles, or other ionizing radiation. Some materials exhibit luminescence under one or more of these circumstances.Radioluminescence typically results from interaction of ionizing radiation with the luminescent material; in radioluminescence dosimetry, however, some or all of the material excitation is caused by interactions with secondary electrons produced by the ionizing radiation rather than direct interaction with the radiation itself. The term radio-photoluminescence is usually reserved for a specific kind of stimulated luminescence which occurs in some silver-doped phosphate glasses.

Radioluminescent light sources make use of radioactive substances, such as tritium gas, radium, or promethium, to excite a phosphor and create light. Tritium-powered devices usually contain tritium in a gas form inside a small sealed glass tube. The inside of the tube is coated with phosphors. When the beta radiation from the tritium strikes the phosphor, it glows. The tubes can be formed into different shapes and combined to produce a dot-matrix display. The tubes will glow for many years, until the tritium has decayed. These types of materials are used in illuminated clocks, gunsights, compass sights, and many other things where electrical light sources are not available or practical. The radioisotope is usually in a gaseous form which reduces health risks, since it poses far less danger than a solid radioisotope that might be ingested or inhaled. Radium and promethium have also been used in the past in commercial aircraft switches, clocks, and watches to provide a glowing indicator, the latter notably in the Apollo program. However, their use declined after radium was found to be dangerously radioactive and promethium rather expensive.

There are three distinct physical processes involved in radioluminescence: excitation of the phosphor by the ionizing radiation, kinetic relaxation of the ionized phosphor, and radiative de-excitation of the phosphor—i.e., the luminescence. The ionizing radiation excites a phosphor either through direct collision or through generation of secondary electrons (delta rays), with the probability of direct excitation generally increasing with the energy of the excitation radiation. At energies below about 50 eV, secondary electrons cease to generate additional secondary electrons. The resulting electron cascade creates a large number of unstable electron configurations within the material, also known as Frenkel defects. (L. Fritzen et al., 2020)

3. Luminescence in Biological Applications

Luminescence phenotypes have a crucial role in a variety of biological research fields (L. Fritzen et al., 2020). Bioluminescence-based imaging offers key benefits, including low autoluminescence, high sensitivity, and deep penetration. Persistent luminescent materials that possess afterglow emission have recently been discovered as a possible tool for luminescence imaging. The necessity for repeated excitation and ensuing tissue damage are missed by these systems. Because of the high absorption of UV–visible light by tissue, these systems also offer a strategy to get around the penetration issues that excitation-based systems face. Luminescence-based sensing technologies have been developed for diagnostics and environmental monitoring with promise for high sensitivity (N. Dunuweera et al., 2024). The construction of universal receptor assays using bioluminescent reporters has made it feasible to identify and characterize corepressors, coactivators, nuclear receptor agonists, and antagonists. Light-emitting reporters that include luciferase reporter genes have been applied successfully in cellular and animal models. The bioluminescence resonance energy transfer (BRET)-induced reaction has been demonstrated as effective for releasing small-molecule drugs including ibrutinib, esomeprazole, rosuvastatin, and duocarmycin. A BRET-based catalysis-driven, chemoselective bioorthogonal chemical reaction was employed to uncage substrates, highlighting broader applications in chemical biology. A novel bioluminescence-based photodynamic therapy (PDT) agent comprising a fused protein conjugated with zinc (II) protoporphyrin IX was created, efficiently delivered to tumor cells, and successfully suppressed breast cancer proliferation through reactive oxygen species (ROS) generation. Bioluminescence imaging provides an economic, noninvasive platform for real-time monitoring of biological molecules and processes, utilizing cameras optimized to detect the low-intensity emission photon flux generated by luciferase enzymes. Compared to fluorescence imaging, in vivo bioluminescence imaging is free of tissue autofluorescence, enhancing clarity and sensitivity in live-animal studies.

4. Industrial Applications of Luminescence

Since the early 1960s, when light-emitting diodes (LEDs) in the visible spectrum became widely available, luminescence became a topic of industrial interest as a new light-source for illumination and indication purposes . Industrial and automotive luminescence applications subsequently employed mercury vapour lamps, LED lamps, fluorescent paints, and radiation- or electrically-pumped phosphors. Radiation-pumped luminescence found extensive use in industrial control and probe devices and is currently employed for industrial lighting and safety applications. The development of vacuum ultraviolet and ultraviolet sources advanced the technology, enabling cathode-ray-tube (CRT) displays, electronic discharge (ED) and plasma displays, luminescent solar concentrators, and daylight collectors. Luminescence of up-converting particles has potential as a new approach for daylight collectors (L. Fritzen et al., 2020).

5. Environmental Monitoring

Modern environmental climate monitoring systems rely on luminescence-based sensors to detect chemicals that harm ecological balance using efficient techniques sensitive to dilute pollutant concentrations (P. Moore, 2010). Long-lived Ru(2,2'-dipyridyl)3 2+ dyes embedded in nanostructured xerogel films impart rapid and sustained luminescence responses to ultratraces of volatile hydrocarbons in marine environments. Statistical optimization models for luminous Vibrio species establish quantitative relationships between analyte exposure and residual bioluminescence output over a wide concentration spectrum, enabling toxicity monitoring of solvents, hydrocarbons, and heavy metals (Hassan et al., 2022). Portable, rugged luminometers featuring split-luciferase assays facilitate rapid, quantitative antibody analysis in low-resource settings to combat endemic diseases and emerging infections (Lebel et al., 2024).

6. Luminescence in Material Science

Luminescence occurs when an excited electron returns to ground state by emitting radiation. The emitted light provides highly sensitive spectroscopic information about the electron's environment. Luminescence materials possess great potential to create new photonic devices that efficiently emit light when excited by light, electricity, or other means. Luminescence properties of materials offer plenty of information about the electron configuration in the ground and excited states, as well as about the energy transfer and energy trapping processes occurring in the material (L. Fritzen et al., 2020). Many

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luminescent materials emitting in the visible and near-infrared (NIR) region have been widely studied for light-emitting devices, lasers, telecommunications, fiber amplifiers, sensor protection, explosive and forbidden weapon detection, and many other applications. Materials presenting a sharp-line emission are able to replace organic and quantum dots in many applications thanks to their resistance to photobleaching, non-toxicity, and long emission lifetimes. Lanthanide ions exhibit extraordinary luminescent properties such as long luminescence lifetime, sharp emission bands, and high resistance to photobleaching, with relatively low toxicity. These make lanthanide-based luminescent materials suitable for many applications in the field of sensors, telecommunication, nanothermometry, and medical imaging and diagnosis. Moreover, sodium yttrium fluoride (NaYF4) doped with trivalent lanthanide ions has been considered the best host for upconversion applications from the ultraviolet to the infrared.

The last decade has witnessed growing interest in luminescent optical sensors fabricated with nanomaterials. Luminescent sensors have proven to be a valid tool in monitoring numerous analytes with practical advantages varying from a simple and cost-effective fabrication to high sensitivity and selectivity. An efficient optical sensor requires fabrics with specific functionalities to strongly interact with the analyte and produce measurable luminescent signal variations. Current luminescent sensors are based on several platforms of films, nanocrystals, xerogels, quantum dots, and polymers. Among them, polymer-based optical sensors show potential in a wide range of applications due to their flexibility in fabrication, the wide choice of functionalization, low production cost, and robust response. Furthermore, the combination of luminescent materials with nanotechnology enhances light–matter interaction for many applications.

7. Nanotechnology and Luminescence

The potential for luminescence applications is expanding due to advances in nanotechnology and optoelectronics. Nanomaterials hold promise for future luminescent technologies since their properties strongly depend on size, shape, and surrounding medium. Luminescent nanoparticles can be used for targeted labelling and bioimaging, security inks and tags, chemical and biological sensing, drug delivery, light-emitting devices, and photodynamic therapy (Li et al., 2019). Development of new colloidal nanomaterials producing near-infrared (NIR) emission is a burgeoning research area within luminescent nanomaterials. Fluorescence in the NIR (700–1400 nm) benefits from reduced tissue autofluorescence and decreased scattering and absorption by biomolecules such as water and haemoglobin, providing a transparency window that enables biological probing and imaging through thicker tissue samples or deeper layers.

Numerous luminescent materials have been developed for use in the NIR range: organic dyes, single-walled carbon nanotubes (SWCNTs), carbon nanodots, semiconductor

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quantum dots (QDs), lanthanide-doped nanocrystals, and organometallic complexes. These materials offer excellent brightness and photostability and have been integrated into composite structures to enhance performance. However, improving NIR image contrast remains a challenge. Engineering efforts aim to optimize the fluorescence brightness of NIR emitters by enhancing their brightness, tunability, and photostability, thereby facilitating greater penetration depths, higher temporal resolution, and expanded imaging timeframes.

8. Challenges and Limitations

Despite the great appeal of luminescence and luminescent methods in technology, industry, and medicine, they still suffer from inherent limitations and practical usage difficulties. Critical problems include the photostability of organic fluorophores and the photoluminescence intensity of colloidal quantum dots, the physiological stability and biocompatibility of organic dyes, as well as the thermal and temporal stability of lanthanide-doped phosphors.

Luminescence-based sensors face issues of chemical and mechanical stability, moderately high prices, and often complicated deposition techniques that complicate control and lead to incomplete separation. The practical applicability of luminescence thermosensors is in many cases limited by their sensitivity in the temperature range of interest. Moreover, investigations of luminescence temperature dependence are typically performed ex situ, away from real measurement conditions, frequently neglecting the influence of various external stimuli and changes in the discussed parameters.

9. Future Directions in Luminescence Research

The luminescence field is showing rapid expansion, presenting a large market potential, with the development of new applications often increasing exponentially. Luminescence-based technologies possess great potential for generating new tools and advancing understanding across a variety of biological and physical phenomena. Numerous current biological and technological paradigms rely on luminescence-based methodologies. Many processes and devices that depend on luminescence cannot be contemplated without the technique. Significant industrial and technological luminescence applications include biological imaging and detection (L. Fritzen et al., 2020) , film projection, chemical engineering, environmental pollution analysis, industrial process controls, and textiles (Li et al., 2019). Continued development and expansion of luminescence-based applications necessitate the design of new materials and processes capable of addressing the inherent limitations of current luminescent systems . Future efforts will likely target the creation of high quantum efficiency, radiation-stable, cost-effective luminophores operating across the UV, visible, and IR spectra, complemented by progress in film support and forming methodologies. Such advances should enable new industrial, technological, environmental, medical, and engineering applications over the forthcoming decades.

9.1. Emerging Technologies

From biology to technological devices, luminescence—the emission of light from a substance without heat—continues to enhance applications in many fields.

Potentially high sensitivity, selectivity, straightforward use and portability, and low cost encourage the widespread use of luminescence for real-time monitoring and for noncontact or remote sensing. Luminescence applications often involve excitation with UV, visible, infrared, or X-ray light, or activation by chemical or physical processes. Luminescence is currently used in such fields as forensic analysis, sensing, imaging, displays, lamps, aerospace, single-molecule detection, mining, and solid-state lighting. It is also widely applied to explosives and toxic materials detection, thermometry, luminescent solar concentrators, multilayer security tags, optical chemical and pH sensing, anticounterfeiting packaging, lighting and display technologies, light-up biomaterials, flat-panel X-ray devices, adaptive optics, data storage, biological detection assays, calcium indicators, nonlinear optics, lasers, nano-optics, probes, and scintillators.

The main luminescence types are photoluminescence, chemiluminescence, bioluminescence, electroluminescence, and radioluminescence. Homogeneous, heterogeneous, and supramolecular catalysts have recently contributed to luminogenic chemical transformations for a range of developing technologies (L. Fritzen et al., 2020). Numerous kinetic analyses are currently conducted in laboratories worldwide using luminescent measurement techniques (Hananya & Shabat, 2019).

9.2. Potential New Applications

Optical luminescence plays a major role in biological, industrial, and technological applications. It forms the basis for a wide range of other applications, including analytical chemistry, medical imaging, displays, security, and emergency and low-level lighting. This section highlights a few of these.

The intensity of photoluminescence can be related to the concentrations of free and bound ammonium ions in soil samples and is used in studies of soil contamination and remediation. The technique offers low-cost, rapid, and portable features well suited to on-site measurements and studies of large-agglomerate soil samples.

10. Conclusion

Key applications of luminescence include biological sensing and imaging, industrial process control, environmental monitoring, forensic science, and the development of efficient light sources. Luminescence has been extensively exploited in biological and chemical sensing, microscopy, digital imaging, chemical lasers, geophysical exploration, archaeological dating, oceanographic studies, anti-counterfeiting technologies, and the fabrication of display monitors (L. Fritzen et al., 2020). A clear example is the pivotal role of luminescence in bioassays used for the detection of various analytes. Measurable luminescence signals offer

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a powerful method for determining cellular localization and genome composition, thus facilitating an understanding of the inner-working processes of living cells (Lebel et al., 2024).

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