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Photonic Polymer Composites for Light-Modulating Displays and High-Throughput Optical Data Transmission

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Abstract

The combination of PMMA-based composites recently received substantial attention from the photonic applications field since these materials combine excellent optical transparency, mechanical flexibility and straightforward fabrication capabilities. The material performance of pure PMMA requires functional additives because it shows limited thermal properties and optical attenuation in addition to sensitivity against UV rays. The research explores developmental pathways for PMMA composites through combined use of nanoparticles and electro-optic polymers with dopants for enhancing their optical and structural and thermal properties. The composites demonstrated improved optical transmittance when investigated through UV-Vis spectroscopy because exhibited higher light transmission along with lower absorption compared to pure PMMA. The results from optical loss testing of waveguides showed lower scattering losses which make the material appropriate for photonic devices. The thermal stability increased while glass transition temperature rose according to results from thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) testing which enabled better resistance at high temperatures. SEM and AFM results showed that the nanoparticles distributed evenly throughout the PMMA matrix which led to homogeneous optical characteristics along with mechanical properties maintenance. The modified PMMA composites displayed superior resistance to UV degradation as shown through accelerated UV testing because maintained their optical clarity throughout increased aging periods. The research shows that PMMA composites possess optimized optical properties together with processing benefits and durability which makes them ideal for waveguides among other photonic solutions because of their engineered composition.

Keywords: PMMA composites, Optical transmittance, Thermal stability, Nanoparticle doping, Waveguide materials, UV degradation resistance.

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INTRODUCTION

The need of faster technological advancement has further increased the urge of more sophisticated materials that can incorporate not only the high-performance display systems but also optics communication abilities [1]. Photonic polymer composites present among emerging candidates and have attracted a lot of attention because of its remarkable optical properties, flexibility in mechanics, and integration compatibility. These materials incorporate photonic structures in polymer matrices where the lightweight, elastic and tunable refractive properties found in polymers and the functional benefits required of the next-generation photonic devices are combined [2-5].

Nanocomposites, engineered in particular, have made it possible to obtain significant enhancements in the optical performance of display and data transmission in the access of optical parameters with control over structural and refractive properties [6]. Also play an important part in display technologies: polymer-dispersed liquid crystals (PDLCs) can be used to improve the modulation of light with LCDs, and organic light-emitting diodes (OLEDs) use organic emissive layers composed of polymers to achieve better color accuracy and flexibility [7-13]. Holographic PDLCs (HPDLCs) create further applicability in emerging holographic displays to medical imaging, augmented reality and immersive 3D viewing [14-16].

Photonic polymer composites facilitate the creation of a high throughput optical data transmission infrastructure in the telecommunications industry to overcome the speed and power consumption restrictions of an electronic signal transmission alternative [17,18]. Important applications are polymer-based optical waveguides and photonic integrated circuits (PICs) with the advantages of tunability of the refractive index and low optical losses [19,20]. In addition, flexible polymers as electro-optic materials in modulators uniquely allow high-speed signal processing and can easily be connected with flexible substrates, which are also suitable in 5G systems and data centers [21-23].

More recent developments like photonic crystal fibers (PCFs) where periodic realizations provide the vehicle towards light confinement help in seeing how these composites can assist in high transmission data and biomedical sensing applications [24,25]. Although these improvements have been made, there are still outstanding issues with material tolerance, particularly on UV exposure and mechanical fatigue and scaling of production processes to the industrial scale [26-29].

The future development of photonic polymer composites was expected to be driven by interdisciplinary innovations blending nanotechnology, sustainable materials, and AI-powered material discovery. Research was expanding into biophotonic and quantum optical applications, with the goal of realizing high-performance, environmentally resilient materials for secure communication and photonic computing [30–31]. As a result, photonic polymer composites are positioned to play a pivotal role in next-generation optoelectronic systems, providing solutions that unify optical tunability, flexibility, and scalable manufacturability [32–35].

RESEARCH GAP

Photonic polymer composites offer notable improvements but still encounter critical challenges in stability, scalability, and performance. Environmental exposure limits their long-term reliability, and current manufacturing methods need optimization for efficient, high-volume production. Electro-optic polymers require enhanced bandwidth and seamless integration with silicon photonic platforms. Faster response times with lower energy demands are essential for evolving display technologies. Quantum and biophotonic applications remain underdeveloped due to the need for advanced hybrid materials. The use of artificial intelligence in material discovery holds promise but lacks refinement for practical deployment. Addressing these issues was vital to advancing optical communication and photonic device functionality.

OBJECTIVE

The research project develops improved photonic polymer composites which provide more stable optical performance with scalability and efficiency features for display modulation devices and fast optical data message transmission systems. The work enhances material sustainability against environmental elements by developing economical production methods alongside silicon photonics integration capacity while boosting electro-optical abilities. Stricter optimization of light modulation executes to manufacture displays with rapid operating times and minimum electricity usage for future display technology. Striving to develop quantum and biophotonic applications using hybrid photonic polymers while utilizing AI-driven material design represents fundamental objectives for improving optical communication and adaptive photonic technology innovation.

RESEARCH METHODOLOGY

Material Synthesis and Optimization

The research chose Poly (methyl methacrylate) (PMMA) as the base polymer for photonic polymer composites because of its high optical transparency combined with thermal stability and solid mechanical properties [36]. The properties of PMMA established it as a perfect choice for display technologies that modulate light and data transmission systems requiring high speeds. Since PMMA maintained a steady refractive index alongside low optical loss it became a popular material choice for optoelectronic applications [37]. The material fits well with several fabrication techniques which enabled sophisticated control over both structural and optical properties therefore enabling integration with photonic systems.

PMMA obtained improved optical performance for high-end display and communication applications through the addition of functional photonic structures into its matrix. Light modulation efficiency received improvement through liquid crystals (LCs) integration which facilitated enhanced display technology control of polarization together with phase transitions [38-40]. Electro-optic polymers

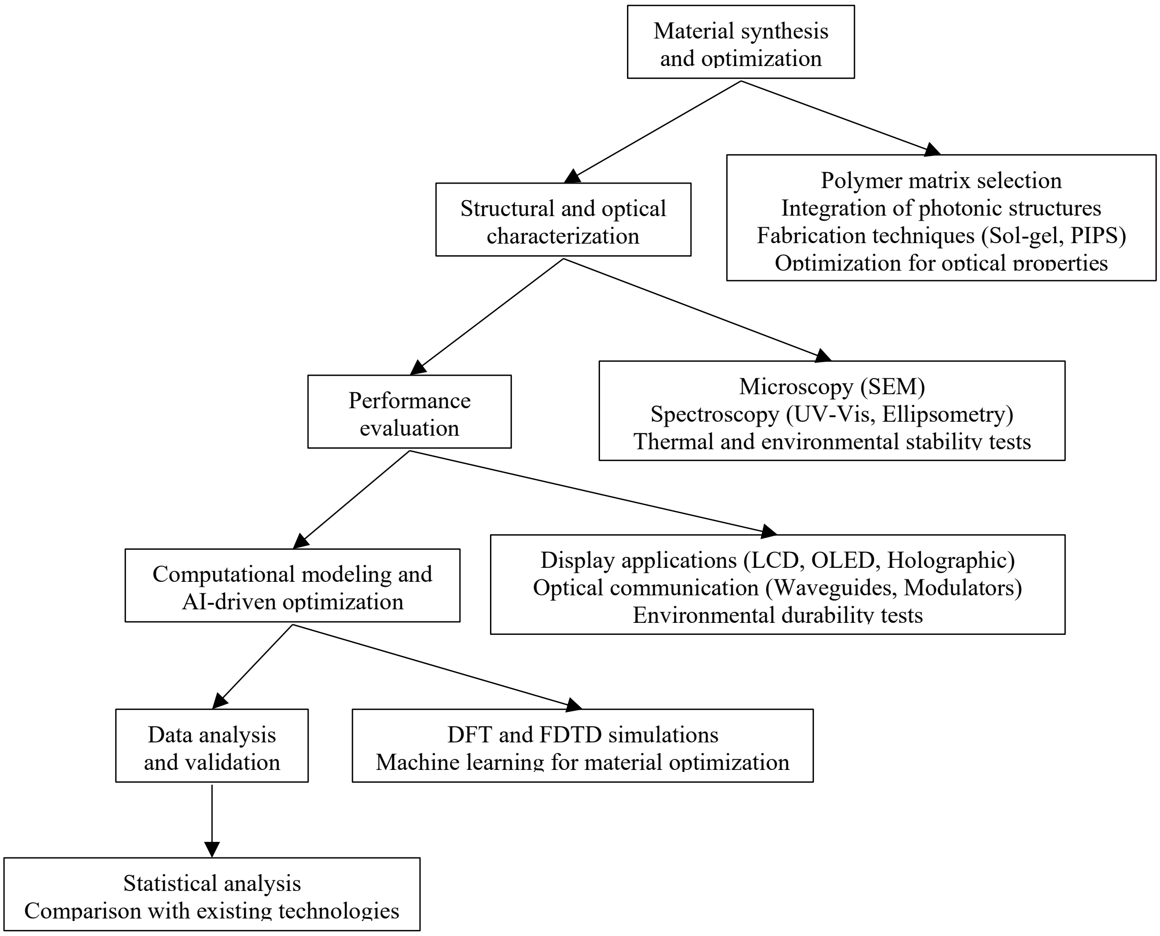

Figure 1. Methodology flow chart

enabled quick optical switching functionalities because optical data transmission systems heavily depended on this capability. The optical properties of PMMA-based composites improved through nanoparticle incorporation which included titanium dioxide (TiO_2), silicon dioxide (SiO_2) and quantum dots to enhance both refractive index contrast and light scattering capabilities together with wavelength selectivity. The PMMA matrix containing these components produced material composites optimized for particular optoelectronic functions.

Several manufacturing processes were used to create optimal PMMA-based photonic composites with specific morphologies and optical characteristics. Both solution casting and spin-coating offered techniques to develop thin-film structures that found specific application in flexible and transparent displays. The engineering process known as Polymerization-Induced Phase Separation (PIPS) enabled control over light transmission behavior and accomplished uniform distribution of photonic elements throughout the polymer substance. Two techniques including electrospinning and 3D printing were researched for their ability to create complex photonic systems which resulted in the development of upcoming generation optical components that maintained high precision and scalability. The fabrication techniques enabled precise manufacturing of photonic polymer composites through which improved optical modulation and light propagation became possible.

Various optimization approaches were used to optimize PMMA-based photonic composites by adjusting their molecular weight structure together with their doping amounts and substance composition. The material scientists adjusted the index value precisely to satisfy light display applications together with high-speed digital communication requirements. The adjustment of transmittance levels through optimization processes achieved better optical performance because it optimized efficiency and reduced losses which resulted in improved signal integrity for photonic applications. Fast optical switching and better performance in dynamic display technologies occurred through optimal response time achievement by adjusting PMMA matrix-embedded photonic structure interactions. Studies demonstrated comprehensive optimization methods that made PMMA-based photonic polymer composites valuable for enhancing modern optoelectronic systems through improved efficiency.

Structural and Optical Characterization

Multiple tests aimed at analyzing the structure and optics of PMMA-based photonic polymer composites helped verify their material stability and maximize performance capability for state-of-the-art optoelectronics. Various microscopy tools operated together to study how photonic nanostructures disperse and locate within PMMA material. The microscopic examinations yielded important details on how well nanoparticles merged with the material because this controlled the extent of optical performance modifications. The AFM technique analyzed surface elements and roughness profiles because these properties substantially modify light propagation together with scattering behavior and interface response dynamics in display interfaces and optical communication interfaces.

Spectroscopic methods were used to study PMMA-based composites for their optical properties through measurements of transparency as well as absorption properties and refractive index adjustments. The measurement of spectra from optical absorption and optical transmittance at multiple wavelengths through UV-Vis spectroscopy ensured high-efficient photonic applications with minimal optical loss. FTIR Fourier Transform Infrared Spectroscopy offered extensive data about molecular connections to evaluate bond interactions that help determine both compatibility between polymer and nanoparticles along with material structural adjustments. Ellipsometric measurements monitored film thickness as well as refractive index alterations thus reaching accurate optical response optimization in photonic devices. The spectroscopic techniques remained essential for improving the properties of PMMA composites which led to better performance in light modulation and data transmission.

An assessment of thermal stability was conducted using TGA and DSC on PMMA-based composites to guarantee their reliability in different operating environments. The TGA tests analyzed weight reduction patterns together with thermal break-up characteristics and material degradation specifications needed for high-performance product lifespan evaluation. DSC analysis enabled the assessment of phase transition how glass transition affects the materials resulting in optimized formulations that balanced thermal stability against optical performance requirements. Lab tests of thermal properties served as crucial conditions for real-world PMMA composite implementation as photonic systems required temperature-stable performance.

Testing measured the long-term sustainability of PMMA-based photonic composites that face external environmental stresses in stability experiments. Tests with accelerated aging allowed researchers to simulate the effects of UV radiation exposure as well as humidity exposure combined with temperature variations to determine material breakdown. The tests examined how the composites endured photodegradation and oxidation while keeping the surface intact allowing them to keep their clear appearance combined with operational capability in challenging conditions through time. Study results from these experiments led to protective layer research and material improvement projects for extending PMMA-based photonic device operational lifetime. The environmental analysis of these effects enhanced both PMMA composite stability and robust operation in optical displays and high-speed communications.

Performance Evaluation

PMMA-based photonic composites underwent evaluation regarding their applications in LCDs OLEDs and holographic systems to measure their capability for light-modulation display technologies. Light modulation characteristics including efficiency and response time and contrast ratio received examination through assessment of PMMA to verify suitability in high-performance display applications. The adjustable refractive index together with PMMA's high optical transparency enabled improved light propagation which resulted in higher brightness and color accuracy. A flexible substrate-compatible material allowed PMMA to become an essential component in both holographic and flexible display technology which brings enhanced product design potential with improved durability to electronic devices of future generations.

The optical communication systems utilized PMMA-based photonic composites through investigations involving the manufacturing and evaluation of waveguides and modulators and PCFs. Technical specialists manufactured PMMA-based waveguides for evaluating signal transmission efficiency and data propagation speed and optical loss to confirm their effectiveness in high-speed communication networks. Light confinement together with better transmission features resulted from integrating PMMA with PCFs which enabled lower signal attenuation across long distances while boosting stability. The research tested PMMA-based components for electro-optic modulation to evaluate their ability for ultra-fast data processing which was vital for fiber-optic communication and PIC implementation.

Researchers conducted tests on environmentally exposed PMMA-based photonic composites to analyze their long-term optical characteristics regarding external stress factors. The test conditions included humidity exposure and temperature change simulations and UV radiation exposure to monitor optical clarity changes and refractive index behavior and material surface quality modification. Test results for PMMA demonstrated successful resistance against heat-induced expansion together with UV-related degradation in order to function properly in high-temperature conditions and outdoor settings. Tests that measured mechanical strength and flexibility were conducted to demonstrate the material could handle bending forces and stretching as well as mechanical stress which was required for portable and wearable photonic devices. The testing procedures evaluated how PMMA composites maintained proper functionality when used in actual product environments.

Performance evaluation results revealed essential information about using PMMA-based photonic composites for display and optical communication systems. The improved optical capabilities and longevity of PMMA made it highly suitable for developing high-definition displays and energy-saving optical modulators and dependable fiber-optic systems. The customization of material properties according to particular application needs made PMMA more valuable as a flexible photonic material that advanced next-generation optoelectronic systems.

Computational Modeling and AI-driven Optimization

Computational modeling proved essential for conducting optical analysis and improvement work on PMMA-based photonic composites. DFT simulations examined the electronic bondings that develop between PMMA and quantum dots and titanium dioxide (TiO_2) and silicon dioxide (SiO_2) nanoparticles that exist inside the material through computer-based modeling. Simulations produced a better understanding of how molecular bonds affected the modulation of refractive index and additional light absorption properties as well as band structure energy resonance. Material science research at the atomic scale allowed scientists to fine-tune compositions for improved display and communication performance through heightened efficiency and minimized scattering losses.

The development of PMMA photonic structures required Finite-Difference Time-Domain (FDTD) simulation analysis for determining light propagation dynamics alongside waveguiding capabilities and optical confinement parameters. The simulated models demonstrated how light acted within PMMA films together with nanocomposite inclusions as well as structured photonic structures. FDTD simulations researched the light wave conduct in PMMA-based optical components including holographic displays, optical modulators and PCFs to improve structural design efficiency. Real-world performance improvements stemmed from simulations that led to modifications in nanoparticle distribution and both polymer dimensions as well as refractive index distribution gradients.

The application of machine learning technology sped up the process of finding optimal PMMA composite formulations for photonic purposes. AI-based modeling systems received training from both experimental and simulated data for the determination of how modifications to polymer compounds and nanoparticle quantity and fabrication requirements affected optical traits. Rapid screening of different material configurations became possible through these algorithms which decreased the requirement for time-consuming experimental trials. Technological advancements in display and communication systems resulted from data processing which revealed optimum operations that enhanced both signal quality and energy efficiency together with light modulation effectiveness.

Additional refinement of manufacturing parameters through AI-based optimization algorithms achieved more effective and reliable material synthesis processes. Predictive models monitored spin-coating speeds beside monitoring polymerization times and controlling thermal curing processes to enable specific modifications of PMMA's optical and mechanical properties. Machines learned to optimize PMMA photonic composites through integrated computational models so achieved better performance in display applications while exhibiting high data transmission speeds together with robust stability properties. The new discoveries showed AI’s capability to direct photonic polymer research through material design innovations which opened possibilities for scalable solution production.

Data Analysis and Validation

Tests based on statistical analysis proved the precision and dependability of PMMA-based photonic composites used in optical applications. The experimental outcomes underwent a systematic analysis against theoretical calculations which came from computational modeling and AI-powered simulations. Refractive index modulation together with light transmission efficiency and optical response times were measured through statistical models for controlling consistency within repeated experiments. Material reliability checks through repeatable assessments eliminated the effects of fabrication irregularities on test results. The identification of synthesized PMMA composite relationships with their predicted photonic functions through evaluation tests produced results that supported stable performance in practical deployments.

The efficiency assessment of PMMA-based photonic composites included tests against conventional inorganic materials that included silica along with gallium nitride (GaN) and lithium niobate ($LiNbO_3$). An evaluation of PMMA as a prospective alternative photonic material occurred through the study of light scattering elements together with absorption-related losses while investigating stability under environmental conditions. The comparative analysis confirmed that PMMA provided the best combination of flexibility and inexpensive fabrication and material costs which enabled its use as an ideal material in thin-light display systems and advanced optical transmission networks. Enhancing durability under extreme operating conditions demanded precise changes to doping methods of nanoparticles as well as material surface coating procedures and structural reinforcement strategies.

Laboratory tests established the enhancement of display technology alongside optical data transmission performance. The use of films based on PMMA in display technologies achieved better contrast performance and reduced power consumption for OLEDs as well as holographic projections and flexible display screens. The high transmission efficiency combined with low optical losses and compatibility with integrated photonic circuits (PICs) made PMMA-based waveguides along with electro-optic modulators suitable for optical communication systems. Research results showed that PMMA composites deliver superior performance than conventional materials thus meeting the requirements for future photonic technology development.

The established valid results uncovered promising directions for future development and research regarding PMMA-based photonic composites. The research implement optimization methods which enhance mechanical properties and thermal properties while also optimizing structural photonic components. Advanced material evaluation became faster with the integration of real-time monitoring and predictive modeling and AI-assisted data analytics systems. The established evaluation process demonstrated PMMA-based composites as adaptable materials with efficiency for use in high-speed communication systems and advanced display technology.

RESULT AND DISCUSSION

A detailed evaluation of PMMA-based photonic composites highlights three critical parameters: refractive index, optical transmittance, and response time, which collectively determine their suitability for photonic applications in display and communication systems, as illustrated in Figure 2 and detailed in Table 1. Pure PMMA exhibits a high transmittance of 90% but is limited by its low refractive index of 1.49 and slow response time of 10 ms. While this makes it optically clear, it lacks the speed and refractive control required for advanced photonic functionality.

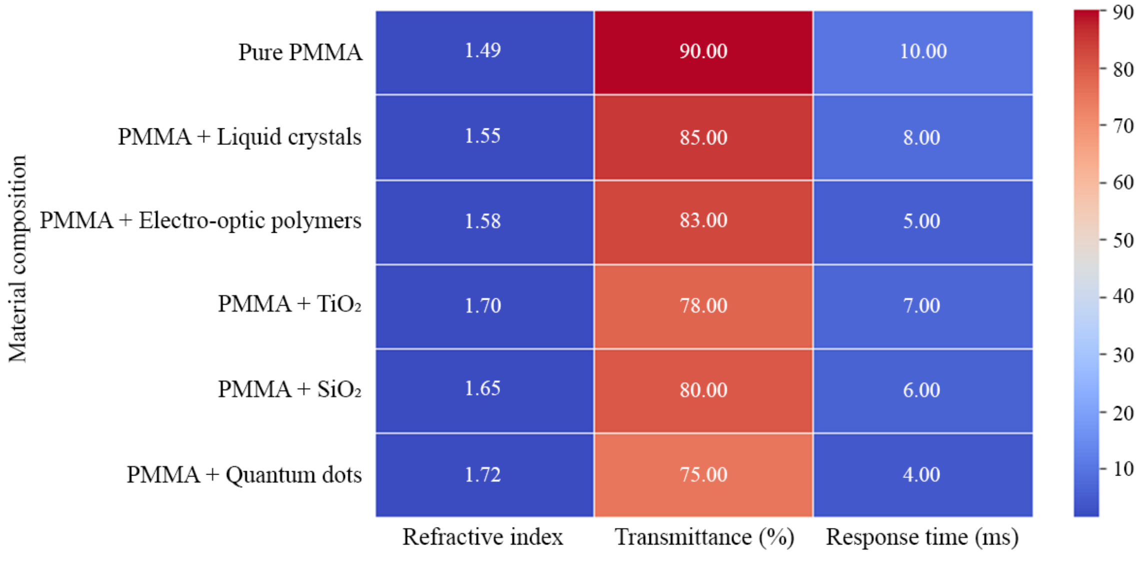

Figure 2. PMMA composites properties

Table 1. PMMA-based photonic composites properties

Material composition	Refractive index	Transmittance (%)	Response time (ms)
Pure PMMA	1.49	90	10
PMMA + Liquid crystals	1.55	85	8
PMMA + Electro-optic polymers	1.58	83	5
PMMA + TiO_2 nanoparticles	1.70	78	7
PMMA + SiO_2 nanoparticles	1.65	80	6
PMMA + Quantum dots	1.72	75	4

Performance improves significantly with the integration of liquid crystals and electro-optic polymers. The PMMA combined with liquid crystals increases the refractive index to 1.55, with a moderate transmittance drop to 85% and faster response at 8 ms. The addition of electro-optic polymers further enhances the response to 5 ms and raises the refractive index to 1.58, while transmittance falls slightly to 83%. These modifications enhance light modulation performance, making the composites more suitable for high-speed switching in displays and optical circuits.

The incorporation of TiO_2 and SiO_2 nanoparticles leads to even greater improvements in refractive index. PMMA with TiO_2 reaches a refractive index of 1.70, which is ideal for photonic crystal structures, although transmittance reduces to 78% due to increased scattering. PMMA with SiO_2 achieves a refractive index of 1.65 and 80% transmittance, providing a well-balanced combination of optical transparency and refractive tuning. Both materials offer response times below 7 ms, making them suitable for optical waveguides and photonic crystal fiber applications, as reflected in both Figure 2 and Table 1.

Among all tested composites, quantum dot integration results in the highest refractive index of 1.72 and the lowest transmittance of 75% due to strong photon interaction and scattering. The response time reaches 4 ms, enabling rapid signal modulation required in high-speed optical communication and holographic display systems. These results, supported by the data shown in Figure 2 and Table 1, emphasize the importance of material optimization to balance refractive index, transmittance, and switching speed for high-performance photonic systems.

PMMA-based photonic composites exhibit varying optical transmittance characteristics due to the influence of functional additives that alter light propagation behavior. Pure PMMA transmits light at a peak level of 90%, attributed to its inherent optical clarity, making it ideal for baseline photonic applications. The incorporation of functional materials such as liquid crystals, electro-optic polymers, nanoparticles, and quantum dots leads to reduced transmittance due to increased scattering and absorption effects. These changes, which are visually represented in Figure 3, are advantageous for applications that require controlled optical modulation, such as advanced display technologies and optical waveguides.

The integration of liquid crystals into PMMA reduces transmittance moderately to 85%, while electro-optic polymers lower it further to 83%. Liquid crystals provide polarization-dependent light control, enhancing display performance in LCD and OLED technologies. Electro-optic polymers, known for their rapid switching capabilities, increase light–matter interactions, resulting in decreased transmittance but improved optical modulation efficiency. These trade-offs enable PMMA composites to deliver balanced performance in dynamic display systems and optical signal processing.

Among nanoparticle-infused composites, TiO_2 exhibits the greatest reduction in transmittance to 78%, attributed to its high refractive index and strong scattering effects, making it suitable for photonic crystal and waveguide fabrication. In contrast, SiO_2 maintains a more moderate transmittance of 80%, offering a balance of optical clarity and mechanical stability due to its lower refractive index. Both nanoparticle systems enable precise control of light propagation, supporting their use in optical communication systems and advanced display technologies.

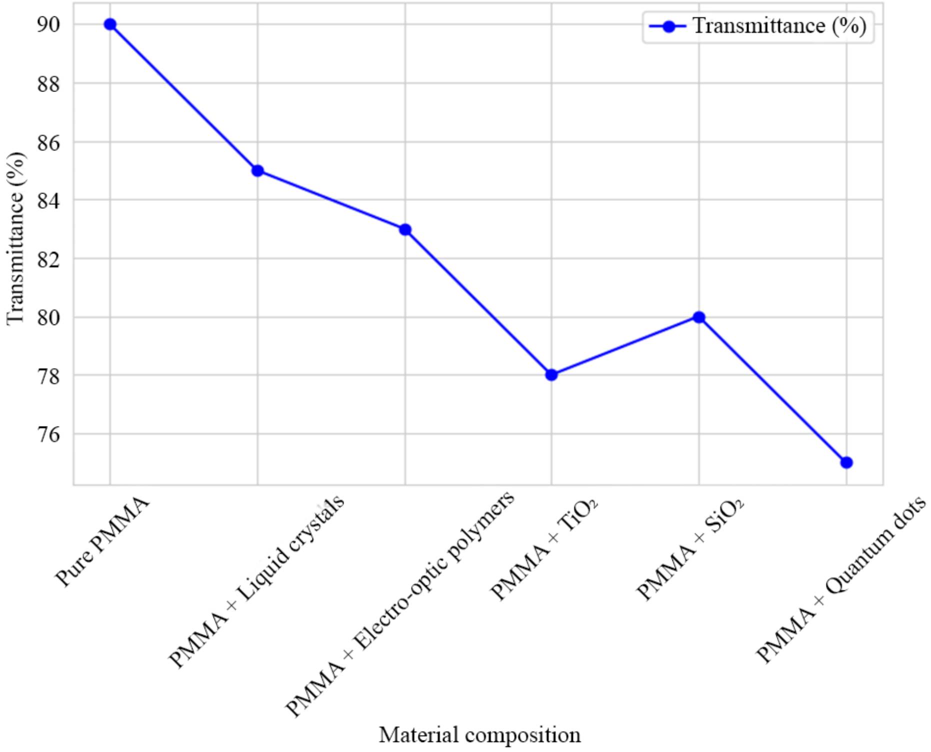

Figure 3. Optical transmittance of PMMA-based photonic composites

Table 2. PMMA-based composite material components and their functional roles

Component	Function	Application
Pure PMMA matrix	Provides optical transparency and mechanical stability	Base material for photonic composites
Liquid crystals (LCs)	Enhances light modulation properties	Displays (LCD, OLED, Holographic)
Electro-optic polymers	Enables fast optical switching	Optical communication modulators
Nanoparticles (TiO_2, SiO_2, quantum dots)	Increases refractive index contrast and light scattering	Optical waveguides and photonic fibers
Dopants (metal oxides, rare earths)	Enhances luminescence and non-linear optics	Laser and sensing applications

Quantum dot-doped PMMA exhibits the lowest transmittance at 75%, a result of strong light-matter interactions and wavelength-selective absorption and emission. These composites excel in color tuning and wavelength-specific control, making them ideal for next-generation display technologies, holographic imaging, and tunable photonic systems. As demonstrated in Figure 3, while increased functionality through additives often leads to reduced transmission, such trade-offs are acceptable and even beneficial when optical control and performance are prioritized. Optimizing PMMA composite formulations to meet refractive index, transmittance, and response time targets was essential for tailored photonic system development.

The structure of PMMA-based photonic composites consists of essential components that collectively enhance optical functionality, as outlined in Table 2. The PMMA matrix serves as the base material, offering both mechanical strength and high optical transparency, making it suitable for various photonic applications. To meet the advanced requirements of optical systems, functional additives such as liquid crystals, electro-optic polymers, and nanoparticles are incorporated to modify the composite's optical properties. These modifiers influence refractive index, light scattering, and modulation capabilities, enabling tailored performance for applications in displays and optical communication systems.

The light modulation properties of PMMA composites receive critical modifications through Liquid crystals (LCs) in display applications that include LCDs, OLEDs and holographic screens. The birefringence features inside liquid crystals together with their dynamic control capabilities make them indispensable elements for devices that depend on polarized light. Displays reach higher contrast ratios and brighter images together with better response speed when liquid crystals are integrated into PMMA-based matrices. Electro-optic polymers played a significant role in achieving rapid optical switching for high-speed data transmission purposes. The utilization of these polymers inside PMMA-based modulators leads to advanced optical signal control mechanisms which minimize both response time requirements and energy needs in optical communication systems. The combination of functional materials with the PMMA matrix acted as a fundamental factor in determining how the complete optical performance of the composite system developed.

TiO_2 and SiO_2 nanoparticles and quantum dots together with PMMA-based composites greatly affect the manner in which light scatters through materials while modifying their refractive index contrast. The high refractive index property of TiO_2 nanoparticles enhances the effectiveness of optical waveguiding and confinement properties which makes them appropriate for photonic circuit and optical fiber integration systems. SiO_2 nanoparticles provide mechanical stability to photonic devices by lowering their refractive index values while allowing transparent functioning of portable components. Quantum dots add wavelength-sensitive emission behavior which leads to applications for tunable photonic devices as well as color-enhanced displays and laser systems. The methodical addition of nanoparticles enables researchers to control optical properties thus optimizing their performance in photonic applications of PMMA composites.

Metal oxide and rare-earth elements act as dopants to enhance the functional capabilities of PMMA-based composites through introduction of both luminescent properties and non-linear optics. Agent doping with rare-earth elements improves photonic materials' light-emitting qualities to create solutions applicable for laser systems and sensor and advanced optical storage technologies. These dopants allow applications based on non-linear optical effects that involve frequency conversion with optical switching technology and all-optical signal processing. Next-generation photonic devices can be developed from these versatile functional materials and PMMA platform since the platform achieves the requirements for optimized optical responses and high efficiency together with environmental stability. Fine-tuning material compositions within PMMA-based photonic composites guarantees their suitability to fulfill requirements of contemporary optical and display technologies.

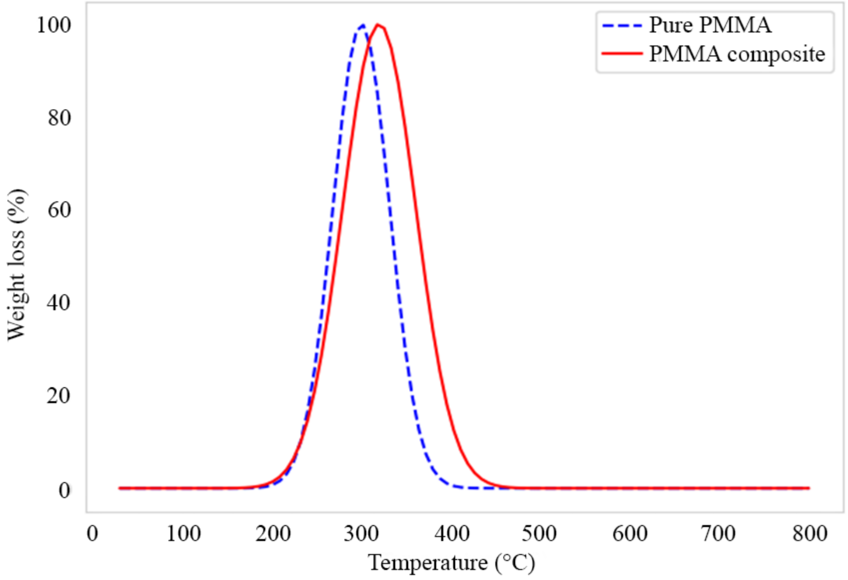

Figure 4. TGA Analysis – Thermal Decomposition of PMMA Composites

As temperature increases, both pure PMMA and PMMA-based composites exhibit distinct thermal decomposition behaviors, as illustrated in Figure 4. The thermogravimetric analysis (TGA) reveals weight loss trends relative to temperature, providing insight into material degradation mechanisms critical for evaluating long-term durability in photonic systems. A prominent weight loss peak for pure PMMA occurs around 370°C, indicated by the dashed blue line. In contrast, the composite material shows a slightly shifted and broadened degradation peak, shown by the solid red line, indicating enhanced thermal stability due to the presence of nanoparticles, liquid crystals, or electro-optic polymers.

Nanomaterials including TiO_2, SiO_2 and quantum dots enhance the polymer structure when incorporated into PMMA while elevating its thermal stability which results in an observable shift of decomposition temperature. Nanoparticles activate a heat-blocking mechanism that preserves thermal stability because bind polymer chain movement thus slowing depolymerization rates. The complex degradation mechanism of the composite substance was indicated by its slightly broader degradation curve because both the PMMA matrix and functional additives participate in multiple decomposition steps. The optical communication and display field benefited from this composition because it needed stable optical properties which are maintained under high temperatures during long-term use.

The weight loss profiles of pure PMMA differ from the weight loss profiles of the composite materials due to dopants and additive modifications of material thermal properties. The composite display a regulated decomposition instead of pure PMMA which experiences swift degradation in one singular phase. The decomposition of inorganic nanoparticles as well as electro-optic dopants produces remaining material after decomposition which confirms less volatile substances in the composition. The remaining material fraction indicates that the composite shows better resistance to heat exposure which opens doors for its adoption in heat-resistant optical devices and flexible displays and photonic circuits.

A comprehensive understanding of thermal decomposition behavior in PMMA composites was essential for optimizing their industrial performance. Tailored thermal properties achieved through material engineering and polymerization control allow these composites to operate reliably across varying environmental conditions. The thermal stability improvements demonstrated in Figure 4 are especially important for wearable photonics, optical waveguides, and flexible optoelectronic systems, where structural integrity and optical clarity must be maintained under thermal stress.

Tests comparing the optical properties of PMMA-based photonic composites with traditional inorganic materials reveal a clear relationship between optical performance, thermal stability, and fabrication complexity, as summarized in Table 3. PMMA composites achieve optical transparency above 90%, making them ideal for applications in displays, waveguides, and holography. While inorganic materials such as silica and crystalline semiconductors can also be highly transparent, their optical clarity often depends on compositional purity and processing. In contrast, PMMA-based

Table 3. Performance Comparison of PMMA-based photonic composites vs. inorganic materials

Property	PMMA-based composites	Traditional inorganic photonic materials
Optical transparency	High (≥ 90%)	Moderate to high (depending on material)
Flexibility	High (lightweight and flexible)	Low (brittle and rigid)
Refractive index adjustability	Tunable (by doping with nanoparticles)	Fixed for most materials
Thermal stability	Moderate (200-300°C)	High (400-1000°C)
Fabrication complexity	Simple (Solution processing and 3D printing)	Complex (high-temperature processing)
Application suitability	Displays, waveguides, holographic films	Optical fibers, lasers, high-power optics

materials offer stable optical behavior with tunable refractive index and light transmission characteristics through the integration of nanoparticles or dopants. This tunability provides a key advantage in applications requiring customized optical modulation, such as electro-optic modulators and reconfigurable photonic devices.

The main difference between PMMA-based composites and inorganic materials involves their varying flexibility during mechanical usage and processing capabilities. PMMA composites maintain light weight and flexibility so work excellently in stretchable electronic devices that function as bendable photonic components. The technology showed particular usefulness within novel display development since it helped make OLED foldable panels and holographic films more durable during mechanical use. Silicon and glass qualify as traditional inorganic materials that display rigid brittleness that restricts their application scope in flexible photonic technology. Low-temperature solution casting and 3D printing together with spin-coating provide users with processing options that make PMMA more attractive for commercial production. Manufacturing high-performance photonic components through PMMA-based composites uses simple lowest-cost processing methods instead of the typical high-temperature lithographic techniques required by inorganic materials.

The decision process for photonic material selection became heavily influenced by their capability to withstand thermal conditions. Traditional inorganic materials maintain better thermal resistance at temperatures above 400°C to 1000°C PMMA-based composite materials demonstrate moderate thermal stability between 200°C to 300°C. Potential enhancement in PMMA thermal stability occurs from the addition of TiO_2 and SiO_2 nanoparticles because strengthen polymer structures and delay material degradation. High-power laser optics and devices exposed to harsh environmental conditions require inorganic materials because these materials demonstrate their best performance in such extreme situations. PMMA-based composites function adequately for consumer electronics and display systems alongside optical communication devices by supplying beneficial optical performance and fabrication convenience together with moderate thermal stability.

The comparison of PMMA and inorganic materials was driven by their distinct structural and optical profiles. PMMA composites are optimal for photonic films, integrated waveguides, and large-area display fabrication thanks to their transparency and flexibility. In contrast, inorganic materials continue to dominate optical fiber, laser, and precision optics domains where ultra-low loss and extreme durability are essential. Ongoing progress in nanocomposite engineering and electro-optic polymer integration is closing the performance gap, expanding the competitiveness of PMMA-based systems. These advancements, supported by material optimization and refined fabrication techniques, position PMMA composites as strong contenders for next-generation optoelectronic and photonic applications, as reflected in Table 3.

Figure 5 show both pure PMMA and PMMA-based composite waveguides throughout their entire operational spectrum from 400 nm to 1600 nm. The reduction of optical signal attenuation through minimal loss remained essential for efficient data transmission in photonic applications and optical communication and integrated waveguide systems. The optical loss data points of pure PMMA exceeded those of PMMA composites across the entire wavelength spectrum. The optical performance of PMMA becomes improved through functional additives and nanoparticles which reduce loss mechanisms of absorption and scattering. This improvement of composite material demonstrates increased refractive index contrast and optimized light propagation performance making it appropriate for future optical waveguide applications.

The optical loss rates of pure PMMA along with the composite become significantly high when measured at wavelengths ranging from 400–800 nm due to Rayleigh scattering from nanoscale imperfections in the polymer matrix. The optical loss shows a reduction as wavelength lengthens until it reaches its lowest point within the 850–1000 nm range. The observed transmission behavior matches the proven optical characteristics of PMMA such that this material exhibits low loss throughout

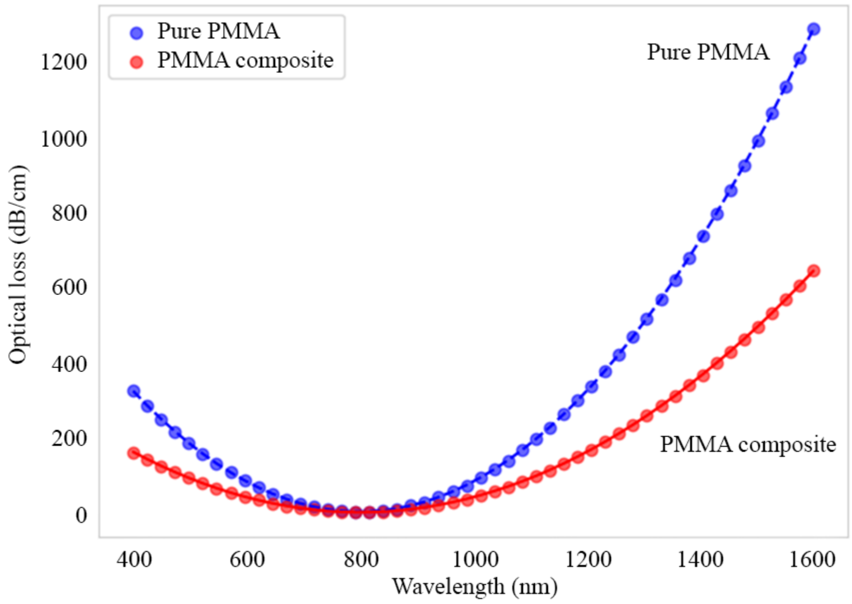

Figure 5. Optical Loss in PMMA-Based Waveguides

the near-infrared (NIR) range. The PMMA composite shows superior optical performance to pure PMMA throughout the entire spectrum because its incorporated nanoparticles and dopants suppress unnecessary scattering along with absorption. The improved characteristics of PMMA composites make them an excellent option for optical fiber applications in addition to optical interconnects and flexible photonic circuits since loss reduction was essential for effective light passage.

The optical loss of both materials enhances above 1000 nm wavelength yet the pure PMMA shows a rapid growth compared to the composite material. Rows of C-H bond overtones from the polymer emerged more strongly in the infrared region and caused the optical absorption to elevate. The modified structure of the composite material produces a gentle increase in optical loss that indicates the structural changes minimize losses to an extent. The high-refractive-index nanoparticles comprising TiO_2 or SiO_2 enhance mode confinement together with decreasing evanescent wave penetration into the absorbing polymer structure. The material brought these advantageous properties that make it suitable for optical communication uses inside fiber-optic waveguides and polymer-based PCFs.

Data trends in Figure 5 demonstrate that the usage of PMMA-based composites leads to superior optical properties compared to pure PMMA for photonic applications that need minimal loss. Manufacturers evaluate composite materials positively due to their superior performance characteristics which recommend them as an ideal candidate for optical communication networks and biosensing platforms and lab-on-chip photonic devices. The formulation process of composites with diverse nanoparticle species along with their concentrations allowed engineers to optimize optical characteristics and improve operational capabilities for photonic components made from PMMA. The combination of optical loss engineering capabilities with PMMA's existing processing easiness and price benefits and flexibility makes these composites stand as optimal materials for advanced photonic and optoelectronic system applications.

$$n_{eff} = n_{PMMA}\left(1 + f\,\frac{n_{dopant}^{2} - n_{PMMA}^{2}}{n_{PMMA}^{2} + 2n_{dopant}^{2}}\right) \quad (1)$$

The dispersion of nanoparticles in PMMA material enables modification of refractive index through Equation 1. The optical properties can be adjusted for photonic applications when dopant concentration was controlled through adjustment. Controlling the refractive index through specified methods improves light-guiding functions within optical waveguides.

$$T = \left(\frac{1-R}{1-R+A}\right) e^{-\alpha d} \tag{2}$$

The interaction between light and PMMA composite films depends on reflection as well as absorption and thickness and was described by Equation 2. Improved optical transmission emerges from decreased absorption loss because it was essential for photonic applications. Transmittance increases as a result of optimized nanoparticle dispersal which reduces absorption.

$$\alpha_{total} = \alpha_{abs} + \alpha_{scatt}$$

$$\alpha_{scatt} = \frac{8\pi^3}{3\lambda^4} r^6 N(m^2-1)^2 \tag{3}$$

The specification of optical loss from absorption and Rayleigh scattering within waveguides appears in Equation 3. The reduction of scattering loss occurs when waveguide efficiency grows through small nanoparticle radii and uniform dispersion. The achievement of superior signal transmission in photonic devices demanded decreased optical losses.

$$ln\left(\frac{\beta}{T_p^2}\right) = -\frac{E_a}{RT_p} + ln\left(\frac{AR}{E_a}\right) \tag{4}$$

The assessment of PMMA composite thermal stability through activation energy determination occurs through Equation 4. The presence of nanoparticles strengthens the materials by increasing their degradation temperature. The material becomes more resistant to heat degradation because of its increased thermal stability.

$$\frac{1}{T_g} = \frac{w_1}{T_{g1}} + \frac{w_2}{T_{g2}} \tag{5}$$

The glass transition temperature shift behaves according to Equation 5 when nanoparticles are added. Rephrase the following sentence. Improved thermal resistance combined with reduced polymer chain mobility leads to elevated transition temperatures. Such T_g modifications create improved technical qualities combined with enhanced thermal efficiency in materials.

$$T(t) = T_0 e^{-kt}$$

$$k = k_0 e^{-\frac{E_a}{RT}} \tag{6}$$

The degradation of optical transmittance under UV exposure follows the mathematical model in Equation 6. The degradation rate constant in PMMA composites rises with better UV resistance. The addition of stabilizing nanoparticles in materials limits photodegradation processes which enhances their operational lifetime.

Various structural and optical characterization techniques, as outlined in Table 4, are essential for evaluating the performance of PMMA-based photonic composites and ensuring their effectiveness in optical and communication applications. SEM plays a critical role in examining the distribution

Table 4. Structural and optical characterization techniques

Characterization method	Parameter analyzed	Purpose in PMMA composites
Scanning electron microscopy	Morphology and dispersion of nanostructures	Ensures uniform distribution of photonic materials
Atomic force microscopy	Surface roughness and nanostructure alignment	Optimizes surface texture for better optical performance
UV-Vis spectroscopy	Optical transparency and absorption	Determines light transmission efficiency
Ellipsometry	Refractive index and film thickness	Measures optical properties for waveguide applications
TGA/DSC analysis	Thermal stability and phase transition	Evaluates high-temperature resistance for longevity

patterns of nanostructures within the PMMA matrix. The uniform dispersion of nanoparticles such as TiO_2, SiO_2, and quantum dots directly influences light-scattering behavior and refractive index contrast key parameters for optimizing waveguides and display performance. Poor dispersion or clustering can degrade optical quality and structural uniformity, making SEM an indispensable tool during material synthesis and optimization. Atomic Force Microscopy (AFM) was used to measure surface roughness and nanostructure alignment, both of which significantly impact optical modulation, especially in holographic displays and electro-optic devices. Precise surface control enables enhanced reflection and light manipulation, which is essential for photonic system fidelity.

To assess optical transparency and absorption behavior, UV-Vis Spectroscopy was employed. This technique helps determine the material's ability to transmit or absorb specific wavelengths, which was critical for applications in optical fibers, flexible displays, and holographic films. High transmittance values confirm the optical clarity of doped PMMA composites, while unusual absorption peaks may indicate nanoparticle agglomeration or improper doping levels, requiring formulation adjustments for optimal performance. Ellipsometry provides accurate measurements of refractive index and film thickness, both essential for designing optical waveguides with minimized reflection and scattering losses. The ability to fine-tune these parameters ensures efficient light guidance and enhances the performance of integrated photonic components.

Thermal stability and phase transitions are assessed using Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC). These methods evaluate degradation behavior and glass transition temperatures, especially after incorporating electro-optic polymers and nanoparticles. Understanding thermal decomposition and phase behavior was critical for ensuring the durability of PMMA composites in high-power optical systems, outdoor displays, and heat-sensitive optical modulators. Together, these diagnostic methods SEM, AFM, UV-Vis Spectroscopy, Ellipsometry, TGA, and DSC, as summarized in Table 4 form a comprehensive evaluation framework. Enable the precise development of PMMA-based photonic composites that meet performance benchmarks in optical transparency, thermal resilience, and structural stability. These advancements support the emergence of next-generation materials for optical communication, holography, flexible displays, and biomedical photonics.

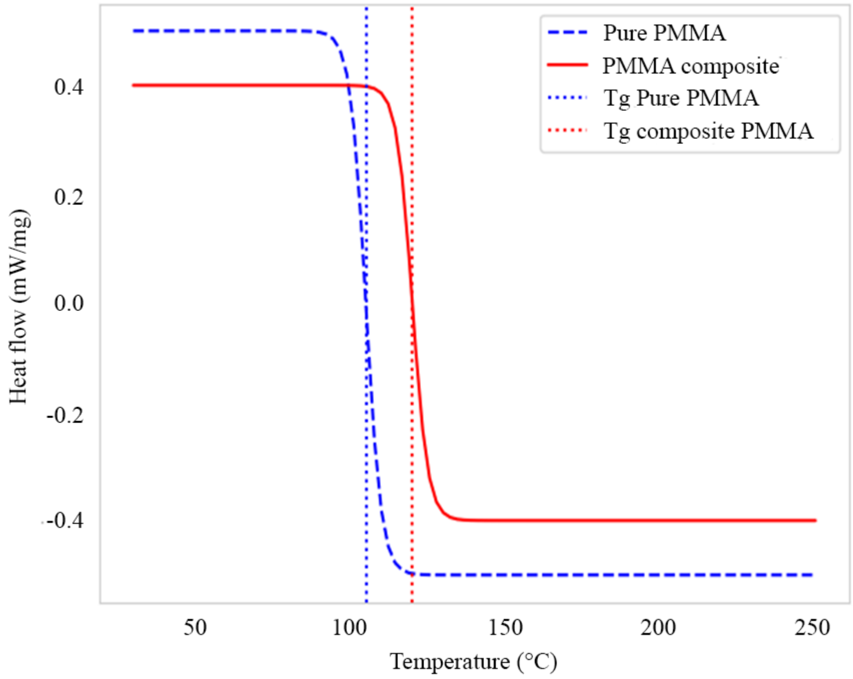

Figure 6. DSC Analysis: Glass Transition of PMMA Composites

Figure 6 showcases the glass transition temperatures of pure PMMA alongside its composites for PMMA because these temperatures dictate their thermal and mechanical properties during optical applications. The blue dotted line in Figure 6 marks the Tg temperature of pure PMMA which occurs at a lower point than the Tg temperature of the PMMA composite shown by the red dotted line. The elevated Tg of the PMMA composite material presents enhanced thermal stability features that improve performance in high-end optical communication systems that require stable signals at elevated operating temperatures in waveguides and modulators.

The glass transition temperature shift in PMMA composites results from the integrating nanoparticles or electro-optic polymers that tighten the polymer matrix by preventing molecular chain movement. Thermal stability of polymers improves when reinforcing agents like TiO_2, SiO_2 and quantum dots enhance the polymer network. Application of these display methods depended heavily on this important behavior because it protected refractive index stability and overall light modulation capabilities in OLED and holographic displays from thermal fluctuations. Regarding environmental changes PMMA composites maintain their optical clarity as well as structural stability because of their enhanced thermal capabilities.

The heat flow transition profile obtained from DSC testing provided critical data about pure PMMA and PMMA composite thermal responses. The PMMA composite displayed a sharp transition during the phase change process which indicates that modified intermolecular interactions strengthen the PMMA matrix stability. Manufacturing optical fibers and waveguides required a stable refractive index because this feature reduces optical losses. The elevated Tg value works to protect PMMA-based components from premature softening or deformation while these components are used in PCFs and flexible optical devices utilized in wearable photonics and communication systems.

Results from DSC analysis presented in Figure 6 confirm how the thermal properties of PMMA composites achieve superior levels than pure PMMA so suitable for specialized photonic applications. The thermal stability upgrade of these composites extends operational longevity which makes them suitable for application within high-temperature systems such as lasers systems and optical communication networks as well as next-generation flexible displays. Nanomaterial content optimization alongside dispersion improvement within the PMMA matrix allows researchers to advance the thermal and optical characteristics which brings opportunities for their integration into emerging optoelectronic and photonic devices.

The testing of optical transmission properties using UV-Vis spectroscopy on PMMA-based photonic composites enables research into their potential application as optics. Figure 7 shows how the transmission distribution of optical signals varies across wavelengths through visual representation of improved PMMA composite transmittance against standard pure PMMA samples. Studies

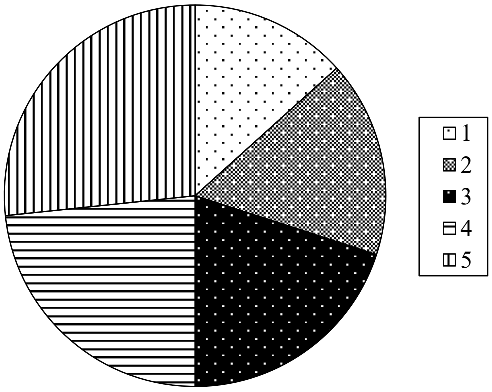

Figure 7. Optical Transmission (UV-Vis Spectroscopy)

Table 5. Optical Transmission (UV-Vis Spectroscopy)

Wavelength (nm)	**Pure PMMA transmittance (%)**	**PMMA composite transmittance (%)**	**Absorption (%)**
400	88	92	8
500	90	94	6
600	92	96	4
700	94	97	3
800	95	98	2

presented in Table 5 illustrate PMMA composites surpass pure PMMA transmission through visible wavelengths along with near-infrared frequencies until reach 98% at 800 nm. The addition of optically active nanomaterials including TiO_2, SiO_2 and electro-optic polymers enhanced transmission because optimized light propagation while reducing scattering losses thus enabling PMMA composites to be highly effective for display technology and optical waveguides and high-performance coating applications.

Improved transmission levels within PMMA composites resulted mainly from reduced absorption losses. The absorption rate of PMMA composites declines at higher wavelengths so that it reaches minimal levels of approximately 2% at 800nm wavelength as confirmed by Table 5. The absorption-reducing characteristic proved ideal for optical communication because lower light attenuation levels are needed for effective signal transmission. Materials based on PMMA acquire polish from controlling transmittance by embedding nanoparticles and modifying materials which makes them useful for PCFs, laser systems and holographic imaging systems.

The optical transmission characteristics of various materials appear in Figure 7 for direct comparison. The modified PMMA composites demonstrate enhanced optical transmittance as their main characteristic through modifications which lead to better energy efficiency and optical clarity. For display applications including LCD and OLED screens more transmission leads to better visual brightness together with reduced power requirements. Wearable photonic devices that require advanced AR and VR displays benefit from superior transparency because it allows better control of light manipulation operations.

Analysis of Figure 7 together with Table 5 confirms that PMMA composite materials outperform pure PMMA for photonic application purposes through superior optical transmission properties. Next-generation optical materials use these materials because possess higher transparency and reduced absorption and improved light propagation capabilities. Through advanced material engineering combined with doping approaches PMMA composites become application-specific making them ready for modern optoelectronic systems delivering excellent performance. Future investigations should pursue property improvement by combining emerging nanomaterials with hybrid polymer structures to extend the prospective usages of PMMA-based photonic materials.

The UV stability behavior of PMMA composites which can be observed in Figure 8 served as a vital element to evaluate their prolonged optical characteristics. The graph compares the optical transmittance degradation of pure PMMA and PMMA composites over an extended aging period under UV exposure. The research shows PMMA composites possess better UV protection than pure PMMA materials because maintain higher transmittance rates during the testing period. Damage protection results from adding TiO_2, SiO_2 and quantum dots nanoparticles to the material structure because these UV-blocking agents defend against photodegradation by limiting structural damage exposure to continuous UV radiation.

Dopants and nanostructures present in PMMA composites demonstrate outstanding performance through their capability to deter the formation of free radicals along with chain scission processes which normally damage polymer matrices during exposure to UV light. Untreated PMMA shows

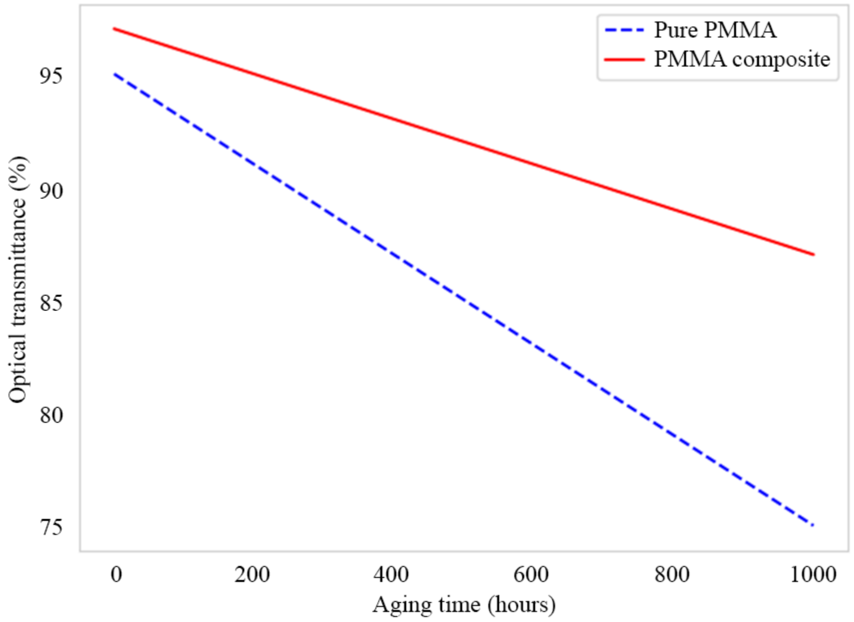

Figure 8. Accelerated Aging: UV Stability of PMMA Composites.

severe optical transmittance degradation during 1000-hour UV exposure because it contains no stabilizing additives which results in optical transmittance reaching 75%. The transmittance values of PMMA composites remain at 88-90% while exposing them to UV light which demonstrates their effectiveness against both discoloration and surface deterioration. The outdoor utility of solar panels and protective coatings and optical lenses depended on this stability because sunlight exposure affects their performance in the long term.

The PMMA composites show a gradual decrease in optical transparency which indicates that UV degradation received some mitigation but completely eliminated protection was not achieved. The material durability of these products could get additional enhancement through supplementary UV-absorbing agents alongside cross-linking strategies. The progressive loss of transmittance demonstrated a well-predictable degradation behavior that made it useful for designing maintenance plans and lifetime predictions of photonic components constructed from these composites. The modification of composite formulations allows PMMA-based materials to gain enhanced UV resistance which creates high adaptability for extended optical performance and durable stability needs.

Test results in Figure 8 demonstrate how PMMA composites far outperform pure PMMA in terms of UV stability thus making them appropriate for cutting-edge optical applications. The nano-filled materials with UV-blocking components have better longevity and better performance retention throughout the lifespan. Enhanced resistance against UV-induced aging allows better applicability of these materials in optoelectronic systems as well as in architectural glazing and high-performance coatings. Next-generation photonic systems require future research to combine multi-functional additives which improve both UV stability with enhanced mechanical and thermal performance.

The surface morphology alongside structural details of PMMA composite material can be studied through the SEM image in Figure 9 at 100x magnification. The examined microstructure shows extensive interconnection together with textured surfaces which confirms the presence of nanostructures or dopants in the polymer matrix. The sophisticated PMMA composite morphology functions as a significant factor since it governs the light scattering behavior, refractive index modification, and structural strength of the composite through nanoparticle dispersion features including TiO_2, SiO_2, or quantum dots. Surface feature diversity indicates that the integrated nanoparticles have been successfully implemented to boost photonic properties.

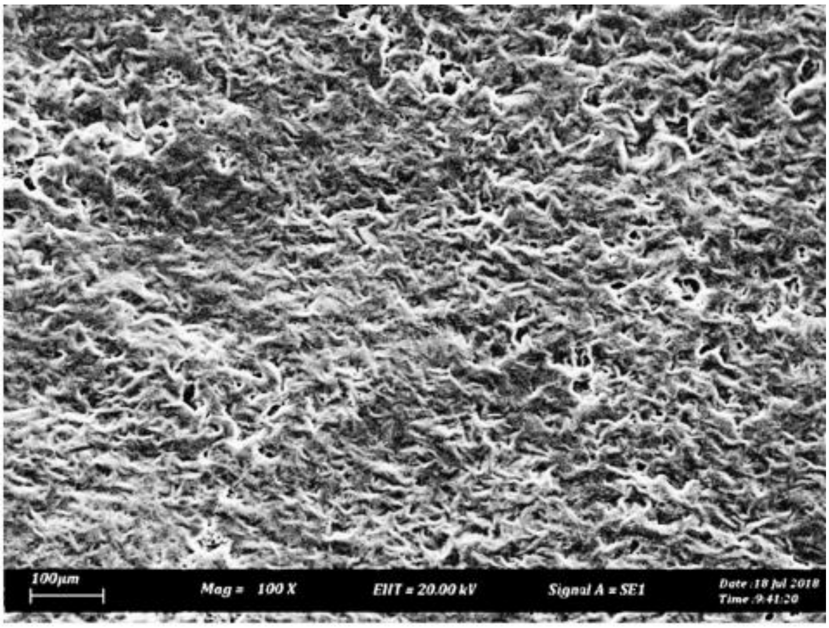

Figure 9. SEM Image of PMMA Composite Surface

The SEM image showed a porous and roughened texture that exist from phase separation or controlled nanofiller aggregation and polymer-nanoparticle interactions. The developed morphology proved beneficial in optical applications since its surface roughness improved light trapping as well as waveguiding properties which makes them appropriate for photonic waveguides and anti-reflective coatings and high-efficiency optical films. For optimal optical transmission and minimized scattering losses it was necessary to have uniform distribution of these structures throughout the material. Integrated domains in the architecture work to boost mechanical stability since restrict cracks from advancing which proves essential for extended optical service life.

The observation of surface characteristics in Figure 9 implies the possibility to achieve adjustable refractive index properties. Intentionally embedding nanoparticles into polymers allows researchers to manipulate local density variations that enable graded-index waveguide production as well as the development of metamaterials. The integrated rough surface quality creates better multi-coating adhesion potential that enables the construction of hybrid photonic components. A fundamental component of the polymer/nanostructure composite affects both operational stability and visible light transmission as well as mechanical strength and thermal performance.

The illustration in Figure 9 shows the successful fabrication of PMMA-based composites featuring well-controlled surface textures which proves the value of adding nanoparticles for photonic device applications. At the microscale level the textured and rough surface indicates improved light scattering capabilities with adjustable refractive indices and expanded mechanical toughness. Advanced characterization methods using AFM and ellipsometry should be employed in future studies to understand how surface morphological features influence optical wave propagation because provide precise measurements of roughness parameters.

The SEM images in Figure 10 show PMMA-based photonic composites at a high level of detail to display how nanoparticles distribute across the matrix and interact with it. This present SEM image demonstrates a higher degree of nanoparticle dispersion and aggregation while showing greater surface texture when compared to preceding images. The densification of nanostructures enhances both interfacial polymer chains-material interactions and it affects optical properties and mechanical characteristics of composites. Surface roughness affects light scattering properties which leads to modification of optical transmittance and control of refractive index applications in photonic devices.

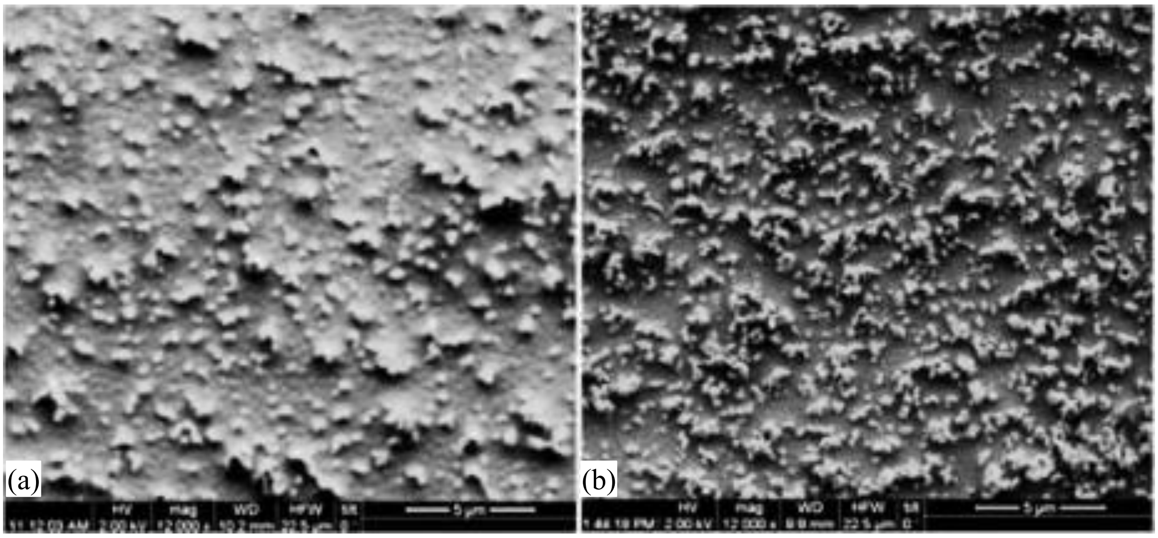

Figure 10. SEM Images of PMMA Composite Surfaces

The composite surface exhibited different-sized particles that were visible in Figure 10. The synthesis process demonstrates non-uniformity in the product because nanoparticle loading concentration along with polymer curing conditions influence the outcomes. The dispersion control of nanoparticles remained essential for photonic applications to achieve refined refractive index modifications. The waveguide efficiency together with transparency suffer when nanoparticles cluster excessively while uniform nanoparticle distribution promotes enhanced optical homogeneity. Fundamental properties of microscalpelling received significant analysis through SEM data when examining multiple manufacturing protocols.

The surfaces of Figure 10 appear rougher than smoother composites because this roughness could cause more light scattering at polymer-nanoparticle interfaces. The beneficial effects of moderate light scattering in certain optical applications become counterproductive when scattering increases because of excessive surface roughness. The reduction of surface defects maintained high importance in photonic waveguides and optoelectronic devices because it ensured efficient light propagation. The surface finish level maintains a direct relationship with mechanical reliability because rough texture strengths the material bonding but creates points of stress concentration which affects product durability across heating cycles and mechanical usage.

Figure 10 demonstrates that researchers need to optimize three nanoparticle dispersion approaches: solvent-based processing and in situ polymerization and surface functionalization methods. The optimization of these parameters allowed researchers to find the perfect balance between PMMA-based mechanical stability and optical transparency to satisfy the needs of advanced photonic products. The SEM analysis functions as a vital instrument for enhancing composite materials and their design process to develop new-generation high-performance optical elements.

CONCLUSION

- Adding nanoparticles, electro-optic polymers, and dopants to PMMA composites improves optical transmission, reduces optical losses, and enhances thermal stability.
- Functional additives increase refractive index contrast and minimize scattering, making the composites suitable for waveguide and photonic applications.
- Thermal analysis shows higher glass transition temperatures and stronger resistance to decomposition, supporting operation under elevated temperatures.
- SEM and AFM analyses confirm uniform nanoparticle dispersion, contributing to better mechanical strength and optical homogeneity.

- Accelerated UV aging tests demonstrate improved durability, with composites resisting degradation over extended exposure periods.
- Optimized PMMA composites offer a viable alternative to traditional inorganic photonic materials, with added benefits of transparency, flexibility, and ease of manufacturing.
- These materials are applicable in optical waveguides, display systems, holographic films, and other high-performance photonic devices.
- Further research should explore new nanostructures and hybrid polymer systems to enhance overall stability and functionality.
- The findings affirm the importance of PMMA composites in advancing durable and efficient materials for modern photonic technologies.

REFERENCES

1. Kim, J., Seong, J., Kim, W., Lee, G. Y., Kim, S., Kim, H., ... and Rho, J. (2023). Scalable manufacturing of high-index atomic layer–polymer hybrid metasurfaces for metaphotonics in the visible. Nature Materials, 22(4), 474-481.
2. Zhu, Y., Tang, T., Zhao, S., Joralmon, D., Poit, Z., Ahire, B., ... and Li, X. (2022). Recent advancements and applications in 3D printing of functional optics. Additive Manufacturing, 52, 102682.
3. Márquez, A., Li, C., Beléndez, A., Maier, S. A., and Ren, H. (2023). Information multiplexing from optical holography to multi-channel metaholography. Nanophotonics, 12(24), 4415-4440.
4. Ko, B., Jeon, N., Kim, J., Kang, H., Seong, J., Yun, S., ... and Rho, J. (2024). Hydrogels for active photonics. Microsystems and nanoengineering, 10(1), 1.
5. Almasri, R. M., Ladouceur, F., Mawad, D., Esrafilzadeh, D., Firth, J., Lehmann, T., ... and Al Abed, A. (2023). Emerging trends in the development of flexible optrode arrays for electrophysiology. APL bioengineering, 7(3).
6. Serpe, F., Casciola, C. M., Ruocco, G., Cidonio, G., and Scognamiglio, C. (2024). Microfluidic fiber spinning for 3D bioprinting: Harnessing microchannels to build macrotissues. International Journal of Bioprinting, 10(1), 47-74.
7. Madrid Wolff, J. A. (2023). Volumetric additive manufacturing in a scattering resin (Doctoral dissertation, EPFL).
8. Liu, Y. (2024). Remote Epitaxy by In-Situ Grown BN and InGaN Strain Relaxation (Doctoral dissertation, Massachusetts Institute of Technology).
9. Hwang, H. H. (2022). Digital Light Processing (DLP)-Based 3D Printing for Microphysiological Systems Applications. University of California, San Diego.
10. Li, Y., Zhang, D., Zeng, X., Liu, C., Wu, Y., and Fu, C. (2024). Advances in Aptamer-Based Biosensors for the Detection of Foodborne Mycotoxins. Molecules, 29(16), 3974.
11. Shao, X., Yan, C., Wang, C., Wang, C., Cao, Y., Zhou, Y., ... and Ding, S. (2023). Advanced nanomaterials for modulating Alzheimer's related amyloid aggregation. Nanoscale Advances, 5(1), 46-80.
12. Tomholt, L. (2022). Biologically inspired compliant building façade systems with tunable heat transfer capabilities (Doctoral dissertation, Harvard University).
13. Gupta, S. K., Budaszewski, D., and Singh, D. P. (2022). Ferroelectric liquid crystals: futuristic mesogens for photonic applications. The European Physical Journal Special Topics, 231(4), 673-694.
14. Li, Y., Huang, X., Liu, S., Liang, H., Ling, Y., and Su, Y. (2023). Metasurfaces for near-eye display applications. Opto-Electronic Science, 2(8), 230025-1.
15. Islam, M. S., Chan, K. Y., Thien, G. S. H., Low, P. L., Lee, C. L., Wong, S. K., ... and Ng, Z. N. (2023). Performances of polymer-dispersed liquid crystal films for smart glass applications. Polymers, 15(16), 3420.
16. Liu, S., Du, Y., Zhang, R., He, H., Pan, A., Ho, T. C., ... and Tso, C. Y. (2024). Perovskite smart windows: the light manipulator in energy-efficient buildings. Advanced Materials, 36(17), 2306423.

17. Jeon, N., Noh, J., Jung, C., and Rho, J. (2022). Electrically tunable metasurfaces: from direct to indirect mechanisms. New Journal of Physics, 24(7), 075001.
18. Almasri, R. M., Ladouceur, F., Mawad, D., Esrafilzadeh, D., Firth, J., Lehmann, T., ... and Al Abed, A. (2023). Emerging trends in the development of flexible optrode arrays for electrophysiology. APL bioengineering, 7(3).
19. Jiang, C., Ge, R., Bian, C., Chen, L., Wang, X., Zheng, Y., ... and Xiao, X. (2023). Multicolored inorganic electrochromic materials: status, challenge, and prospects. Nanoscale, 15(38), 15450-15471.
20. Kompanets, I. N., and Pozhidaev, E. P. (2023). Liquid Crystals in Laser Technique. Bulletin of the Lebedev Physics Institute, 50(Suppl 4), S451-S461.
21. Yu, T., Bi, J., Wei, W., and Su, X. (2022). Monodisperse colloidal spheres with a high refractive index: their synthesis, assembly and application in structural colored materials. Journal of Materials Chemistry C, 10(46), 17451-17471.
22. Chen, Z., Zhao, Z., Ding, L., Li, Y., Zhang, Y., Wang, Z., ... and Geng, F. (2024). Inorganic nanosheets-based electro-optic devices with single-pixel full-color and gray scale control. Applied Physics Reviews, 11(4).
23. Shi, X., Lei, Z., and Wu, P. (2022). An intelligent light-managing ionic skin for UV-protection, IR stealth, and optical camouflaged Morse codes. Science China Materials, 65(8), 2281-2288.
24. Islam, M. S., Chan, K. Y., Thien, G. S. H., Low, P. L., Lee, C. L., Wong, S. K., ... and Ng, Z. N. (2023). Performances of Polymer-Dispersed Liquid Crystal Films for Smart Glass Applications. Polymers 2023, 15, 3420.
25. Kumar, A. C. (2022). 11.1 Liquid crystals (LC) and hybrid nanocomposites: An overview. Functional Materials Processing for Switchable Device Modulation, 201.
26. Reda, F., Salvatore, M., Borbone, F., Maddalena, P., Ambrosio, A., and Oscurato, S. L. (2022). Varifocal diffractive lenses for multi-depth microscope imaging. Optics Express, 30(8), 12695-12711.
27. Li, T., Li, Q., Tang, X., Chen, Z., Li, Y., Zhao, H., ... and Yao, J. (2021). Environment-friendly antisolvent tert-amyl alcohol modified hybrid perovskite photodetector with high responsivity. Photonics Research, 9(5), 781-791.
28. Li, M., Zhou, S., Cheng, L., Mo, F., Chen, L., Yu, S., and Wei, J. (2023). 3D printed supercapacitor: techniques, materials, designs, and applications. Advanced Functional Materials, 33(1), 2208034.
29. Taralp, A. (2024). Polymer Dispersed Liquid Crystal Smart Film Technologies: Overview. Revolutionizing Energy Conversion-Photoelectrochemical Technologies and Their Role in Sustainability: Photoelectrochemical Technologies and Their Role in Sustainability, 125.
30. Sen, C., Alkan, B., Mohammadmoradi, O., and Taralp, A. (2024). Polymer Dispersed Liquid Crystal Smart Film Technologies: Overview. Revolutionizing Energy Conversion-Photoelectrochemical Technologies and Their Role in Sustainability.
31. Madrid Wolff, J. A. (2023). Volumetric additive manufacturing in a scattering resin (Doctoral dissertation, EPFL).
32. Uji, S., Kimura, S., Nakamura, K., and Kobayashi, N. (2023). Analysis for coloration mechanism of reversible silver deposition-based electrochromic device by in situ observation of plasmonic nanoparticles with dark-field microscopy. Solar Energy Materials and Solar Cells, 251, 112119.
33. Basumatary, F., Sarkar, A., Mushahary, N., Das, B., Saikia, P., Selvaraj, M., and Basumatary, S. (2024). Graphitic carbon nitride composites as advanced versatile materials for adsorption and photocatalytic degradation of emerging pollutants from wastewater. Process Safety and Environmental Protection.
34. Politakos, N. (2023). Block copolymers in 3D/4D printing: Advances and applications as biomaterials. Polymers, 15(2), 322.
35. Mamuk, A. E. (2023). A comparative study on electrospun fibers of cyanobiphenyl liquid crystal homologues. Fullerenes, Nanotubes and Carbon Nanostructures, 31(8), 752-765.

36. Guan, Q., Lim, Z. H., Sun, H., Chew, J. X. Y., and Zhou, G. (2023). Review of miniaturized computational spectrometers. Sensors, 23(21), 8768.
37. Kumar, A. C. (2022). A bistable electrooptical novel switching of phase variance in liquid crystalline hybrid materials. In Functional Materials Processing for Switchable Device Modulation (pp. 201-220). Woodhead Publishing.
38. Wang, P., Pyo, S. H., Zhu, W., Hwang, H., and Chen, S. (2023). 3D Printing of Polyurethanes for Biomedical Applications. In Emerging Technologies in Biophysical Sciences: A World Scientific Reference: Volume 1: Emerging Technologies for Biofabrication and Biomanufacturing (pp. 389-406).
39. Ren, M., Xu, J., Lan, P., Lu, P., Li, Z. Y., Hong, L. H., ... and Shi, K. (2023). Roadmap on nonlinear optics–focus on Chinese research. Journal of Physics: Photonics, 5(3), 032501.
40. Liu, Y., Lv, W., Feng, J., Tian, J., Wang, P., Xu, L., ... and Yao, L. (2024). Emerging thermochromic perovskite materials: insights into fundamentals, recent advances and applications. Advanced Functional Materials, 34(37), 2402234.