Journal of Intelligent Material
https://www.ffspub.com/index.php/jim/index
ISSN 3104-8994 (print)
E-mail: jim.office@ffspub.com

Review

Laser Modification of Organic Fluorescent Materials for Optical Information Storage Applications

Yuhang Zhang[1], Weiwei Zhao[1], Fang Yang[1], Hongwei Liu[1,†] Junpeng Lu[2]
[1]*Academy of Physical Science and Technology, Nanjing Normal University, Nanjing 210023, China*
[2]*Advanced Ocean Institute, Southeast University, Nanjing 210096, China*
[†]*E-mail: 06254@njnu.edu.com*

Received: December 11, 2025 / Revised: January 26, 2026 / Accepted: January 28, 2026 / Published online: January 31, 2026

Abstract: Laser direct writing technology employs a laser as a tool to perform functionalization processes, including reduction, doping, and stripping of materials, thereby offering a highly efficient and groundbreaking approach for tailoring and manipulating materials in the future. This review delves into the advanced intersection between lasers and organic fluorescent materials, systematically outlining the physical mechanisms underlying femtosecond laser-mediated modulation of fluorescence material properties, current technological advancements, and potential future applications. Through an examination of optical storage applications, the key advantages of laser direct writing technology in achieving high-resolution modulation at the micro- and nanoscale levels are uncovered, emphasizing the strategic significance and future development trajectories of organic fluorescent materials in the transformation of optical storage techniques.

Keywords: Laser-Induced; Optical Storage; Organic Fluorescent Materials
https://doi.org/10.64509/jim.11.61

1 Introduction

The advancement of 5G/6G communication and quantum computing has driven a surge in demand for high-density, low-power optical storage materials [1]. Organic fluorescent materials, with their tunable energy levels and photoluminescence properties, are considered ideal candidates for next-generation storage media [2]. On femtosecond timescales, laser–matter interactions occur faster than phonon-mediated thermal relaxation, making nonlinear photon–material effects the dominant mechanism for altering material properties [3]. Femtosecond laser direct writing effectively avoids the precision limitations caused by thermal diffusion in conventional micro/nanofabrication [4]. This technique is increasingly being applied to macromolecular fluorescent polymers and two-dimensional fluorescent materials [5], showing broad potential in cutting-edge fields such as biomimetic medicine [6], encrypted information storage [7], bioimaging [8], and disease diagnosis and treatment.

Stimulated emission describes the process by which atoms generate electromagnetic radiation under an external radiation field. Photoluminescence is one form of stimulated emission [9]. In fluorescent materials, the photoluminescence process generally involves three stages: absorption of radiation energy, electron transition, and subsequent photon emission. Materials exhibiting such luminescent behavior are collectively termed fluorescent materials [10]. Different fluorescent materials vary significantly in their structure [11], excitation mechanisms [12], and application scenarios. Organic fluorescent materials, typically composed of small molecules or conjugated systems [13], offer advantages such as high structural tunability and adjustable absorption/emission wavelengths. These properties have attracted considerable research interest in areas like optical metasurfaces [14], encrypted storage [15], and tunable photonic devices [16].

Organic small molecules usually possess simple architectures, a limited number of atoms, and no repeating structural units, with molecular weights typically below 1000. In contrast, organic polymers are macromolecules formed by the covalent repetition of one or more monomer units, featuring well-defined repeating segments and molecular weights commonly ranging from tens of thousands to several hundred thousand [17]. However, organic fluorescent small molecules (e.g., D–A, D–π–A, COF, and MOF systems) often exhibit limited photostability and quantum yield, which restricts their use in high-performance optical applications [18]. Polymeric

† Corresponding author: Hongwei Liu
*Academic Editor: Zhou Li

organic fluorescent materials (e.g., organic polymers [19], hydrogels [20], and cellulose derivatives) frequently possess excellent fluorescence properties, broad absorption spectra, and narrow emission bands, demonstrating considerable potential in bioimaging, display technologies, and photodetection. Organic–inorganic hybrid fluorescent materials also play important roles in fluorescence labeling, lasing, and anti-counterfeiting due to their unique energy-level structures and good photostability [21].

As novel fluorescent materials continue to emerge, there is a growing need for higher-precision tools to achieve refined and customized control of material properties [22]. Consequently, the integration of laser direct writing with fluorescent materials is becoming an emerging research focus [23]. Advances in laser technology now allow high-resolution modulation of fluorescent materials across spatial and temporal scales, opening new avenues for their practical application and performance optimization [24]. Figure 1 presents a schematic illustration of the organic fluorescent materials employed in this study for laser writing applications.As fluorescent materials find expanding roles and demonstrate excellent performance in emerging fields, ultrafast laser micro/nanofabrication is further accelerating the development of materials engineered for specific functional needs [25].

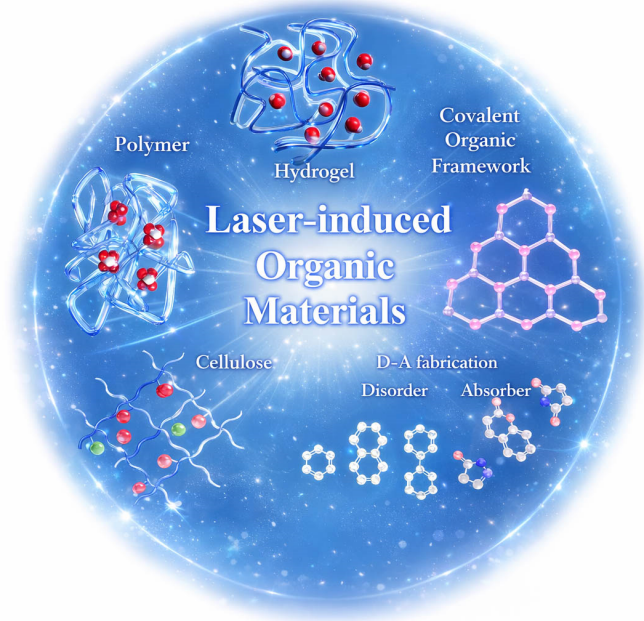

Figure 1: Diagram of Laser-Modified Organic Materials.

2 Laser Modification Mechanisms

In materials science and engineering, laser processing and modification technology has created unprecedented pathways for developing and applying novel functional materials [26]. With advances in mode-locking technology, ultrashort-pulse lasers—spanning picosecond to femtosecond and even attosecond durations—have emerged, offering revolutionary means for material preparation and giving rise to the interdisciplinary field of laser micro/nanofabrication [27].

Owing to their ultrahigh peak power and ultrashort interaction time, ultrashort-pulse lasers enable non-thermal-equilibrium precision processing on or inside materials, significantly shrinking the heat-affected zone and avoiding common defects such as melting, resolidification, and micro-cracking that occur with traditional methods [28]. This "cold processing" characteristic makes laser modification suitable not only for metals, but also widely applicable for structurally modulating and optimizing semiconductors [29], ceramics, polymers, and even biocompatible materials. At the micro-scale, nonlinear effects such as multiphoton absorption, tunneling ionization, and avalanche ionization induced by laser-matter interactions concentrate energy into extremely small volumes, thereby triggering lattice reconstruction, phase transitions, defect engineering, and even the formation of new phases [30].

By controlling laser parameters—wavelength, pulse width, repetition rate, scanning speed, and energy density—researchers can precisely tailor surface morphology and functional characteristics of materials. For example, femtosecond laser irradiation can produce periodic nanoscale ripple structures (LIPSS) on metal surfaces [31], markedly enhancing hydrophilicity and cell adhesion, which supports the functional design of biomedical implants. Furthermore, laser modification has been used to tune mechanical [32], electrical, and magnetic properties of materials. In the realm of two-dimensional materials such as graphene and transition-metal dichalcogenides, laser irradiation can controllably introduce vacancy defects or achieve chemical doping, thereby regulating carrier concentration and mobility and expanding their applications in flexible electronics and sensors [33].

It is important to note that the physical mechanisms underlying laser modification are highly complex, involving multiscale coupled processes across time and space, including electron excitation dynamics, energy transfer pathways, phase-transition kinetics, and plasma evolution [34]. Research in this area not only deepens the fundamental understanding of laser-matter interactions but also provides theoretical support for the intelligent and customized design of materials.

2.1 Laser Power Density Below Threshold

In laser processing, when the laser power density remains below the material's critical threshold, modification occurs primarily through non-thermal mechanisms, which include photochemical and photophysical effects [35]. Photochemical effects refer to structural and phase changes—such as chemical-bond rearrangement, surface oxidation, and amorphization—induced by photon energy that is insufficient to remove material macroscopically but sufficient to trigger these transformations [36]. This process does not involve melting or vaporization; instead, it achieves precise reconstruction of surface chemical composition and functional groups via multiphoton nonlinear absorption. High-energy photons can directly break chemical bonds, initiating rapid and selective reactions such as cross-linking, chain scission, and radical generation.

Photophysical effects involve the excitation of carriers and phonons by photons, which can alter electronic state densities and promote the formation of new material phases.

Under ultrafast laser irradiation, these effects become especially pronounced: femtosecond-scale laser electric fields can perturb the electronic potential wells of atoms or molecules over extremely short times, driving transient reconstruction of orbital energy levels and thereby modulating physical properties such as fluorescence. As shown in Figure 2(a), Bobrinetskiy et al. [37] performed laser-patterning studies on monolayer graphene grown by chemical vapor deposition (CVD) and observed, for the first time, that oxidative etching could occur even below the threshold energy density. Figure 2(b) displays that using XPS to analyze elemental composition before and after laser modification—with green, orange, blue, and cyan spectral lines representing sp^2 carbon, sp^3 carbon, C–O–C/C–OH, and C=O/COOH, respectively—the study confirmed an increase in the proportion of sp^3 carbon and oxygen. This work revealed the competitive interplay between photochemical and photothermal effects, offering a novel high-precision, low-damage route for the flexible manufacturing of micro/nano-electronic devices.

When the laser power density stays below the material's critical threshold, non-thermal effects prevail, resulting from the combined action of photochemical and photophysical mechanisms: the former reconstructs surface chemistry through multiphoton absorption, while the latter transiently modifies electronic structure to influence physical properties. Together, these effects advance the development of sophisticated micro- and nanofabrication technologies.

2.2 Laser Power Density Near Threshold

When the laser power density approaches the material's critical threshold, photochemical and photothermal effects coexist and jointly interact with the material surface, inducing significant changes in geometric morphology [38]. Near the threshold, these effects exhibit a competitive–synergistic relationship. A typical outcome is the formation of laser-induced periodic surface structures (LIPSS), where photochemical processes alter surface chemistry while photothermal effects drive phase transitions or melting via lattice-thermal diffusion [39]. In recent years, researchers have explored modification mechanisms near the laser threshold by controlling parameters such as wavelength, pulse width, repetition rate, scanning speed, and energy density, thereby achieving precise tuning of surface morphology and functional properties. Que et al. [40] systematically studied femtosecond-laser modification of the cyclo-olefin polymer Zeonex. They demonstrated two distinct modification regimes under different power levels: Type I, characterized by molecular-structure reconstruction and refractive-index modulation, suitable for optical optimization at lower powers; and Type II, accompanied by the formation of carbonized clusters and enhanced photoluminescence, which typically yields fluorescent behavior at higher powers. Near the threshold, photochemical and photothermal effects do not act in isolation but jointly govern the evolution of surface microstructures through dynamic competition and synergy. The formation of LIPSS represents a classic manifestation of this coupled mechanism.

2.3 Laser Power Density Above Threshold

When the laser power density exceeds the material's critical threshold, nonlinear optical effects induce complex physical processes such as ionization, melting, and phase-change evaporation. These are accompanied by strong thermal effects that trigger dramatic phase transitions and material removal, resulting in the formation of complex microstructures [41]. The laser penetration depth is closely tied to the material's optical properties; polymers with similar molecular structures exhibit comparable absorption behaviors and processing characteristics [42]. However, when the power density is far above the threshold, the process often generates considerable ionized sputtering debris, severely compromising the precision and quality of micro-/nanofabrication and causing irreversible thermodynamic damage to the material surface [43].

Above the threshold, nonlinear optical effects and intense thermal processes operate together: nonlinear phenomena drive ionization, melting, and evaporation, creating intricate microstructures, though excessively high power densities tend to produce ionized debris that degrade processing accuracy. Pan et al [44] investigated the electron dynamics in fused silica under temporally shaped femtosecond double-pulse irradiation. Figure 2(c) presents a 2D distribution of the electron density for double-pulse and single-pulse irradiation, while Figure 2(d) shows the 2D transmission mapping and the evolution of electron density at the center of filaments induced by double pulses with 200 fs delay.

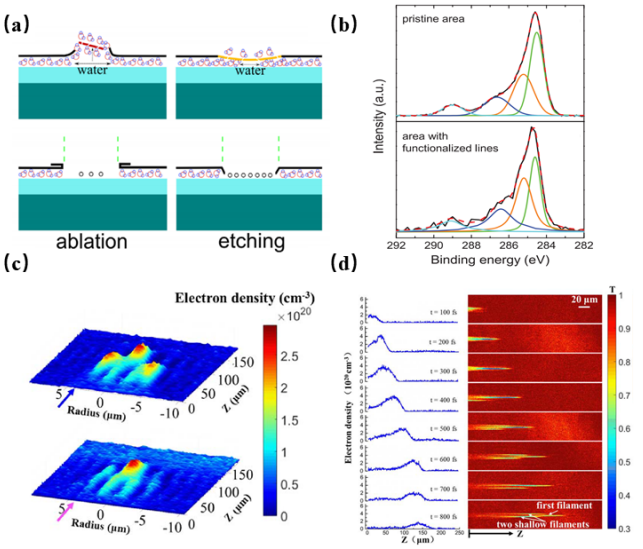

Figure 2: Mechanism Diagrams of Ultrafast Laser Interaction with Organic Materials. (a) Schematic diagram of graphene ultrafast laser-induced patterning: left side shows the material ablation process under conditions above the threshold, and right side shows the oxidation etching process under conditions below the threshold energy; (b) XPS spectra and curve fitting results of the original graphene and laser-processed areas (Adapted with permission [37]. Copyright 2016, IOP Publishing Limited). (c)2D distribution of the electron density of double pulse and single pulse. (d)2D transmission mapping and electron density evolution in the center of filaments induced by double pulses with 200 fs.(Adapted with permission [44]. Copyright 2019, IOP Publishing Limited)

A hierarchical analysis of laser modification mechanisms reveals a continuous spectrum spanning non-thermal to thermal-nonlinear composite effects, offering a theoretical framework for the precise modulation of material properties [45]. By dynamically regulating the power-density-to-threshold relationship, cross-scale fabrication—from molecular-level chemical reconstruction to macroscopic structure formation—can be realized, thereby advancing technologies in flexible electronics [46], photonic integration, and micro-/nanorobotics.

Looking ahead, laser modification technology is expected to evolve toward greater precision, efficiency, and integration. The incorporation of artificial-intelligence algorithms for autonomous process optimization could enable a closed-loop "on-demand" manufacturing paradigm for tailoring material properties. Concurrently, the growing emphasis on green manufacturing is pushing laser processing toward lower energy consumption and reduced environmental impact, further broadening its application prospects in strategic fields such as aerospace, new energy, and biomedical engineering. With continued advances in fundamental theory and engineering techniques, laser modification is poised to remain a key enabler in the development of next-generation functional materials, serving as a major engine for innovation in materials science.

3 Optical Storage Applications of Different Organic Fluorescent Materials

3.1 Polymers

Organic polymers are high-molecular-weight compounds formed by polymerizing organic small-molecule monomers. They typically exhibit molecular weights ranging from 10^4 to 10^7 and are characterized by long chains of repeating structural units [47, 48]. As a common class of organic materials, they are widely employed in industrial production and daily life, with familiar examples including PMMA, PVC, PVP, and PC. In recent years, advances in laser direct-writing technology have spurred growing research interest in their applications for optical storage [49–52].

Current research focuses on designing novel polymer systems to achieve high-density, dynamic, or encrypted information storage. These functions are realized by precisely modulating the optical properties of the materials, such as fluorescence, phosphorescence, and solvatochromism. For instance, Liu et al [53] used the switching-mode fluorescence of MEH-PPP films for rapid image encoding. Figure 3(a) shows schematic of the laser modification setup; Figure 3(b) presents the fluorescence optical image of the modified material under UV irradiation; and Figure 3(c) displays the change in photoluminescence (PL) intensity over UV-exposure time. This work demonstrates the feasibility of laser-based optical storage in organic polymers. Li et al. [54] endowed covalent organic polymers (COPs) with solvatochromic and solid-state fluorescent properties through molecular design, enabling anti-counterfeiting encryption. Yu et al. [55] implemented a dynamic anti-counterfeiting system by doping different polymer matrices to achieve multiple decay pathways, including room-temperature phosphorescence and thermally activated delayed fluorescence.

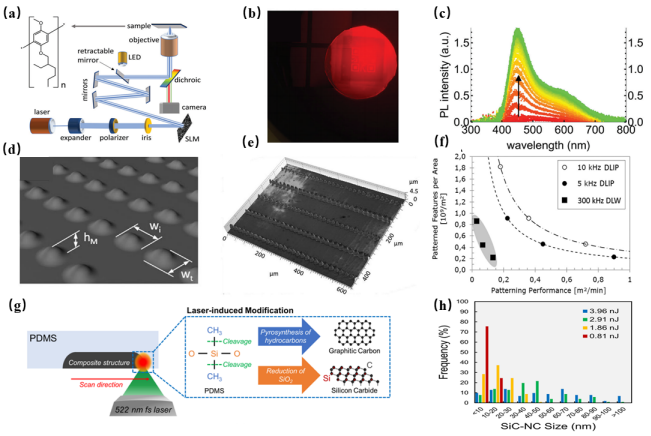

Figure 3: Optical Storage Applications of Polymers under Laser Action. (a) Schematic diagram of a device for laser processing of polymers; (b) Optical image of the processed material under a combination of ultraviolet light and a 600 nm long-pass filter; (c) Changes in the PL intensity spectrum of the material over ultraviolet laser irradiation time [53]; (Adapted with permission [53]. Copyright 2024, John Wiley and Sons); (d) Schematic diagram of material surface structure parameters obtained by laser processing; (e) Surface optical image of the material after laser processing; (f) Comparison of patterning performance achieved by laser direct writing and laser interference patterning (DLIP) techniques[56]; (Adapted with permission [56]. Copyright 2016, John Wiley and Sons); (g) Schematic diagram of the laser-induced modification process of polydimethylsiloxane (PDMS); (h) Relationship between silicon carbide (SiC) nanocrystal size and incident laser power [57]. (Adapted with permission [57]. Copyright 2023, American Chemical Society).

As noted earlier, when laser power exceeds the material threshold, thermal effects dominate, inducing severe phase transitions and material removal to form complex microstructures. Using lasers as the core processing tool, researchers achieve precise alterations in the physical structure or chemical properties of polymers through surface or internal light–matter interactions. By controlling laser parameters—wavelength, pulse width, repetition rate, scanning speed, and energy density—the key scientific questions center on photothermal and photochemical interaction mechanisms, with applications targeting micro-/nanostructure fabrication and device functionalization. For example, Lang et al. [56] employed laser interference to induce local expansion and ablation of polycarbonate, efficiently producing periodic micropatterns. Figure 3(d) illustrates the scheme for laser-controlled surface structuring; Figure 3(e) shows an optical image of the laser-modified material; and Figure 3(f) compares the patterning performance of direct laser writing and direct laser interference patterning (DLIP).

Notably, Terakawa et al. [57] investigated ultrashort-pulse laser modification of polydimethylsiloxane (PDMS). By tuning photon energy and repetition rate, they achieved precise control over the composition of modified products (Figure 3(g)). Moreover, regulating the incident laser power enabled accurate size control of SiC nanoparticles (Figure 3(h)). This approach opens new routes for fabricating novel electronic and photonic devices such as semiconductor units and optical sensors. Although current progress is still limited by the thermal-effect efficiency of femtosecond lasers, this field holds broad promise for ultrashort-pulse laser modification of polymers. Together, these studies highlight the diversity and innovation of laser-induced polymer modification for optical storage—spanning rapid encoding, efficient processing, precise material tailoring, multifunctional luminescence design, and green low-cost fabrication. Each case demonstrates distinct advantages and application prospects within its specific domain.

3.2 Hydrogels

Hydrogels are gels with water as the dispersion medium, formed by chemically or physically crosslinked hydrophilic polymers into three-dimensional networks. They can absorb large amounts of water—often tens to thousands of times their own weight—without dissolving, thereby retaining their original three-dimensional structure [58, 59]. In the field of laser-driven optical storage in hydrogels, a series of breakthrough studies are creating intelligent material systems that combine functionality with practical value through material innovation and process optimization [60].

Recently, researchers have employed laser direct writing along with efficient and precise patterning techniques to achieve high-level anti-counterfeiting functions in hydrogel materials [61]. For example, the Guo team [62] used carbon dioxide infrared laser engraving to rapidly generate colorful patterns with physically unclonable features on hydrogel surfaces by controlling thermokinetic parameters. The processing schematic and resulting fluorescence patterns are shown in Figure 4(a), while Figure 4(b) presents fluorescence images of the material surface obtained by varying the laser scanning speed. This approach, which combines high efficiency with precision, offers a viable solution for the industrial production of anti-counterfeiting labels. Meanwhile, the Lin team [59] developed orthogonal photothermal hydrogels that incorporate different fluorophores within microcapsules, enabling high-precision temperature response and multi-level encryption.

Through clever molecular design and system integration using hydrogels as a matrix, researchers have endowed materials with dynamic, tunable, and even biomimetic intelligent response capabilities [63]. The Zheng team [64] developed WLE hydrogels that achieve reversible fluorescence color switching by modulating chromophore morphology, offering flexible “write-read” functionality for information storage. The read–write process is illustrated in Figure 4(c–e) show the corresponding chromaticity coordinates and fluorescence spectra of the hydrogel under different laser processing times, respectively. This design provides the flexible advantage of “write once, read many” for information encryption, with twice faster response speed and photostability two orders of magnitude higher than conventional fluorescent materials. In another study, the Chen team [65] created supramolecular fluorescent hydrogels that integrate broad-spectrum color change, self-healing, and remodeling capabilities, and have demonstrated prototype validation in biomimetic applications such as soft-robot camouflage. Together, these works are driving the evolution of hydrogels from single-response materials toward multifunctional, integrated intelligent systems.

Focused on the fluorescence properties of hydrogels, these studies have enabled crossover applications—from fundamental mechanism exploration to practical anti-counterfeiting encryption and soft robotics—through laser induction, molecular design, and microstructure control. They vividly demonstrate the considerable potential of materials science in the fields of information storage and dynamic response.

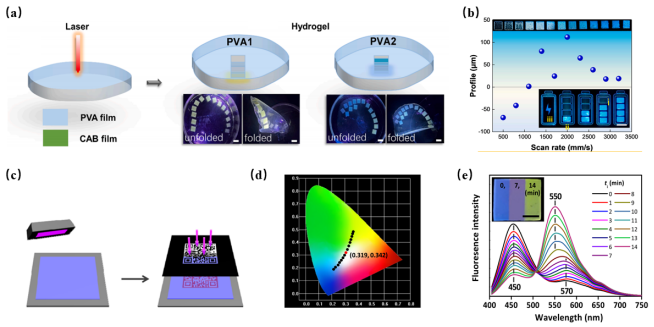

Figure 4: Optical Storage Applications of Hydrogels under Laser Action. (a) Fluorescence patterns formed on PVA1/PVA2 hydrogels under ultraviolet light irradiation after laser patterning; (b) Material surface fluorescence images obtained by varying the scanning rate (500-3500 mm/s) of the laser direct writing technology[62]; (Adapted with permission [62]. Copyright 2025, Elsevier); (c) Schematic of the read-write process of fluorescence hydrogels prepared by photolithography; (d) and (e) Chromaticity coordinates and fluorescence spectra of the fluorescence hydrogel under different laser processing times, respectively[64]. (Adapted with permission [64]. Copyright 2018, American Chemical Society).

3.3 Cellulose-Based Materials

In the field of cellulose-based optical storage, laser technology demonstrates remarkable innovative potential and application value, emerging as a key driver for advancing this area. From various perspectives, new strategies for integrating lasers with cellulose-based materials have been explored, together highlighting the broad prospects of cellulose optical storage in information encryption, bioengineering, intelligent sensing, and beyond [66].

Representative work by the Zhou team [67] involved in situ fluorescence writing on cellulose acetate butyrate (CAB) films using a pulsed carbon dioxide laser. Figure 5(a) illustrates the schematic of carbon dot formation via laser direct writing and thermal decomposition of cellulose. Figure 5(b) compares the elemental composition of the original CAB film and the laser-processed surface, revealing a notable increase in carbon content after irradiation. Figure 5(c) presents the photoluminescence (PL) spectra of CAB under different

excitation wavelengths and a fluorescence image of the patterned material. The core advantages of this approach lie in its operational simplicity, environmental friendliness, and the precise control over pattern microstructure and performance through laser parameters, offering an effective technical route for fabricating low-cost, scalable information-storage media.

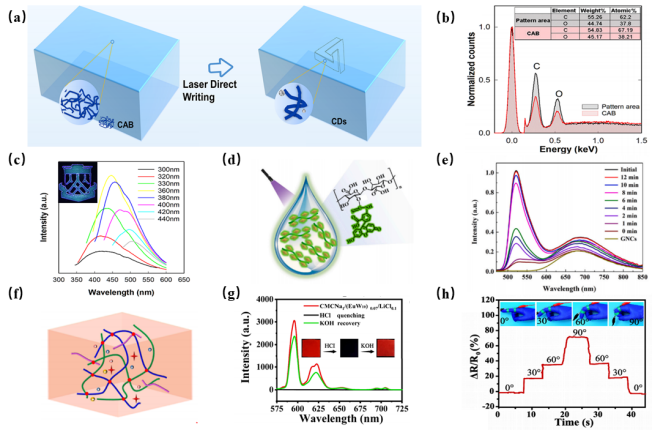

Figure 5: Optical Storage Applications of Cellulose under Laser Action. (a) Schematic of carbon dot formation by laser direct writing and thermal decomposition of cellulose; (b) Energy dispersive spectroscopy (EDS) analysis and elemental proportion comparison between the original CAB film and the laser-processed surface; (c) Photoluminescence emission spectra of CAB under different excitation wavelengths [67]; (Adapted with permission [67]. Copyright 2022, American Chemical Society); (d) Schematic of fluorescence emission of CNC-FITC cellulose under ultraviolet irradiation; (e) Variation curve of the PL spectra of CNC-FITC cellulose with time after ultraviolet excitation [69]; (Adapted with permission [69]. Copyright 2018, Elsevier); (f) Schematic of the organic gel structure based on cellulose; (g) Variation curve of the fluorescence intensity of the organic gel with pH value; (h) Relationship between the electrical conductivity of the organic gel and deformation angle [70]. (Adapted with permission [70]. Copyright 2025, American Chemical Society).

Beyond fluorescence, researchers have also endowed cellulose-based materials with various stimulus-responsive behaviors and unique functions through molecular design and system engineering, targeting advanced information encryption and intelligent sensing applications [68]. For instance, the He team [69] used cellulose nanocrystals as a structural platform to construct time-dependent fluorescent encryption materials, realizing a dual-locking mechanism based on "time–color" correlation; Figure 5(d) depicts the fluorescence emission schematic of CNC-FITC cellulose under ultraviolet irradiation, and Figure 5(e) shows the corresponding time-dependent evolution of its photoluminescence (PL) spectra following UV excitation. Separately, the Dai team [70] developed multi-responsive organogels based on sodium carboxymethyl cellulose, which exhibit sensitive feedback to mechanical force, pH, and metal ions, and integrate both electrical and optical signal outputs. Figure 5(f) presents a schematic of the gel's cellulose-based structure; Figure 5(g) and Figure 5(h) respectively show the variation of its fluorescence intensity with pH and the relationship between its electrical conductivity and deformation angle, quantifying its dual-mode stimulus-response behavior.

In summary, although these studies follow distinct paths, each ingeniously leverages laser technology and the inherent properties of cellulose-based materials to achieve breakthroughs in information encryption, bioengineering, and intelligent sensing. They not only demonstrate the substantial potential of lasers in cellulose optical storage but also provide valuable insights and inspiration for the future development of related materials and technologies—indicating that cellulose-based optical storage will continue to shine in an expanding range of high-tech applications.

3.4 D–A, D–π–A Organic Small Molecules

Research on organic small molecules for optical storage spans multiple directions, including specialized photochemical reaction mechanisms and functional material design, reflecting significant progress from fundamental exploration to practical application [71]. These studies not only deepen the understanding of the optical response behavior of organic small molecules but also provide key concepts and experimental models for developing novel optical functional materials [72]. For instance, the Cao team [73] designed a donor–acceptor (D–A) based TSB-TFP cocrystal. Figure 6(a) shows the predicted morphology, corresponding crystal planes, hydrogen-bonding interactions, and molecular packing of TSB-TFP, while Figure 6(b) presents its emission spectra in organic solvents under different excitation wavelengths. This system achieves multicolor emission and rewritable functions through photoinduced solid–liquid phase transitions and electrochromism, offering a template for high-density information storage.

Unlike conventional organic molecules, the optical and physical properties of designed small molecules can be finely tuned by modifying the composition of electron-withdrawing and electron-donating groups within the molecular framework. This enables the development of high-efficiency, high-stability emitters for specific applications such as lighting and imaging [74]. The Chen team [75] custom-designed a PSFP organic monomer (structure shown in Figure 6(c)) and obtained a supramolecular fluorescent polymer via self-assembly (process illustrated in Figure 6(d), along with the corresponding fluorescence image). Figure 6(e) displays the variation in absorbance (420 nm) over time under different solvent contents. This work demonstrates a fast, reversible, and reprogrammable fluorescence switch, providing a new approach for "write-once, verify-many" encryption scenarios. In another study, the Zhang team [76] reported a room-temperature phosphorescence emitter, DMACPPY, which achieves efficient white-light emission and thermal stability through excited-state regulation, targeting solid-state lighting applications. Meanwhile, the Guo team [77] systematically enhanced the quantum yield of fluorophores in aqueous solution via molecular-structure modification, directly addressing fields that demand high fluorescence brightness, such as bioimaging and environmental monitoring.

In organic small-molecule systems, functional optimization can be achieved through precise molecular design and synthesis strategies that leverage the distinct characteristics of functional groups to meet specific requirements [78]. Moving forward, two-dimensional organic materials—such as covalent organic frameworks (COFs) and metal–organic frameworks (MOFs)—are expected to lead the way in frontier areas including optical storage, information encryption, and white-light lighting, forming a complete innovation chain from basic research to application [79]. With a deeper understanding of optical response mechanisms, combined with advanced synthesis techniques and characterization methods, this field is poised to deliver further breakthroughs in material performance and application scenarios, thereby providing sustained momentum for technological advances in optoelectronics, information security, and energy-efficient lighting [80].

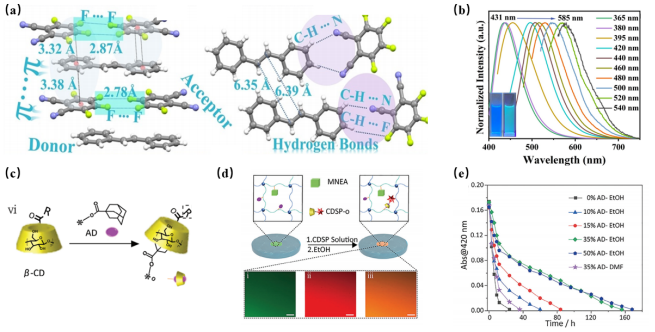

Figure 6: (a)Predicted morphology, corresponding crystal planes, hydrogen bonding interactions, and molecular packing structure of the TSB-TFP molecule designed based on a D–A configuration; (b) Emission spectra of the TSB-TFP molecule in organic solvents under different excitation wavelengths [73];(Adapted with permission [73]. Copyright 2025, John Wiley and Sons); (c) 3D structure and growth schematic of the organic fluorescent molecule PSFP; (d) Cross-sectional laser confocal fluorescence image of PSFP-0; (e) Variation of the absorbance (420 nm) of the organic molecule with time under different solvent contents[75]. (Adapted with permission [75]. Copyright 2024, John Wiley and Sons).

4 Summary and Outlook

This review systematically examines innovative research advances in organic materials under laser irradiation for optical storage and related applications, illustrating a coherent progression from fundamental mechanistic studies to practical implementation. These investigations not only deepen the understanding of the optical response behaviors of organic small molecules but also offer key insights and experimental models for developing novel optical functional materials.

Building on this foundation, recent research has concentrated on the precise control of core photochemical pathways such as photo-isomerization, photo-induced electron transfer, and photo-triggered cycloaddition. By incorporating donor–acceptor (D–A) structural motifs, organic molecular systems with reversible optical responses have been designed, significantly improving the comprehensive performance of materials in terms of writing speed, storage density, and cycling stability. For instance, the cis–trans isomerization of azobenzene derivatives under UV/visible light has been widely used in binary information-coding systems; their high on–off ratio and millisecond-scale response time make them ideal candidates for dynamic optical storage. Meanwhile, spiropyran and diarylethene derivatives, owing to their thermal irreversibility and excellent fatigue resistance, show great promise for long-term data archiving.

Notably, the introduction of multiphoton absorption mechanisms has led to breakthroughs in three-dimensional bulk-storage technology. Using spatially selective excitation by femtosecond laser pulses, researchers have successfully constructed sub-micron-scale information-recording units, substantially expanding storage capacity per unit volume. This approach typically relies on two-photon polymerization or localized radical-generation processes, demanding materials with strong nonlinear optical responses. For this purpose, a series of extended conjugated aromatic systems have been synthesized and optimized, exhibiting efficient two-photon absorption cross-sections in the near-infrared region. This effectively reduces light-scattering effects in deep tissues or thick films and provides a physical basis for high-throughput, low-damage data writing.

Furthermore, the trend toward functional integration has driven the development of intelligent photo-responsive materials. Combining photochromic units with polymer backbones, liquid crystals, or nanocarriers not only enhances processability and mechanical stability but also enables synergistic multi-stimuli responsiveness. For example, certain composite systems can undergo color changes upon illumination while simultaneously modulating dielectric constants or refractive indices, making them suitable for rewritable holographic storage and optically controlled switching devices. More advanced logic-gate arrays based on molecular-machine concepts demonstrate the feasibility of information processing at the molecular scale, signifying an evolution of optical-storage technology from passive recording to active computing.

Looking ahead, sustained progress in this field faces several key challenges: improving the long-term environmental stability of materials, reducing the optical driving power to minimize energy consumption, and establishing standardized performance-evaluation protocols. At the same time, interdisciplinary convergence will serve as a crucial catalyst—integrating computational chemistry for molecular-energy-level prediction and leveraging artificial-intelligence algorithms to optimize structure–property relationship models, thereby accelerating the rational design of high-performance materials. With deepening insights into the nature of light–matter interactions, organic optical functional materials are poised to play increasingly vital roles in next-generation high-density storage, quantum information processing, and even biocompatible implantable devices, thereby providing a solid material foundation for innovations in information technology.

Funding

This work was supported by the National Key Research and Development Program(2024YFB3211701), the National

Natural Science Foundation of China (62404105, 12274234, U25A20511). Research Fund for Advanced Ocean Institute of Southeast University, Nantong, Key Program KP20010003. We would like to express our special thanks to the National Key Laboratory of Crystal Materials, Shandong University for its open project (KF25).

Author Contributions

Writing and editing, Yuhang Zhang; Supervision, Weiwei Zhao, Fang Yang; Project administration and funding acquisition, Hongwei Liu, Junpeng Lu; All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

All the authors declare that they have no conflict of interest.

References

[1] Malinauskas, M., Zukauskas, A., Hasegawa, S., Hayasaki, Y., Mizeikis, V., Buividas, R., Juodkazis, S.: Ultrafast laser processing of materials: from science to industry. Light: Science & Applications **5**(8), e16133 (2016). https://doi.org/10.1038/lsa.2016.133

[2] Guo, W., Li, Z., Huang, L., Qian, M., Tour, J.M., Ye, R.: Laser-assisted materials engineering at the atomic and nanoscales. Nature Synthesis **4**, 1488–1503 (2025). https://doi.org/10.1038/s44160-025-00936-y

[3] Carbone, F., Baum, P., Rudolf, P., Zewail, A.H.: Structural preablation dynamics of graphite observed by ultrafast electron crystallography. Physical Review Letters **100**(3), 035501 (2008). https://doi.org/10.1103/PhysRevLett.100.035501

[4] Raciukaitis, G.: Ultra-Short Pulse Lasers for Microfabrication: A Review. IEEE Journal of Selected Topics in Quantum Electronics **27**(6), 1–12 (2021). https://doi.org/10.1109/JSTQE.2021.3097009

[5] Asahi, T., Sugiyama, T., Masuhara, H.: Laser fabrication and spectroscopy of organic nanoparticles. Accounts of Chemical Research **41**(12), 1790–1798 (2008). https://doi.org/10.1021/ar800125s

[6] Visan, A.I., Popescu-Pelin, G.F.: Advanced Laser Techniques for the Development of Nature-Inspired Biomimetic Surfaces Applied in the Medical Field. Coatings **14**(10), 1290 (2024). https://doi.org/10.3390/coatings14101290

[7] Wang, H., Ji, X., Page, Z.A., Sessler, J.L.: Fluorescent materials-based information storage. Materials Chemistry Frontiers **4**(4), 1024–1039 (2020). https://doi.org/10.1039/C9QM00607A

[8] Wang, S., Ren, W.X., Hou, J.-T., Won, M., An, J., Chen, X., Shu, J., Kim, J.S.: Fluorescence imaging of pathophysiological microenvironments. Chemical Society Reviews **50**(16), 8887–8902 (2021). https://doi.org/10.1039/d1cs00083g

[9] Zhu, S., Song, Y., Zhao, X., Shao, J., Zhang, J., Yang, B.: The photoluminescence mechanism in carbon dots (graphene quantum dots, carbon nanodots, and polymer dots): current state and future perspective. Nano Research **8**(2), 355–381 (2015). https://doi.org/10.1007/s12274-014-0644-3

[10] Yao, J., Yang, M., Duan, Y.: Chemistry, Biology, and Medicine of Fluorescent Nanomaterials and Related Systems: New Insights into Biosensing, Bioimaging, Genomics, Diagnostics, and Therapy. Chemical Reviews **114**(12), 6130–6178 (2014). https://doi.org/10.1021/cr200359p

[11] Bauri, K., Saha, B., Banerjee, A., De, P.: Recent advances in the development and applications of non-conventional luminescent polymers. Polymer Chemistry **11**(46), 7293–7315 (2020). https://doi.org/10.1039/D0PY01285H

[12] Ding, Z., Zhang, Z., Xin, B., Yang, X.: Dual-ligand strategy enables electrospun PAN-EPT nanofiber membranes with synergistic fluorescence-mechanical properties for advanced anti-counterfeiting and flexible photonic devices. Dyes and Pigments **246**, 113281 (2026). https://doi.org/10.1016/j.dyepig.2025.113281

[13] Grimm, J.B., Lavis, L.D.: Caveat fluorophore: an insiders' guide to small-molecule fluorescent labels. Nature Methods **19**(2), 149–158 (2022). https://doi.org/10.1038/s41592-021-01338-6

[14] Li, J., Wang, J., Li, H., Song, N., Wang, D., Tang, B.Z.: Supramolecular materials based on AIE luminogens (AIEgens): construction and applications. Chemical Society Reviews **49**(4), 1144–1172 (2020). https://doi.org/10.1039/C9CS00495E

[15] Huang, Y., Ning, L., Zhang, X., Zhou, Q., Gong, Q., Zhang, Q.: Stimuli-fluorochromic smart organic materials. Chemical Society Reviews **53**(3), 1090–1166 (2024). https://doi.org/10.1039/D2CS00976E

[16] Luo, Z., Yao, Y., Liang, M., Tian, F., Sun, H., Xu, Y., Zhao, Q., Yu, Z.: Molecular layer modulation of two-dimensional organic ferroelectric transistors. Nanotechnology **34**(27), 27L01 (2023). https://doi.org/10.1088/1361-6528/acca28

[17] Diab, R., Boltaev, G., Kaid, M.M., Fawad, A., El-Kaderi, H.M., Al-Sayah, M.H., Alnaser, A.S., El-Kadri, O.M.: Fabrication of heteroatom-doped graphene-porous organic polymer hybrid materials via femtosecond laser writing and their application in VOCs sensing. Scientific Reports **15**(1), 3682 (2025). https://doi.org/10.1038/s41598-025-87681-6

[18] Lustig, W.P., Mukherjee, S., Rudd, N.D., Desai, A.V., Li, J., Ghosh, S.K.: Metal-organic frameworks: functional luminescent and photonic materials for sensing applications. Chemical Society Reviews **46**(11), 3242–3285 (2017). https://doi.org/10.1039/C6CS00930A

[19] You, J., Yin, C., Wang, S., Wang, X., Jin, K., Wang, Y., Wang, J., Liu, L., Zhang, J., Zhang, J.: Responsive circularly polarized ultralong room temperature phosphorescence materials with easy-to-scale and chiral-sensing performance. Nature Communications **15**(1), 7149 (2024). https://doi.org/10.1038/s41467-024-51203-1

[20] Zhang, H., Zhao, Z., McGonigal, P.R., Ye, R., Liu, S., Lam, J.W.Y., Kwok, R.T.K., Yuan, W.Z., Xie, J., Rogach, A.L., *et al*.: Clusterization-triggered emission: Uncommon luminescence from common materials. Materials Today **32**, 275–292 (2020). https://doi.org/10.1016/j.mattod.2019.08.010

[21] Hu, Z., Deibert, B.J., Li, J.: Luminescent metal-organic frameworks for chemical sensing and explosive detection. Chemical Society Reviews **43**(16), 5815–5840 (2014). https://doi.org/10.1039/C4CS00010B

[22] Li, J., Yan, J., Li, X., Qu, L.: Research Advancement on Ultrafast Laser Microprocessing of Transparent Dielectrics. Chinese Journal of Lasers **48**(2), 0202019 (2021). http://doi.org/10.3788/CJL202148.0202019

[23] Liu, J., Qin, Y., Li, X., Wang, R., Guo, H., Tang, J., Liu, J., Liu, L.: One-step synthesis of graphene quantum dots by laser-induced polymer. Materials Science in Semiconductor Processing **153**, 107146 (2023). https://doi.org/10.1016/j.mssp.2022.107146

[24] Saraceno, C.J., Sutter, D., Metzger, T., Abdou Ahmed, M.: The amazing progress of high-power ultrafast thin-disk lasers. Journal of the European Optical Society-Rapid Publications **15**(1), 15 (2019). https://doi.org/10.1186/s41476-019-0108-1

[25] Song, M.-M., Li, J., Lu, H., Wang, J.-X., Zeng, M.-F., Qi, X.-W., Zhou, T., Zhang, J., Li, B.-J., Zhang, S.: Laser-Writing Multicolor Fluorescent Polyurethane for Facile Display and Potential Application in Luminescent Labeling. ACS Applied Materials & Interfaces **17**(17), 25861–25872 (2025). https://doi.org/10.1021/acsami.5c05451

[26] Trusovas, R., Ratautas, K., Račiukaitis, G., Barkauskas, J., Stankevičienė, I., Niaura, G., Mažeikienė, R.: Reduction of graphite oxide to graphene with laser irradiation. Carbon **52**, 574–582 (2013). https://doi.org/10.1016/j.carbon.2012.10.017

[27] Guo, B., Sun, J., Lu, Y., Jiang, L.: Ultrafast dynamics observation during femtosecond laser-material interaction. International Journal of Extreme Manufacturing, **1**(3), 032004 (2019). https://doi.org/10.1088/2631-7990/ab3a24

[28] Kallepalli, L.N.D.: Femtosecond-laser direct writing in polymers and potential applications in microfluidics and memory devices. Optical Engineering **51**(7), 073402 (2012). https://doi.org/10.1117/1.OE.51.7.073402

[29] Zhang, Y., Li, X., Lu, L., Guan, Y.: Anti-icing polyurethane coating on glass fiber-reinforced plastics induced by femtosecond laser texturing. Applied Surface Science **662**, 160077 (2024). https://doi.org/10.1016/j.apsusc.2024.160077

[30] Koskinen, P., Karppinen, K., Myllyperkio, P., Hiltunen, V.M., Johansson, A., Pettersson, M.: Optically Forged Diffraction-Unlimited Ripples in Graphene. The Journal of Physical Chemistry Letters **9**(21), 6179–6184 (2025). https://doi.org/10.1021/acs.jpclett.8b02461

[31] Yang, Z., Liu, X., Tian, Y.: Novel metal-organic superhydrophobic surface fabricated by nanosecond laser irradiation in solution. Colloids and Surfaces A: Physicochemical and Engineering Aspects **587**, 124343 (2020). https://doi.org/10.1016/j.colsurfa.2019.124343

[32] Hu, J., Vanacore, G.M., Cepellotti, A., Marzari, N., Zewail, A.H.: Rippling ultrafast dynamics of suspended 2D monolayers, graphene. Proceedings of the National Academy of Sciences **113**(43), E6555–E6561 (2016). https://doi.org/10.1073/pnas.1613818113

[33] Turunen, M.T., Hulkko, E., Mentel, K.K., Bai, X., Akkanen, S.T., Amini, M., Li, S., Lipsanen, H., Pettersson, M., Sun, Z.: Deterministic Modification of CVD Grown Monolayer MoS2 with Optical Pulses. Advanced Materials Interfaces **8**(10), 2002119 (2021). https://doi.org/10.1002/admi.202002119

[34] Lange, C.M., Daggett, E., Walther, V., Huang, L., Hood, J.D.: Superradiant and subradiant states in lifetime-limited organic molecules through laser-induced tuning. Nature Physics **20**, 836–842 (2024). https://doi.org/10.1038/s41567-024-02404-4

[35] Koivistoinen, J., Sládková, L., Aumanen, J., Koskinen, P., Roberts, K., Johansson, A., Myllyperkiö, P., Pettersson, M.: From Seeds to Islands: Growth of Oxidized Graphene by Two-Photon Oxidation. The Journal of Physical Chemistry C **120**(39), 22330–22341 (2016). https://doi.org/10.1021/acs.jpcc.6b06099

[36] Huo, J., Xiao, Y., Sun, T., Zou, G., Shen, D., Feng, B., Lin, L., Wang, W., Zhao, G., Liu, L.: Femtosecond Laser Irradiation-Mediated MoS_2-Metal Contact Engineering for High-Performance Field-Effect Transistors and Photodetectors. ACS Applied Materials & Interfaces, **13**(45), 54246–54257 (2021). https://doi.org/10.1021/acsami.1c12685

[37] Bobrinetskiy, I., Emelianov, A., Nasibulin, A., Komarov, I., Otero, N., Romero, P.M.: Photophysical and Photochemical Effects in Ultrafast Laser Patterning of CVD Graphene. Journal of Physics D: Applied

Physics **49**(41), 41LT01 (2016). https://doi.org/10.1088/0022-3727/49/41/41LT01

[38] Li, D.W., Zhou, Y.S., Huang, X., Jiang, L., Silvain, J.F., Lu, Y.F.: In Situ Imaging and Control of Layer-by-Layer Femtosecond Laser Thinning of Graphene. Nanoscale **7**(8), 3651–3659 (2015). https://doi.org/10.1039/C4NR07078J

[39] Zhang, Z., Deng, C., Fan, X., Li, M., Zhang, M., Wang, X., Chen, F., Shi, S., Zhou, Y., Deng, L., *et al.*: 3D Directional Assembly of Liquid Crystal Molecules. Advanced Materials **36**, 2401533 (2024). https://doi.org/10.1002/adma.202401533

[40] Que, R., Houel-Renault, L., Temagoult, M., Herrero, C., Lancry, M., Poumellec, B.: Space-Selective Creation of Photonics Functions in a New Organic Material: Femtosecond Laser Direct Writing in Zeonex Glass of Refractive Index Change and Photoluminescence. Optical Materials **133**, 112651 (2022). https://doi.org/10.1016/j.optmat.2022.112651

[41] González-Fernández, L., Anagnostopoulos, A., Karkantonis, T., Bondarchuk, O., Dimov, S., Chorążewski, M., Ding, Y., Grosu, Y.: Laser-induced carbonization of stainless steel as a corrosion mitigation strategy for high-temperature molten salts applications. Journal of Energy Storage **56**, 105972 (2022). https://doi.org/10.1016/j.est.2022.105972

[42] Saifutyarov, R., Petrova, O., Taydakov, I., Akkuzina, A., Barkanov, A., Zykova, M., Lipatiev, A., Sigaev, V., Avetisov, R., Korshunov, V., *et al.*: Optical Properties Transformation under Laser Treatment of Hybrid Organic–Inorganic Thin Films. Physica Status Solidi (a) **216**(4), 1800647 (2019). https://doi.org/10.1002/pssa.201800647

[43] Heffner, H., Soldera, M., Ränke, F., Lasagni, A.F.: Surface Modification of Fluorine-Doped Tin Oxide Thin Films Using Femtosecond Direct Laser Interference Patterning: A Study of the Optoelectronic Performance. Advanced Engineering Materials **25**(10), 2201810 (2023). https://doi.org/10.1002/adem.202201810

[44] Pan, C., Jiang, L., Sun, J., Wang, Q., Wang, F., Lu, Y.: The temporal-spatial evolution of electron dynamics induced by femtosecond double pulses. Japanese Journal of Applied Physics **58**(3), 030901 (2019). https://doi.org/10.7567/1347-4065/ab00a8

[45] Yong, J., Wu, D.: Femtosecond Laser Biomimetic Regulation of Material Surface Wettability: Current Progress and Challenges. Chinese Journal of Lasers **51**(1), 0102002 (2024). https://dx.doi.org/10.3788/CJL231403

[46] Bobrinetskiy, I.I., Emelianov, A.V., Smagulova, S.A., Komarov, I.A., Otero, N., Romero, P.M.: Laser Direct 3D Patterning and Reduction of Graphene Oxide Film on Polymer Substrate. Materials Letters **187**, 20–23 (2017). https://doi.org/10.1016/j.matlet.2016.10.073

[47] Assaf, Y., Kietzig, A.-M.: Optical and Chemical Effects Governing Femtosecond Laser-Induced Structure Formation on Polymer Surfaces. Materials Today Communications **14**, 169–179 (2018). https://doi.org/10.1016/j.mtcomm.2018.01.008

[48] Wang, L., Cao, X.-W., Lv, C., Xia, H., Tian, W.-J., Chen, Q.-D., Juodkazis, S., Sun, H.-B.: Formation of Deep-Subwavelength Structures on Organic Materials by Femtosecond Laser Ablation. IEEE Journal of Quantum Electronics **54**(1), 1–7 (2018). https://doi.org/10.1109/JQE.2017.2753040

[49] Jin, Y., Yu, H., Wang, L.: Advancement in Functional Polymer-Based Security Features and Pattern Printing Technologies for Anti-Counterfeiting Applications. Progress in Organic Coatings **211**, 109753 (2026). https://doi.org/10.1016/j.porgcoat.2025.109753

[50] Obilor, A.F., Pacella, M., Wilson, A., Silberschmidt, V.V.: Micro-Texturing of Polymer Surfaces Using Lasers: A Review. The International Journal of Advanced Manufacturing Technology **120**, 103–135 (2022). https://doi.org/10.1007/s00170-022-08731-1

[51] Wood, M.J., Coady, M.J., Aristizabal, F., Nielsen, K., Ragogna, P.J., Kietzig, A.-M.: Femtosecond Laser Micromachining of Co-Polymeric Urethane Materials. Applied Surface Science **483**, 633–641 (2019). https://doi.org/10.1016/j.apsusc.2019.03.296

[52] Kalinichev, A.A., Smirnova, O.S., Povolotskiy, A.V.: The Formation of Broadband Color Centers in PMMA by Femtosecond Laser Radiation. Technical Physics Letters **45**(11), 1089–1091 (2019). https://doi.org/10.1134/S1063785019110063

[53] Liu, X., Kleybolte, M.E., Hantro, M., Butler, C., Vagin, S.I., van Dyck, C., Fleischauer, M., Veinot, J.G.C., Rieger, B., Meldrum, A.: A Fluorescent Polymer for Facile One-Step Writing of Polychromic Hidden Information in Flexible Films. Advanced Functional Materials **34**(37), 2402033 (2024). https://doi.org/10.1002/adfm.202402033

[54] Lai, Q., Xin, F., Li, L.: Covalent Organic Polymers with Reactive Site Side Chains: Synthesis, Fluorescence Effects and Solvent-Based Colour Development. Journal of Photochemistry and Photobiology A: Chemistry **466**, 116370 (2025). https://doi.org/10.1016/j.jphotochem.2025.116370

[55] Xiao, Y., Xie, Z., Shen, M., Wang, H., Li, J., Huang, R., Yu, T.: Construction of Multi-Decay Pathways and Realizing Polymer-Regulated Organic Smart Luminescent Materials. FlexMat **1**(2), 193–202 (2024). https://doi.org/10.1002/flm2.24

[56] Lang, V., Roch, T., Lasagni, A.F.: High-Speed Surface Structuring of Polycarbonate Using Direct Laser Interference Patterning: Toward 1 m^2 min^{-1} Fabrication Speed Barrier. Advanced Engineering Materials **18**(8), 1342–1348 (2016). https://doi.org/10.1002/adem.201600173

[57] Hayashi, S., Terakawa, M.: Direct Writing of Fluorescent Semiconducting Nanoparticles on Polydimethylsiloxane by Ultrashort-Pulsed Laser Processing: Implications for Electronic and Photonic Device Fabrication. ACS Applied Nano Materials **6**(3), 2125–2132 (2023). https://doi.org/10.1021/acsanm.2c05134

[58] Sun, Y., Le, X., Zhou, S., Chen, T.: Recent Progress in Smart Polymeric Gel-Based Information Storage for Anti-Counterfeiting. Advanced Materials **34**(41), 2201262 (2022). https://doi.org/10.1002/adma.202201262

[59] Lin, Z., Wang, H., Xiang, H., Wu, J., Cui, J., Chen, J., Chen, X.: Orthogonal Photo- and Thermo-Responsive Fluorescent Polymeric Hydrogels for Multi-Level Information Encryption and Anti-Counterfeiting. Advanced Optical Materials **12**(35), 241604 (2024). https://doi.org/10.1002/adom.202401604

[60] Wu, X., Duan, Q., Bin, F., Zheng, M.: Femtosecond Laser Two-Photon Polymerization for 3D Hydrogel Microstructure Fabrication and Applications. Chinese Journal of Lasers **50**(21), 2107401 (2023). http://dx.doi.org/10.3788/CJL230764

[61] Afshar, H., Kamran, F., Shahi, F.: Advances in Smart Chromogenic Hydrogel Composites for Next-Generation Digital Applications. Polymers for Advanced Technologies **36**(4), e70179 (2025). https://onlinelibrary.wiley.com/doi/10.1002/pat.70179

[62] Guo, Y., Gao, Y., Wang, Y., Lee, Y.-K., French, P.J., Umar Siddiqui, A.M., Li, H., Zhou, G.: Rapid in Situ Photochemical Synthesis of Carbon Dots in Polymer Coating by Infrared CO_2 Laser Writing for Color Tunable Fluorescent Patterning. Chemical Engineering Journal **504**, 158749 (2025). https://doi.org/10.1016/j.cej.2024.158749

[63] Su, G., Li, Z., Dai, R.: Recent Advances in Applied Fluorescent Polymeric Gels. ACS Applied Polymer Materials **4**(5), 3131–3152 (2022). https://doi.org/10.1021/acsapm.1c01504

[64] Zhu, C.N., Bai, T., Wang, H., Bai, W., Ling, J., Sun, J.Z., Huang, F., Wu, Z.L., Zheng, Q.: Single Chromophore-Based White-Light-Emitting Hydrogel with Tunable Fluorescence and Patternability. ACS Applied Materials & Interfaces **10**(45), 39343–39352 (2018). https://doi.org/10.1021/acsami.8b12619

[65] Liu, H., Wei, S., Qiu, H., Si, M., Lin, G., Lei, Z., Lu, W., Zhou, L., Chen, T.: Supramolecular Hydrogel with Orthogonally Responsive R/G/B Fluorophores Enables Multi-Color Switchable Biomimetic Soft Skins. Advanced Functional Materials **32**(9), 2108830 (2022). https://doi.org/10.1002/adfm.202108830

[66] Quan, Z., Zhang, Q., Li, H., Sun, S., Xu, Y.: Fluorescent cellulose-based materials for information encryption and anti-counterfeiting. Coordination Chemistry Reviews **493**, 215287 (2023). https://doi.org/10.1016/j.ccr.2023.215287

[67] Guo, Y., Wang, Q., Li, H., Gao, Y., Xu, X., Tang, B., Wang, Y., Yang, B., Lee, Y.K., French, P.J., *et al.*: Carbon Dots Embedded in Cellulose Film: Programmable, Performance-Tunable, and Large-Scale Subtle Fluorescent Patterning by in Situ Laser Writing. ACS Nano **16**(2), 2910–2920 (2022). https://doi.org/10.1021/acsnano.1c09999

[68] Liu, Y., Zu, B., Dou, X.: Cellulose-based fluorescent materials for chemical sensing applications. Coordination Chemistry Reviews **532**, 216505 (2025). https://doi.org/10.1016/j.ccr.2025.216505

[69] Liu, H., Lu, Y., Peng, B., Wei, J., Dai, H., Wang, L., Zhu, H., He, H.: Cellulose self-erasing material with dual functions in information encryption. Carbohydrate Polymers **357**, 123444 (2025). https://doi.org/10.1016/j.carbpol.2025.123444

[70] Jiang, J., Luo, Q., Yang, S., Xu, W., Jia, R., Qin, R., Ren, H., Xu, Y., Zeng, B., Yuan, C., *et al.*: Carboxymethyl Cellulose-Based Organogel for Anticounterfeiting via Synergistic Optoelectronic Dual-Signal Encoding. ACS Applied Polymer Materials **7**(19), 13199–13209 (2025). https://doi.org/10.1021/acsapm.5c02677

[71] Du, J., Sheng, L., Xu, Y., Chen, Q., Gu, C., Li, M., Zhang, S.X.-A.: Printable Off–On Thermoswitchable Fluorescent Materials for Programmable Thermally Controlled Full-Color Displays and Multiple Encryption. Advanced Materials **33**(20), 2008055 (2021). https://doi.org/10.1002/adma.202008055

[72] Liu, H., Cheng, X., Bian, Z., Ye, K., Zhang, H.: Four organic crystals displaying distinctively different emission colors based on an ESIPT-active organic molecule. Chinese Chemical Letters **29**(10), 1537–1540 (2018). https://doi.org/10.1016/j.cclet.2018.08.003

[73] Li, S., Huang, X., Xing, M., Zhao, D., Li, S., Cao, X.: Manipulating Dynamic Light-Driven Solid-Liquid Transition and Static Reversible Photochromism by an Organic Cocrystal Strategy. Angewandte Chemie International Edition **64**(15), e202500238 (2025). https://doi.org/10.1002/anie.202500238

[74] Huang, R., Liu, T., Peng, H., Liu, J., Liu, X., Ding, L., Fang, Y.: Molecular design and architectonics towards film-based fluorescent sensing. Chemical Society Reviews **53**(13), 6960–6991 (2024). https://doi.org/10.

1039/D4CS00347K

[75] Tian, Y., Huang, B., He, S., Zhao, Y., Zang, K., Wang, H., Zhao, X., Cui, J., Chen, J.: Reprogrammable Supramolecular Fluorescent Polymers for Rewritable Information Encryption and Anti-Counterfeiting. Advanced Functional Materials **35**(17), 2419865 (2024). https://doi.org/10.1002/adfm.202419865

[76] Du, M., Shi, Y., Zhou, Q., Yin, Z., Chen, L., Shu, Y., Sun, G.Y., Zhang, G., Peng, Q., Zhang, D.: White Emissions Containing Room Temperature Phosphorescence from Different Excited States of a D-pi-A Molecule Depending on the Aggregate States. Advanced Science **9**(5), e2104539 (2022). https://doi.org/10.1002/advs.202104539

[77] Lv, X., Gao, C., Han, T., Shi, H., Guo, W.: Improving the quantum yields of fluorophores by inhibiting twisted intramolecular charge transfer using electron-withdrawing group-functionalized piperidine auxochromes. Chemical Communications **56**(5), 715–718 (2020). https://doi.org/10.1039/C9CC09138F

[78] Gu, P., Xu, X., Zhou, F., Zhao, T., Ye, G., Liu, G., Xu, Q., Ge, J., Xu, Q., Lu, J.: Study of Linear and Nonlinear Optical Properties of Four Derivatives of Substituted Aryl Hydrazones of 1,8-Naphthalimide. Chinese Journal of Chemistry **32**(3), 205–211 (2014). https://doi.org/10.1002/cjoc.201300842

[79] Hayashi, S., Koizumi, T.: Elastic Organic Crystals of a Fluorescent π-Conjugated Molecule. Angewandte Chemie International Edition **55**(8), 2701–2704 (2016). https://doi.org/10.1002/anie.201509319

[80] Sakai, K.-i., Tsuchiya, S., Kikuchi, T., Akutagawa, T.: An ESIPT fluorophore with a switchable intramolecular hydrogen bond for applications in solid-state fluorochromism and white light generation. Journal of Materials Chemistry C **4**(10), 2011–2016 (2016). https://doi.org/10.1039/C5TC04290A